

Condition Assessment of High Voltage Insulation in Power System Equipment

R.E. James and Q. Su

Condition Assessment of High Voltage Insulation in Power System Equipment

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The Institution of Engineering and Technology

Published by The Institution of Engineering and Technology, London, United Kingdom

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First published 2008

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British Library Cataloguing in Publication Data

James, R. E.

Condition assessment of high voltage insulation in power system equipment. - (Power & energy series; v. 53)

1. Electric insulators and insulation - Testing 2. High Voltages

I. Title II. Su, Q. III. Institution of Engineering and Technology

621.3'1937

ISBN 978-0-86341-737-5

Typeset in India by Newgen Imaging Systems (P) Ltd, Chennai
Printed in the UK by Athenaeum Press Ltd, Gateshead, Tyne & Wear

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Preface

The need for increased reliability and optimum economic performance of high-voltage power systems has become of greater importance in recent years. A major factor in achieving these objectives is the provision of efficient maintenance of the wide range of equipment. This applies especially to the assessment of the condition of the insulating materials, many of which are subjected to high electrical stresses in critical locations. The rates of deterioration of these materials are dependent on the operating conditions and, in some cases, materials are expected to retain their useful properties for forty years. In order to monitor any dangerous changes in the insulating materials, much work is being carried out worldwide in the universities and similar establishments, as well as by utilities and plant manufacturers.

This book introduces the reader to the manner in which the more important components in a power system are interrelated. The various electrical insulating materials are reviewed and particular properties identified as being suitable for condition assessment and monitoring. A guide is given as to how electric stress calculations may assist in explaining insulation failures. Analyses are included of some of the fault scenarios occurring in high-voltage power-system equipment. The second half of the book is devoted to presentation of a wide range of insulation-condition assessment techniques. Recent advances in the application of digital techniques for measurement and analysis of partial discharges are discussed. Descriptions are given of the high-voltage test apparatus necessary for applying withstand tests according to the various equipment standards. In the last three chapters new condition monitoring methods in use or under development are presented. These include applications of new sensors, online problems with particular solutions and the use of artificial-intelligence techniques for incipient fault diagnoses. Extensive references are included.

The subject matter of the book is suitable for final-year courses in electrical power engineering, for short courses on insulation-condition assessment and for postgraduate programmes involved with the study of insulating materials. Power-system engineers associated with high-voltage equipment should find the book of value in relation to fault investigations, maintenance requirements, insulation testing and condition monitoring.

Both authors have significant industrial experience in the United Kingdom (REJ) and China/Singapore (QS) and in teaching and research at Portsmouth Polytechnic (REJ), University of NSW (REJ, QS) and Monash University (QS). During the latter periods many consultancies concerned with industrial high-voltage insulation problems were undertaken. We wish to acknowledge the value of our association with many ex-colleagues in industry and the universities and those in the various utilities with whom we have worked.

Our thanks are especially due to our wives and families – Felicia (REJ), Liling and daughter Shirley (QS) – for their patience and understanding during writing of the book.

R.E. James
Q. Su

Chapter 1

Introduction

- Power system components
- Insulation coordination concepts and high-voltage test levels
- Need for insulation condition monitoring

A high-voltage power system consists of a complex configuration of generators, long-distance transmission lines and localized distribution networks with above- and below-ground conductors for delivering energy to users. This introductory chapter indicates the wide range of high-voltage components whose successful operation depends on the correct choice of the electrical insulation for the particular application and voltage level. The condition of the insulating materials when new, and especially as they age, is a critical factor in determining the life of much equipment. The need for effective maintenance, including continuous insulation monitoring in many cases, is becoming an important requirement in the asset management of existing and planned power systems.

As the voltages and powers to be transmitted increased over the past hundred years the basic dielectrics greatly improved following extensive research by industry and in specialized laboratories, where much of this work continues. It is of interest to note that paper, suitably dried and impregnated, is still used for many high-voltage applications. New dielectrics are being introduced based on many years of research and development and are becoming more widespread as operational experience is obtained. In order to ensure an economic power-supply system with a high level of reliability, it is important to be able to monitor the dielectric parameters of the various insulations being utilized – when new and in service. Later chapters describe the materials and their applications, including examples of possible fault scenarios, dielectric testing techniques for completed equipment, new and existing condition monitoring systems and, finally, the application of artificial intelligence in incipient fault diagnosis and condition assessment.

Present power systems are ageing significantly and in many cases 40 per cent of the equipment is older than the conventional ‘design life’ of 25 years. This figure was probably chosen because of the uncertainties in estimating the anticipated lives of

the practical insulation structures and for commercial reasons. In fact, many system components are still functioning satisfactorily after much longer periods. This is possibly due to the relatively low average electric stress values used to allow for inherent inaccuracies in calculations of maximum values within the complex structures. The development of suitable computer programs has enabled much improved designs to be achieved. Also, in many systems the circuits were operated in parallel to cater for overloading and possible failure of one line or unit. This configuration probably resulted in the average dielectric temperatures being below the allowable maxima. The situation is changing with the need for the managed assets to realize maximum economic returns. It is only by effective condition monitoring over long periods that data can be acquired, thus enabling the rate of deterioration of the insulation structures to be determined in service. This would naturally include the influence of possible generic manufacturing and design faults as well as inappropriate maintenance. Trends in such data assist in the more reliable prediction of the remaining life of equipment, possibly including the application of probabilistic techniques.

1.1 Interconnection of HV power system components

Contemporary system voltages range up to 1 000 kV(RMS three-phase) or higher and 600 kV(DC), although the more usual AC values are 500/750 kV and below. Bulk powers greater than 1 000 MW may be transmitted by a single three-phase circuit over long distances, in some cases for more than several hundred kilometres. Local delivery ratings may be of many tens of MVA down to a few kVA.

The application of renewable sources – for example solar devices, wind generators, biomass generation and small hydro-plants – is becoming more important. Within ten years it might be expected that embedded generation from such sources could contribute between 10 and 20 per cent of the total power in some countries, although commercial problems may limit the developments [1]. The form of the existing power system infrastructures would probably not change significantly for such conditions, especially where high levels of energy are required at a particular location. The newer sources will operate locally at low voltages and include conventional step-up systems where they are coupled to the main distribution/transmission system. Special insulation problems will be involved but these are outside the scope of the conditions considered in this book. Descriptions of how renewable sources are being developed and the possible effects of their dispersion within the established power systems are discussed in the literature.

Although the majority of power systems transmit at alternating frequencies, a significant number incorporate direct voltages. This requires special equipment and introduces different insulation problems, some of which are considered later.

1.1.1 Alternating voltage systems

The major components of a system with their possible relative locations at a power station and in substations are indicated simply in Figure 1.1.

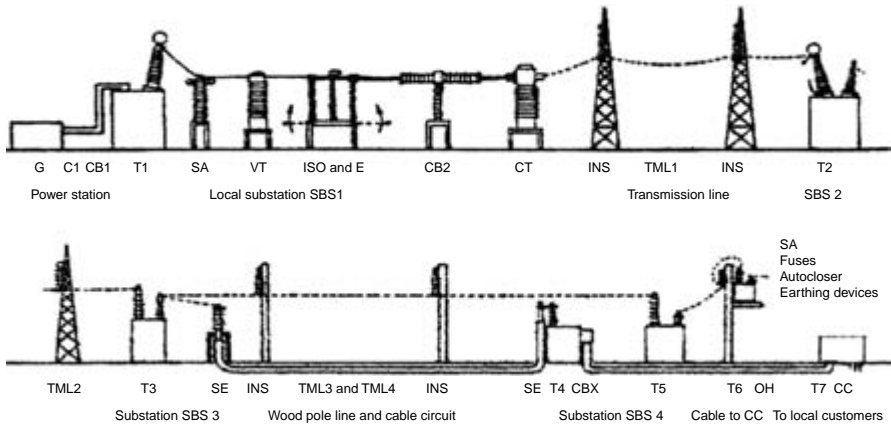


Figure 1.1 Basic system for generation, transmission and distribution of AC power

The systems are based on three-phase configurations, although many of the individual elements are single-phase. Each device must have appropriate electrical insulation for its particular structure. Many of the methods by which this is achieved are discussed in Chapters 3–5 and techniques for assessing the condition of the materials when new and in service are described in subsequent chapters.

At the power stations the generators (**G**) may be driven by diesel (oil) engines, gas turbines, water turbines or steam turbines – the last of these being most usual for the larger machines. Generation voltages in large systems range from 12 kV to 24 kV (perhaps up to 33 kV in a few cases) with current ratings of 1 500 A up to 16,000 A or larger. These high currents are fed through cables (**C1**), or metal-enclosed bus conductors of large cross sections, to the low-voltage windings of the step-up ‘generator’ transformers (**T1**). High-current circuit breakers (**CB1**) may be installed between the generator and transformers. The conductors required from the high-voltage terminals of **T1** are of reduced dimensions, thus allowing power transfer by the use of bare overhead cables through a local substation (**SBS1**) and then over long distances (**TML1**) or, within cities, through fully insulated underground cables (**TML4**).

At the receiving end of the various lines, a step-down ‘transmission’ transformer (**T2**) is connected. Such units are often wound as autotransformers, especially if the lower voltage is at an intermediate level (e.g. 145 kV) for secondary transmission (**TML2**) or for supplying a city’s major distribution system. The system feeds double-wound transformers (**T3**) with outputs of the order of 66–33 kV (**TML3** and **TML4**) for reduction of the voltages (**T4–T7**) to customer operating levels in the range 12 kV to 415 V/220 V/110 V. A cable-fed control cubicle (**T7CC**) is shown for underground supply to a number of domestic customers. Large industrial organizations may purchase power at the higher voltages and install their own local substation. The choice of voltage ratios, and the required transformer impedance

values between windings depend on many factors related to the particular supply and load conditions. Numerous books and technical papers have been published on this subject [2].

At the major changes in voltage where primary lines (or generator(s)) feed a number of other lines a substation (**SBS1–SBS4**) is constructed for control of the individual circuits: for monitoring the real and reactive power flows possibly including an optical fibre-coupled thyristor firing system for operation of static VAR compensators (perhaps of the relocatable form [3]) and for protection of the system when subjected to faults and overvoltages. The various devices, some of which are represented in Figure 1.1, must be insulated for the different service voltages – including surges – to ground and between phases. Switching and isolation are provided by circuit breakers and air isolators (**CB2** and **ISO**). The current magnitudes and steady state voltages are monitored by current (**CT**) and voltage (**VT**) transformers of various designs. Surge voltages due to lightning and switching are limited by surge arresters (**SA**) and air gaps – for example across transformer bushings (**T2**), circuit-breaker insulation and at the entry to a substation. Where a high-voltage conductor passes through an earthed tank a bushing is required as in power transformers, ‘dead tank’ instrument transformers, some older oil circuit breakers and in gas-insulated systems (GIS). The overhead lines (**TML1–TML3**) must be supported with insulator strings or similar (**INS**) capable of withstanding the various voltages and adverse weather conditions – again rod gaps and surge arresters may be utilized for protection.

The machine floors of a steam-turbine-generator and a hydro-generator power station are depicted in Figures 1.2 and 1.3 respectively. The complexity of outdoor substations is indicated in photographs, Figures 1.4–1.6, in which may be identified many of the items in Figure 1.1. The components in substation SBS1 are present in one form or other in all levels of high-voltage substations often including cable-sealing ends (SE) as in SBS3 and SBS4. A large system would involve many lines and plant items.

Following the development of GIS, it has been possible to design and build compact substations for very high voltages. Many examples of this application exist where space is limited – near or in major cities.

At the lower voltages much maintenance is necessary to ensure high reliability of supply in the local distribution system. In Figure 1.7 are shown different aspects of such a system in a built-up area. The 415 V house supplies are fed from the 11 kV overhead lines through a pole-mounted transformer, Figure 1.7(a), and Figure 1.1 (T6), by means of either overhead wires (Figure 1.7(a)) or a three-phase cable to cubicles located several hundred metres away in a housing complex (Figure 1.7(c)). Each unit (Figure 1.7(c) and T7CC in Figure 1.1) contains a step-down transformer with appropriate protection for the outgoing 415 V cable circuits. The items of particular interest in relation to insulation are the surge arresters, cable and sealing ends, 11 kV fuses, the various line and stand-off insulators, the oil-filled transformer and, of course, the wooden poles. The pole in Figure 1.7(b) was being replaced because of termite damage but this operation could have been necessary following a lightning strike or even a bush fire.



Figure 1.2 Steam turbine-generator [4] [reproduced by permission of CIGRE]



Figure 1.3 Hydro-generator [5] [reproduced by permission of CIGRE]



Figure 1.4 330 kV substation. Note (from left to right) – current transformers, SF₆ circuit breakers, support insulators for air isolators/automatic earthing arms [reproduced by permission of TRANSGRID, New South Wales]



Figure 1.5 330 kV substation. Note insulator strings and corona rings [reproduced by permission of TRANSGRID, New South Wales]



Figure 1.6 132 kV isolator with good corona design. Note automatic earthing arms in foreground

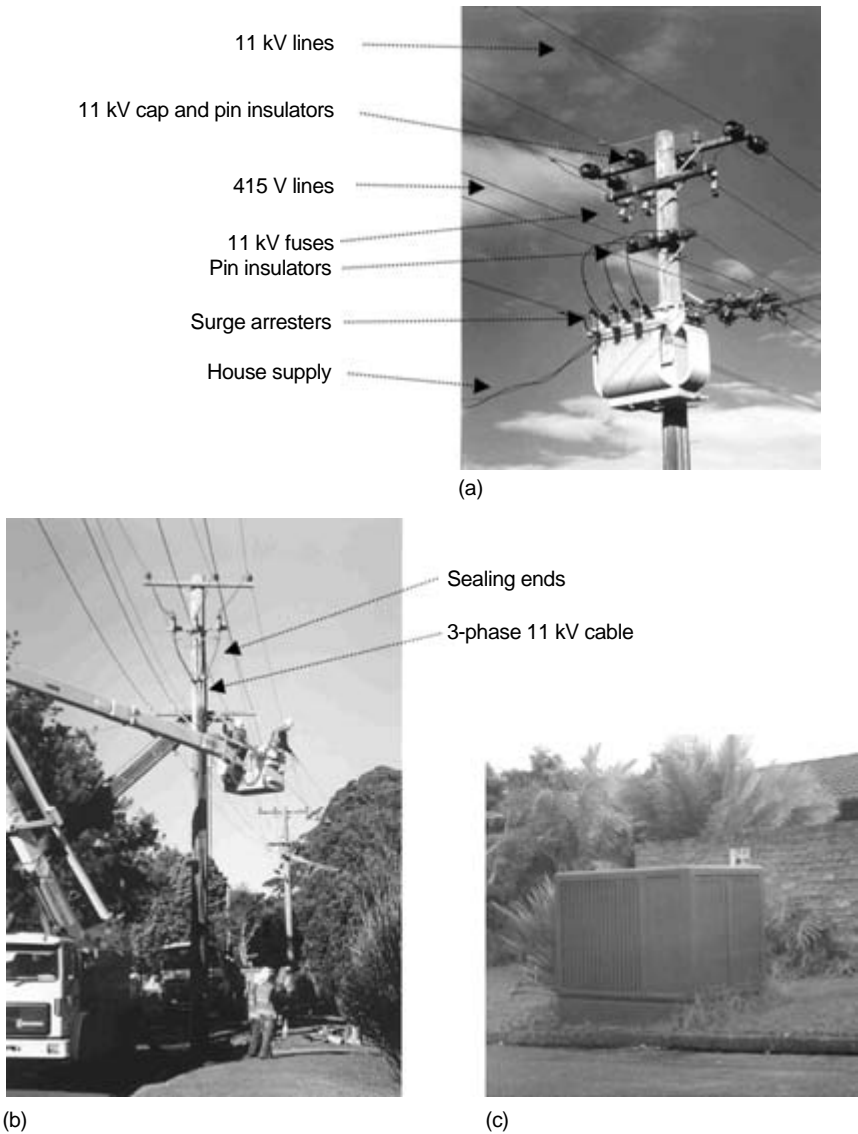


Figure 1.7 11 kV and 415 V local supply systems. (a) 11 kV/415 V pole-mounted transformer; (b) 11 kV overhead line to 11 kV three-phase cable. Pole maintenance; (c) A 415 V cubicle substation. Note surge arresters, 11 kV cable sealing ends, 11 kV fuses, line insulators and 415 V wires to houses.

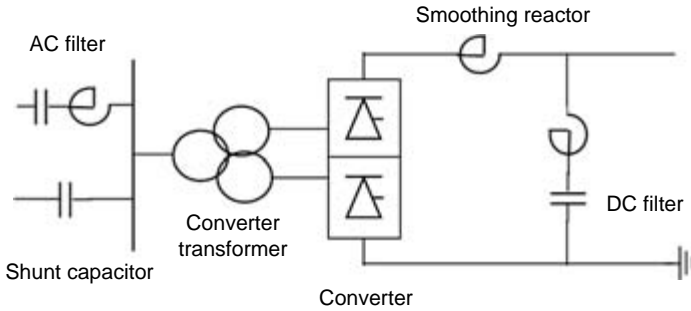


Figure 1.8 Principle of an HVDC transmission scheme

1.1.2 Direct-voltage systems

In effect a direct-voltage system is a hybrid circuit incorporating AC and DC components (see Figure 1.8). The incoming power is from an alternating source, which is rectified and filtered before transmission through the DC system, inversion taking place at the receiving end in order to provide the usual AC supply conditions. The harmonics produced by the converters are reduced by filters comprising R, L and C elements. The earlier significant systems included that from the Swedish mainland to Gotland (150 kV, 1954), the original cross-Channel connection between France and England (± 100 kV, 1961), the crossing between the North and South Islands of New Zealand (± 250 kV, 1965), the 50 Hz/60 Hz tie in Japan (125 kV, 1965), the link between Sardinia and the Italian mainland (200 kV, 1967), the overhead line from Volgograd to Donbass (± 400 kV, 1965) and the Pacific Intertie in the USA (± 400 kV, 1970).

These groundbreaking systems (and a few others) incorporated mercury-arc technology, which tended to reduce the attraction of HVDC transmission due to various operating problems. However, with the development of reliable high-voltage, high-power thyristors, the situation changed and there are now many systems worldwide. Such schemes are well established, transmitting 60 GW or more of the world's power [6]. Typical voltage levels, powers transmitted and line lengths, together with commissioning dates, are included in Table 1.1. The number of such schemes is probably approaching one hundred.

Modern systems use two 6-pulse bridges giving a 12-pulse converter bridge. One 'valve' consists of a number of thyristors – perhaps 100 series-connected units for 600 kV, each of which may be rated at about 8.5 kV maximum peak voltage withstand capability [7]. The number of thyristors required for 100 MW is quoted as 18 (compared with 234 thirty years ago) in Reference 8. The complexity of these structures has resulted in rigorous insulation testing procedures (see Section 7.11).

The advantages in respect of lower corona noise and losses, smaller wayleaves and the capability of being able to utilize cables for long lengths because of the reduction in losses compared with the three-phase AC equivalent may, in some applications,

Table 1.1 Examples of HVDC transmission schemes: thyristor valves

| System | Voltage (kV) | Year | Capacity (MW) | OH line (km) | Cable (km) |
|---------------------------------|----------------|-----------|---------------|--------------|------------|
| Skagerrak | ± 250 | 1976/77 | 500 | 113 | 127 |
| Vancouver | ± 280 | 1977/79 | 476 | 41 | 33 |
| Nelson River BP2 | ± 250 | 1975/85 | 2 000 | 930 | – |
| Hokkaido Honshu | ± 250 | 1979/93 | 600 | 124 | 44 |
| China | ± 500 | 1987/98 | 1 200 | 1 100 | – |
| Itaipu BP | ± 600 | 1987 | 3 000 | 783 | – |
| Cross Channel 2 | ± 270 | 1986 | 1 000 | – | 72 |
| USSR | ± 750 | 1985 | 1 500 | 2 400 | – |
| Rihand–Dadri (Delhi) | ± 500 | 1991 | 1 500 | 840 | – |
| E–W Malaysia | ± 350 | 1995 | 1 000 | – | 600 |
| Garabi, Brazil | BtB Converters | 2000/2002 | 2 200 | | |
| Three Gorges – Changzhou, China | ± 500 | 2003 | 3 000 | | |

offset the increased costs of converter stations compared with a corresponding AC system. These features will, of course, also be advantageous where environmental requirements are at a premium. The reliabilities of a significant number of the schemes are monitored regularly by WG 14.04 of SC 14 of CIGRE [9]: this report covers 28 thyristor valve and 5 mercury-arc valve systems operating during 1997/1998. Data were obtained initially in 1968.

Of special interest in respect of insulation assessment and possible monitoring are the converter transformers, which may be subjected to combined alternating and direct voltages, the smoothing reactors, the overhead line insulators, the bushings and especially any cables/accessories, particularly as used for underwater crossings.

With the new systems utilizing voltage-sourced converters (see Subsection 1.4.4) it appears that the insulation of equipment may be subjected to periodic impulse-type voltages [8], the effects of which have not been extensively investigated.

1.2 Insulation coordination

Insulation coordination design of power systems aims at minimizing outages of major items of plant and critical circuits caused by switching or lightning surges. The traditional protective methods use various forms of air gaps connected across particular equipment or transmission-line components. Because of the lack of matching between the V-T (volt-time) characteristics of the gaps and those of the non-restoring insulations in, for example, power transformers, the application may not be as effective as required. Also the gaps may allow the passage of high-value power frequency follow-through arcs.

These limitations have been overcome to a large extent by the introduction of surge arresters (see Chapters 4 and 7) incorporating nonlinear resistors. The units are more complex than gaps, but have better response times and can suppress potential arcs. The reliability of surge arresters has increased greatly, especially with the development of the gapless type, which has raised confidence in their performance. Condition monitoring under steady-state conditions is sometimes considered necessary.

In order to assist in the planning of insulation coordination of a power system, international standards have been produced for determining appropriate insulation levels in relation to the operating voltages. These levels are based on the expected overvoltages that might be produced by the occasional power-frequency fault and surges due to switching and lightning. During the detailed design of the power system, estimates of such disturbances must be made. This is a very complex process, depending on many factors. Technical discussions and exchange of data have taken place over many years through CIGRE and the IEC working groups, enabling agreed levels to be set and making a major contribution to the design and construction of reliable and safe systems [10, 11]. In the case of HVDC systems such standardization is not complete.

1.3 High-voltage test levels

The test voltages for power-frequency systems – short-duration and surge – standardized by the IEC for preferred values of U_m – are listed in IEC 60071-1. It should be noted that U_m is the highest operating voltage classification of equipment (kV-RMS) between phases, although the majority of tests are to ground. The basis for the choice of the test levels and the associated voltage forms are discussed below.

The voltages chosen for a given level of U_m will depend on local conditions, the type of line, the method of protection adopted for surge suppression and any possible pollution problems that might affect the power-frequency performance. The various choices can be complex, requiring extensive analyses. Some guidance regarding the concepts and procedures are given in the IEC documents 60071-2 and 60071-3 [10].

The situation for HVDC transmission systems is not well established and the required test levels are determined by the user and manufacturer. IEC 60071-5 [11] does not include preferred standardized levels. IEC publication 61378-2 covers the application of converter transformers in HVDC supply systems [12].

A wide range of tests is applied to the individual components comprising the power supply systems. The main proving high-voltage tests for new power-frequency equipment involve the application of overvoltages. These tests include power frequency, lightning impulse and switching impulse depending on the chosen voltage class, as indicated in Table 1.2. The values in relation to the operating voltages were chosen following agreement within the industry based on long-term research and experience.

Tables are also available for wet tests with the different voltage forms.

The forms of the voltages that might exist in a power-frequency system are summarized in Table 1.3 together with possible test shapes where applicable. The relative breakdown strengths of non-restoring insulation when subjected to different forms of voltage are indicated in Figure 1.9 for a simple sample arrangement.

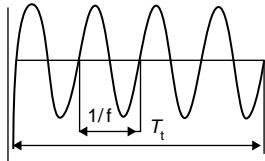
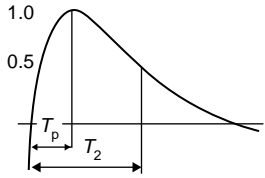
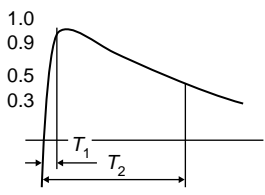
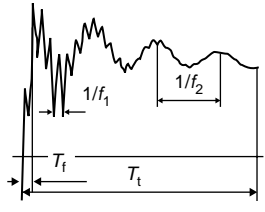
Table 1.2 Possible test levels for particular system voltages. See IEC 60071-1 for details and Table 1.3 for test voltage shapes

| Highest system voltage, U_m (phase–phase) kV(RMS) | Short-duration power frequency withstand test voltage to earth kV (RMS) | Lightning impulse withstand test voltage to earth kV (peak) | |
|---|---|--|-------|
| 12 | 28 | 95 | |
| 36 | 70 | 170 | |
| 72.5 | 140 | 325 | |
| 145 | 230 | 650 | |
| 245 | 395 | 1 050 | |
| Switching impulse withstand test voltages | | | |
| | Phase to earth test voltage kV peak | Phase to phase value referred to phase to earth test voltage | |
| 300 | 850 | 1.5 | 1 050 |
| 362 | 950 | 1.5 | 1 175 |
| 420 | 950 | 1.5 | 1 425 |
| 525 | 1 175 | 1.5 | 1 550 |
| 765 | 1 550 | 1.6 | 2 100 |

Extensive development testing and experience with prototypes contributed to the choice of the relative test levels finally selected for equipment-proving tests – for example as in Table 1.2. In addition, it is vital that the equipment insulation structures withstand the test voltages with an economically acceptable ‘safety factor’ (SF). This factor may be simply defined as the estimated breakdown voltage \div specified test voltage for each voltage form. The chosen value of SF allows for many conditions, including complex insulation configurations, manufacturing variations, non-uniform electric stress distributions and the natural (statistical) scatter in breakdown strength of the materials of liquids, solid or gas/air. The choice of safety factors varies among manufacturers and users and is a critical part of the design and manufacturing processes. As condition-monitoring techniques are improved for application during the high-voltage test procedures, it may be possible to use lower SF values, thereby resulting in a more economic product.

In practical equipment the ratio of the ‘one-minute’ test value to operating voltage is as high as 2.8–3.5, for example transformers, bushings and switchgear. These values have served the industry well and have ensured that equipment designed to withstand such test levels will operate satisfactorily for 25 years or more, sustaining overvoltages caused by lightning, earth faults and some switching events. If a

Table 1.3 Shape of AC and impulse test voltages

| Class | Shape | Frequency and time duration |
|-------------------------|---|--|
| AC tests |  | (1) $f = 50$ or 60 Hz (2) VLF, e.g. 0.1 Hz (3) Resonance voltage (20–300 Hz) (4) Induced voltage tests (100/120–400/480 Hz) (5) $T_t = 10$ seconds to 60 minutes |
| Switching-impulse tests |  | $T_p = 250 \mu s$ $T_2 = 2500 \mu s$ |
| Lightning-impulse tests |  | $T_1 = 1.2 \mu s$ $T_2 = 50 \mu s$ |
| Fast-impulse tests |  | $100 \text{ ns} \geq T_f > 3 \text{ ns}$ $0.3 \text{ MHz} < f_1 < 100 \text{ MHz}$ $30 \text{ kHz} < f_2 < 300 \text{ kHz}$ $T_t \leq 3 \text{ ms}$ |

high standard of maintenance and in-service monitoring is incorporated in the operational programmes, lives of 40 years are now being predicted. From Table 1.2 it will be seen that for values of $U_m = 300$ kV and above a short-time-duration power-frequency test is not specified, a switching surge test (see Subsection 1.3.3) being considered more appropriate. However, steady-state-test overvoltage proving tests are retained in some form or other. In the case of transformers this includes a partial discharge test (see Chapter 7) at, perhaps, $1.5 \times U_m \sqrt{3}$ for 60 minutes or more for $U_m \geq 300$ kV units. In many cases such tests are called for on lower-voltage equipment. The methods of producing the voltages for test purposes and procedures

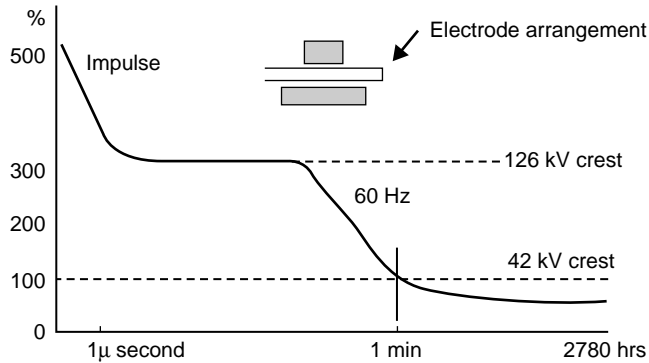


Figure 1.9 Volt-time curve for treated pressboard in oil – 1/16-inch-thick pressboard at 25°C [13]

for determining insulation properties are described in Chapter 6 and applications to particular apparatus in Chapter 7.

1.3.1 Power-frequency voltages

A power-frequency overvoltage test level of the same form as the operating voltage has been the traditional method for proving the integrity of equipment insulation as indicated in Table 1.3. An increase in frequency may be necessary for induced testing of transformers and in resonance-type tests as included in the table.

1.3.2 Lightning-impulse voltages

The need for tests to reduce failures due to lightning was appreciated very early in the development of transmission systems. This applied particularly to the transformers, as a power-frequency-induced test does not prove the integrity of complex inductive/capacitive structures when subjected to surges. The implications are analysed in Chapter 5, where it is shown that the behaviour under such conditions is a dominant feature in the insulation design of large transformer windings.

In the 1920s and 1930s it was realized that the reduction of the earthing (footing) resistance of the support towers of the overhead lines and the provision of overhead earth wires could give a moderate degree of protection. It was possible to measure lightning currents during a strike to the towers and to develop scenarios for determination of the magnitudes and forms of the surges to be expected. These include induction from near strikes, back flashovers due to high earth resistances and direct strikes to the power conductors. The various measurements, and basic observations, of strikes to lightning conductors – for example at the Empire State Building in New York and in South Africa – enabled a consensus to be established regarding the shape and magnitude of the stroke currents: in the range up to 150–300 kA with an average of perhaps 25 kA. Using this information in conjunction with calculated line-surge impedances, the shapes and magnitudes of expected voltages were estimated

and agreement reached as to the form of ‘standard’ waves to be applied to equipment for particular voltage systems. The basic shape is 1.2/50 microseconds as defined in Table 1.3 and selected levels listed in Table 1.2. It will be noted that impulse-voltage magnitudes are of the order of 3.5 to 5 times the peak of the operating voltages to ground.

1.3.3 Switching surges

As the voltage levels of the transmission systems increased, it became apparent that the surges produced by switching could be more significant than the short-duration power-frequency overvoltages caused by faults and other operational abnormalities. The magnitudes of these surges are less than the lightning disturbances but are of slower rise-time and oscillatory in form. Thus, it was considered necessary to introduce a test to cover this condition. Although the surges are, in effect, oscillatory with frequencies in the range up to tens of kHz, this proved a difficult condition to simulate as a high-voltage test. Because an insulation failure or flashover – especially across air clearances in the transmission system – would be expected to occur during the first peak, it was agreed within the industry that a wave having a rise time of 250 microseconds and a decay of 2 500 microseconds would be representative and should be adopted as a standard test (see Table 1.3). Some of the recommended values are given in Table 1.2. The magnitudes are of the same order as the peaks of the short-duration power-frequency test voltages specified in previous versions of the standards.

1.3.4 Very fast transient tests (VFTT)

Following the extensive application of gas-insulated switchgear it became apparent that very fast transients were being injected into the power system during operation of disconnectors. These surges have rise times of tens of nanoseconds with superimposed oscillations in the range of tens of kHz up to 100 MHz as depicted in Table 1.3. Such disturbances can be dangerous if the gas-insulated switchgear equipment is directly connected to, for example, a transformer. The problems are under close scrutiny within CIGRE and elsewhere (see Chapter 8 of Reference 14).

1.3.5 Direct-voltage tests

Direct-voltage acceptance tests for HVDC equipment are of the order of two to three times the system operating values. The voltages are applied for long periods of, perhaps, 30 minutes to ensure the insulation system is in a stable, charged condition and the stress distribution across multiple dielectrics is identical to the service situation. Allowance must be made for systems where service polarity reversals are involved. Levels for converter transformers are included in IEC Standard 61378-2 [13] and a wide range of tests for the complex components of the thyristor valves in IEC Standard 60700.

Under certain conditions direct voltages are used for testing AC equipment, e.g. when withstand voltage testing of large rotating machines and cables where

the charging currents are too high for normal AC test equipment. HV DC test sources are also incorporated in HV impulse generators. At lower voltages DC techniques are applied in the measurements of a number of material dielectric properties as required for monitoring the insulation condition.

1.4 Power system developments

During recent years, in order to achieve increased utilization of the existing power system infrastructure, there has been a trend towards operating plant and line components much nearer to their maximum ratings and for longer periods than previously considered advisable from an engineering aspect. Such developments tend thermally to stress the equipment more highly and probably result in the specification of fewer planned time-based routine maintenance outages. The success of the changes will depend greatly on maintaining the insulating materials and structures in good condition. This applies to the more highly stressed designs now being introduced as well as to the ageing equipment that is required to remain in service.

1.4.1 Reliability requirements

An acceptably reliable system operating at or near full load demands that existing and new components must be monitored effectively. The manner in which this is achieved in relation to the system development and its overall operating and replacement costs is subject to much planning, necessitating complex decisions by the asset managers of present-day power supply systems.

The reliability requirements expected in a system depend on the continuous availability of adequate generation and the efficient maintenance of the supply network incorporating overhead lines and cables, together with the various associated plant items.

Statutory regulations specify that the voltage levels must be maintained during changes in the load conditions. Failure to meet the contractual requirements can result in high economic penalties. This will apply if a shutdown is necessary and may include liability for environmental damage due to malfunctioning of plant. As far as possible the safety of personnel must be ensured.

Some applications of artificial intelligence for incipient fault diagnosis and condition assessment are discussed in Chapter 10. It is clear that effective methods for monitoring of the various insulating materials must be included in the economic and technical development of existing and new power systems.

1.4.2 Condition of present assets

In many organizations system development includes the determination of the value of the existing assets in terms of predicted remaining life. This is a difficult process with plant ranging from ages of more than 25 years, perhaps on the upturn of the 'bathtub' curve, through to modern equipment of high capital cost incorporating updated designs and some new types of materials.

Again, assessment of the condition of the insulating materials can be an extremely useful tool in acquiring data for the overall costing procedures. This is especially effective if methods for continuous monitoring from new are incorporated in critical plant items, thereby enabling 'trend' statistics to be obtained for the equipment type and insulation system.

1.4.3 Extension of power system life

As part of the procedures related to the development of a system it is highly desirable to consider techniques for extending the lives of equipment beyond their expected retirement date. Much work is proceeding with the reconditioning of plant, including large generators and transformers. The restringing of overhead lines and the replacement of items such as cables, instrument transformers and switchgear become necessary for life extension. The appropriate time for commencing such work depends on many factors, the state of the insulation being of major significance. Reliable and informative data for insulation condition monitoring are essential as part of the decision-making process. A range of established and newer techniques are described in Chapters 6–10.

1.4.4 New systems and equipment

In the immediate future, power system technological developments involving insulation will include more extensive use of composite insulators for the overhead lines, the increased application of gas-filled equipment possibly with minimization of the SF₆ content, utilization of fibre-optic instrument transformers and installation of plastic – in particular XLPE – cables up to the highest voltages.

Some of the newer developments could include the application of 'cable' wound generators, motors and transformers for direct connection to the transmission/distribution systems [15] and the use of high-temperature superconductivity (HTS) cables [16] for large power transfers in metropolitan areas. HTS research and development are well advanced in the USA, Europe and Japan.

Considerable activity is continuing in the development of HVDC as a major contributor to the overall expansion in developing areas and as a backup to existing networks. On a smaller scale, the technology is being applied for local interconnections. A particular example of a small-scale development (± 80 kV, 50 MW, 70 km XLPE cables) based on voltage source converter (VSC) technology is described in Reference 7. The 220 MW VSC Murraylink interconnection between Victoria and South Australia incorporates a 176 km land cable and the 330 MW VSC scheme from the USA mainland to Long Island a 40 km cable [17]. A comprehensive review of the components comprising a VSC scheme and possible operating characteristics are described in the CIGRE Brochure No. 269 [18] prepared by members of WG B4.37. Although experience with VSC systems is limited, the report is optimistic about the future of the technology. The highest ratings of systems in service (2004) were ± 150 kV and 350 MVA.

The various developments will inevitably require new insulation assessment and monitoring techniques.

1.5 Future insulation monitoring requirements

The above survey of some of the complexities of a power supply system has highlighted a number of components in which the maintenance of electrical insulation in good condition is essential in order to achieve efficient and safe operation. Such objectives can be realized at the engineering level only by the application of appropriate monitoring techniques, in particular those associated with assessing the state of the insulating materials in equipment when new and during lives of up to forty years or longer. It must be accepted that insulating materials inevitably deteriorate with time – the rate being very dependent on usage and the quality of maintenance achieved.

The choice of whether or not to incorporate simple or advanced monitoring instrumentation will depend on many factors including the replacement/repair cost of the particular equipment and, probably more importantly, the overall economic effects and associated disruption of the power system following a major problem or failure.

At the lower voltages the application of periodic steep pulses [10] in, for example, HV motor-control devices may require special insulation monitoring systems. Also, sensitive local distribution networks could justify the development of new techniques.

Descriptions and analyses of some of the more advanced industrial monitoring methods now in use or under development are described in later chapters. These follow a review of the materials applied, their location in particular power equipment, possible fault conditions and details of established insulation assessment techniques.

1.6 Summary

In this introductory chapter the principle of an AC high-voltage power system is presented together with an indication of the types of equipment involved. The order of magnitude of the operating and associated test voltages are reviewed. The concept of insulation coordination for protecting power equipment insulation from damage due to lightning and switching surges is described. In addition, the developments in HVDC transmission are considered, including recent progress in localized schemes. Appropriate references are given. The need for future insulation assessment and monitoring is emphasized.

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1.8 Problems

1. From personal observations and use of the Web, identify and record examples of the power system components mentioned in the chapter. Take advantage of visits to power stations and HV substations.
2. What is meant by 'embedded' generation and how is it utilized? Describe at least two such power sources and the methods for connecting them to the main high-voltage transmission system.

3. Discuss the reasons for the various high-voltage tests as applied to power-system equipment. Indicate why and on what bases were the relative levels and forms established by the industry.
4. Describe the advantages and disadvantages of HVDC transmission systems, including their relationship to the AC systems. Discuss the application of the newer developments involving VSC technology.

Chapter 2

Insulating materials utilized in power-system equipment

- The main insulating materials
- Characterization of insulation condition
- Modes of insulation deterioration and failure
- Electrical operating stresses

The successful operation of high-voltage power-system equipment is very dependent on the correct choice of insulating materials and maintaining them in good condition throughout their life. This requires knowledge of the types of traditional and contemporary materials available and how they would be expected to behave in the particular operating environment, especially over long periods.

The acceptance by the industry of new materials is a slow process because of cost restrictions, changes in production techniques and the requirement that a high probability of reliable continuous performance for periods exceeding 25 years can be achieved. Such estimates are based on experience, experimental test results and statistical analyses. Numerous test specifications have been written in order to assist in determining such reliabilities. Some of the methods are discussed in Chapter 6. The most important developments with the newer materials have been associated with the use of SF₆ gas in switchgear and transformers, plastics in high-voltage cables and different forms of synthetic polymers and glass fibres in machines, power/instrument transformers and insulators.

In this chapter a range of insulating materials and their special areas of application in the power system are reviewed. This includes the well-established materials, as these still form much of the insulation, i.e. air, hydrogen, wood, porcelain, glass, hydrocarbon oil, oil-impregnated paper, oil-impregnated pressboard, wrappings of synthetic-resin-bonded paper, resin-bonded wood laminates, resin-bonded paper laminates, and the newer materials.

In the review of insulating materials (Section 2.1) reference is made to the electrical parameters – permittivity (ϵ), resistivity (ρ), dielectric dissipation factor

(DDF) and partial discharge characteristics (PD) – and to dissolved-gas-in-oil analyses (DGA), all of which are significant in the monitoring of insulation systems in power equipment. These quantities are defined in Section 2.2 and an indication given of how they can be utilized to characterize the condition of the materials. Some of the possible deterioration and failure mechanisms of practical materials are presented in Section 2.3, followed by consideration of the relationships between the magnitudes of breakdown stresses for samples/prototypes and a range of operating stresses (Section 2.4).

An understanding of these various factors and the expected behaviour of the materials enables the most appropriate techniques for insulation-condition assessment to be chosen and assists in interpretation of the complex output data recorded by the measurement and monitoring systems. Such appreciation contributes to improved operation and maintenance of the power system, both economically and technologically.

2.1 Review of insulating materials

The materials are reviewed under the general headings of gases, liquids and solids; the last of these includes composites and conditions where an impregnant is necessary in order to obtain the required dielectric strength. Detailed properties are not covered, as these can be found in various publications – for example references 1 to 3 and in specifications of insulation manufacturers. To assist in the choice of appropriate materials for specific temperatures, a classification guide was introduced within the IEC standards system in 1957. A number of Guidelines and Standards ([S2/1] to [S2/4]) have been issued since that time covering determination of thermal endurance properties, identification of insulation systems for particular temperature conditions, associated ageing mechanisms and diagnostics, appropriate statistical methods and functional tests for evaluating the expected performance in service. In IEC 60085 [S2/1] the insulation thermal classifications are tabulated according to the recommended operating temperatures. Also included is the earlier method of alphabetical classification as this is still used in the power industry.

The prime objective of the present review is to outline the major characteristics of the insulating materials and indicate in broad terms how the parameters relate to power system applications. Some practical configurations are described in Chapters 3–5.

2.1.1 Gases

In addition to air, a number of other gases are used as insulants in power systems. These include sulphur hexafluoride (SF_6), nitrogen and Freon (e.g. C_2F_6 and $\text{C}_2\text{F}_5\text{C}_1$) for applications in equipment such as switchgear, cables and transformers and hydrogen in large turbine-generators.

The electrical properties of air are well documented, as it comprises the major insulation in many components of the overhead power system. In some cases the predictable breakdown strength and self-restoring properties of air are used in protective

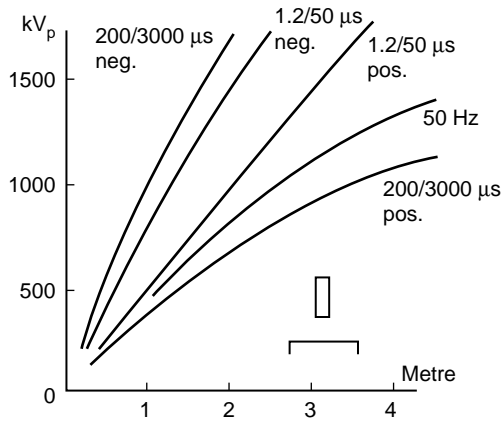


Figure 2.1 Relative air gap flashover voltages in non-uniform fields

devices, for example rod gaps and gap-type surge arresters. At very high voltages, and therefore long gaps, it is found that switching surges will cause flashovers at relatively low voltages if the more highly stressed electrode is at positive potential. This factor is of importance in the design of transmission lines and substations for the higher system voltages [4]. The order of magnitude of the breakdown strength of a non-uniform field in air is indicated in Figure 2.1. The actual flashover values will depend on the configuration and the atmospheric conditions.

Knowledge of the characteristics of air in the presence of moisture is extremely important because, in contrast to the majority of insulations, it must perform satisfactorily under adverse climatic conditions. Adjustments of flashover voltage levels are made with respect to humidity values when testing in the high-voltage laboratory. The insulation characteristics of air at interfaces, as associated with porcelain and synthetic polymer surfaces, are of great importance in practical equipment. Flashover curves for various overhead line configurations may be found in Reference 5.

The behaviour of SF_6 has been studied in great detail, the earlier work being in the 1950s. Investigations have included breakdown tests at pressures up to 0.8 MPa (~ 8 bar) for a wide range of electrode configurations related to switchgear, current transformers, power transformers, substation hardware and cables. This has been in addition to studies of the chemical structures and long-term stability of the electronegative gas. It is necessary to achieve dew points of -20° or better at working pressures in order to avoid moisture problems.

In practical applications the effect of particles within the SF_6 gas of gas-insulated systems (GIS) can be very significant [4, 6]. Following a flashover within GIS equipment or disconnector operation dangerous surges with rise times of the order of tens of ns may be injected into the local power system. The volt-time characteristics tend to be flat after about $10 \mu\text{s}$ (4).

Descriptions of the processes involved in air and SF_6 breakdowns have been published widely in many research papers and a number of books. Both of these

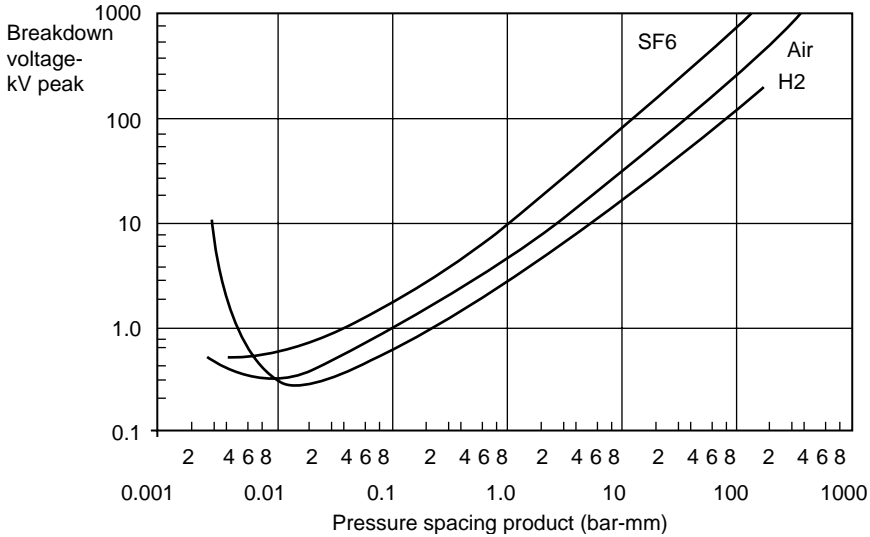


Figure 2.2 Approximate breakdown strengths of gases in a uniform field – ‘Paschen Curves’

gases exhibit increased electric breakdown stresses at small spacings and in near uniform fields [7]. The approximate relationships based on data published in *Electra* Nos. 32 and 52 are depicted in Figure 2.2, which also includes results for hydrogen. In these types of fields once a partial discharge event occurs complete breakdown would be expected. This is especially significant with direct voltages, as, for example, within the air gaps of impulse generators (see Chapter 6).

The relationship for air [8] can be approximately represented by the equation

$$V_{\text{peak}} \text{ (kV)} \approx 6.72\sqrt{\text{pd}} + 24.36\text{pd} \tag{2.1}$$

where (pd) is in bar-cm. The equation is valid for $\text{pd} > 0.1$ bar-mm.

The reduction in strength for non-uniform field conditions for air is indicated in Figure 2.1. In such configurations high stresses are produced at sharp electrodes and will trigger the ultimate flashover. However, partial breakdown can be maintained without failure in some gap types resulting in the phenomenon of corona. This may be observed visually in air, for example on overhead lines and insulators, and has been studied very extensively from basic physical characteristics [8] through to the effect of the associated finite losses on the performance of the lines.

Nitrogen is used at pressures up to 1.0 MPa in standard capacitors and in some forms of cables, while the low density of hydrogen is exploited in large water-cooled turbo-generators. As shown in Figure 2.2, the breakdown strength of hydrogen at atmospheric pressure is about half that of air. Operating pressures are in the region of 0.4/0.5 MPa with moisture contents corresponding to dew points of the order of -20°C .

2.1.2 Vacuum

In its pure state a high vacuum is an ideal dielectric over short distances, since no electron multiplication is possible. However, in practical equipment such as high-voltage circuit breakers, contamination from the metallic and insulation surfaces, together with residual oil and gases, limits the voltage stresses that can be achieved [9]. With good design and appropriate electrode materials, vacuum circuit breakers are now used in circuits up to and including 36 kV.

2.1.3 Liquids

The use of oil as an insulant is very common, either on its own or as an impregnant for achieving the good properties of a laminated or porous 'solid' material – in the case of transformers and some designs of high-voltage cables it acts as a heat-transfer medium between the active conductors and water or air coolers.

The type and quality of oil required is dependent on the particular application. The specifications range from normal hydrocarbon oils as supplied for use in switchgear and transformers through to special types for cables and capacitors [10]. When used as impregnants, the liquids are carefully dried, degassed and filtered to produce structures of high dielectric strength.

The motivation for using 'paraffinic'-based oils in place of 'naphthenic' types seems to have diminished. Much work was carried out on the former, especially with respect to viscosity at low temperatures and ageing characteristics [11].

The qualities of the various oils are checked by tests laid down in specifications [e.g. S2/5–S2/7] but the results do not necessarily indicate how the liquids will behave when built into a complex structure over a long period.

A simple example is the reduction in partial discharge and breakdown stresses with increase in spacing or volume in a uniform field gap as indicated in Figure 2.3 for 50 Hz and impulse voltage conditions. The graphs are representative of a wide spread of results from several sources, as reviewed in reference [12], and are included here only as an indication of an important trend when applying data from a particular sample to a configuration of different dimensions. The absolute stress magnitudes will depend on the condition of the oil tested or being used in the equipment.

During recent years concern has arisen regarding the effect of particles on the strength of oil as utilized in high-voltage power transformers. Some earlier experimental results [13] showed that an increase in the density of suspended particles ($>5 \mu\text{m}$) from 2 000/100 cm^3 to 12 000/100 cm^3 reduced the breakdown voltage of large oil volumes by the order of 40 per cent. The test electrodes were concentric cylinders and the oil volume approximately $4 \times 10^5 \text{ cm}^3$. The average breakdown stresses for low-particle contents were of the same order as indicated in Figure 2.3 (b). A later report by CIGRE [14] contains data from 15 laboratories and an indication of the particle concentrations to be expected in practical transformers. Such data are applied in design, although further information is probably required relating to partial-discharge inception stresses, especially under surge voltages.

The macroscopic behaviour of oil in small and long gaps has been extensively researched and is still the object of experimental studies, e.g. References 15 and 16.

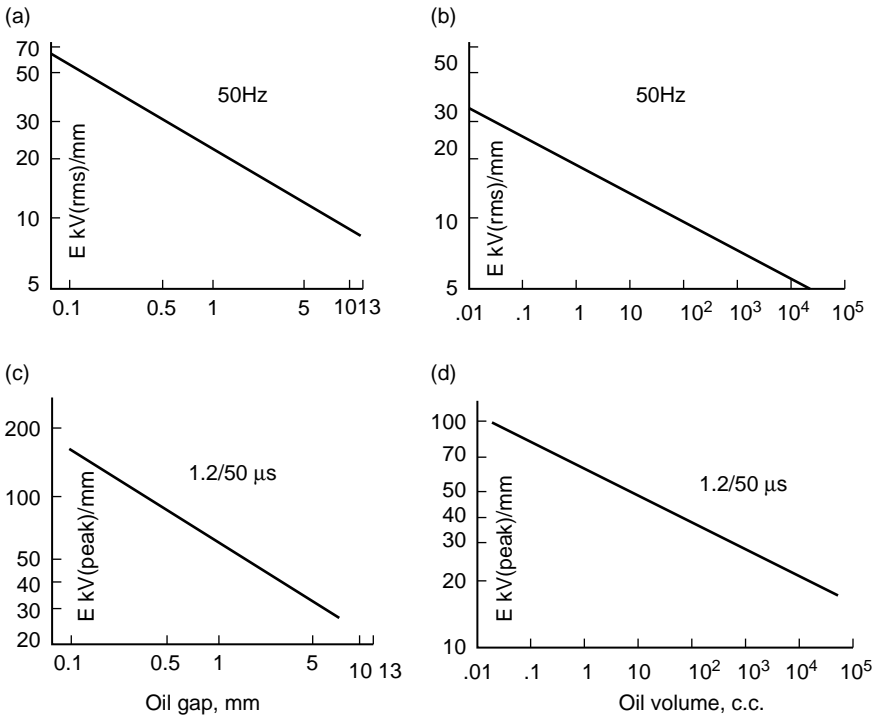


Figure 2.3 Reduction in oil partial-discharge inception and breakdown stresses in uniform fields – range of experimental results [12]. (a) 50 Hz PD inception stresses; (b)–(d) Breakdown stresses

This work is aimed at understanding the breakdown mechanisms and, more importantly, the partial-discharge phenomena with and without contaminants – in particular moisture, conducting and non-conducting particles and air.

As the gas-absorbing characteristics of oils can vary, some difficulties may arise in the interpretation of gas-in-oil analyses. These gas-absorbing oils are now used in transformers as well as cables and capacitors. In the latter cases they help minimize the formation of bubbles in the tightly packed insulation structures. A new test incorporating a point-sphere electrode system for checking the partial discharge characteristics of oils has been developed by CIGRE (SC 15) and is now an IEC Standard [S2/8].

An oil characteristic that continues to be of interest is concerned with the electrostatic charging effect produced by flow rates of, perhaps, 1.5 metres/second within the insulation configuration of certain designs of high-voltage power transformers. Extensive studies have been made in Japan, the USA and Europe. It appears that localized charges can be built up on insulation surfaces that may produce dangerous partial discharges and even flashover at the interface or in the bulk oil. Techniques have been developed for assessing the electrostatic charging tendencies (ECT) of the

different oils (new and aged) on their own [17] or in conjunction with pressboard surfaces [18], as also investigated by Study Committees 12/15 of CIGRE [19].

Synthetic liquids were introduced for use in distribution transformers many years ago in order to overcome the fire hazards associated with hydrocarbon oils. One of the commoner liquids consisted predominantly of polychlorobiphenyl (PCB), a substance that is now unacceptable for environmental and health reasons. Extremely low concentrations are allowed in existing equipment – for example <0.5 ppm.

The destruction of PCB liquids has required the development of special collection and waste-disposal techniques, at considerable cost to the electrical industry. An advantage of PCB liquids was their high permittivity when used in capacitors. Replacement oils, including silicone liquids, are now available for use in smaller transformers and, for power capacitors, a wide range of individually designed synthetic oils has been developed [15, 16]. A well-established synthetic liquid is dodecylbenzene (DDB) for impregnation of wrapped insulation in high-voltage cables. It is claimed that the liquid has better ageing and gas-absorption characteristics than the natural oils. If low-temperature cables prove to be commercially viable, it appears that liquid nitrogen and/or helium will be considered as possible fluids for impregnation of lapped plastic dielectrics.

2.1.4 Solids

Clearly the structures of all the power-system equipment must include solid insulating materials capable of efficiently supporting, and isolating from each other, conductors at different potentials. Such materials must have adequate puncture and creep/tracking strengths. They must be able to withstand the expected thermal, mechanical and chemical conditions and maintain electrical stresses to give economic and technically acceptable designs. The orders of magnitude of achievable stresses are summarized in Section 2.4 for sample and equipment configurations. The materials reviewed include a limited number of the more important synthetic polymers applied in power system engineering. The industrial development of these materials is continuous but the insulation engineer must be cautious when assessing a new material for a particular application. The well-established might be the best solution, especially in relation to long-service performance.

2.1.4.1 Wood

Wood is one of the oldest insulations used by electrical engineers and despite limitations in the natural form it is widely applied. The outstanding application is in overhead line systems, where its relative cheapness and insulation properties are attractive [20]. It is also utilized in transformers, some older switchgear and generators in a laminated form suitably dried and glued/impregnated with resins to give a high mechanical strength and acceptable electrical properties.

2.1.4.2 Porcelain

For many years porcelain, and to a lesser degree glass, had no competitor as an insulation for overhead line insulators. It weathers well, even under moderate pollution,

and has good flashover characteristics, and methods have been developed to meet the stringent mechanical requirements. A disadvantage is its density when it is being handled and the susceptibility to crack or fracture when subjected to sudden physical shocks.

Although it has a relatively low puncture strength, porcelain is used extensively in bushings, high-voltage instrument transformers, stand-off insulators and similar components (see Chapters 4 and 5). In most of these applications the resistance of the material to atmospheric conditions and possible flashover without catastrophic failure is the insulating property being invoked.

2.1.4.3 Glass

In addition to its application for sheds of overhead line insulators, glass is used in the power industry in fibre form for the production of insulation components, including tapes, tubes, boards and the tie rods in composite insulators.

2.1.4.4 Rigid laminates

A large group of insulating materials may be classed as 'laminates'. These include paper and cloth based boards glued with resin, special plywoods either fully or partially impregnated with resin, layers of glued pressboard for oil impregnation and the high-quality materials of glass fibre lays impregnated, for example, with silicone, epoxy or polyester formulations [1, 3].

For external use, and in some dry-type equipment, the choice of material will often depend on its tracking properties and resistance to deterioration due to moisture and dirt.

For applications where good mechanical strength or support is required in high electric fields, as in power transformers, the presence of voids between layers of the laminates can result in partial discharges. Also, the losses in unsuitable resins can produce excessive local dielectric heating and any impurities in layers parallel to the field may give a low breakdown strength.

2.1.4.5 Sheet composites and tapes

Polymers are used in the production of sheet composites, which may be formed as required and cured *in situ*, e.g. for machine slot insulation and interwinding wraps in dry-type transformers. The application of Melinex/Mylar (polyethylene terephthalate film) with polyester fibre mat produces a material suitable for Class 130 (Class B) temperatures. At higher temperatures, Nomex (polyamide paper) for Class 155 and Kapton (polyamide film) for Class 180 (Class H) and above (Class 200) may be used for specific applications. Nomex is a sheet material also applied in dry-type transformers impregnated with resin, usually under vacuum, operating in the Class 130 (Class B) range.

These types of material may be used in tape form, especially for machines. Research continues in order to develop tapes for insulating conductors and leads suitable for operating at higher temperatures and more onerous conditions. Mica-based resin systems in formed or tape configurations are widely used in high-voltage

rotating machines – both motors and generators. An analysis of the behaviour of mica insulation systems is presented in Reference 21. The techniques are specialized but are of considerable interest in power station operations. Studies continue in respect of the partial discharge characteristics. The action of the mica-resin system in resisting high PD levels is not fully understood. Thousands of picocoulombs may be withstood for many years of operation.

2.1.4.6 Epoxy resins

The use of cast resins in power engineering is well established. Manufacturers offer a wide range of components in which designs incorporating traditional materials have been modified to exploit the advantages of cast resins, e.g. thermoset epoxy resin systems. The final characteristics are influenced by the type and quantity of filler – for example, glass fibre, silica or other inorganic materials. Dielectric constants are in the range 3.0 to 4.0 depending on the epoxy filler.

Apart from thermal difficulties due to the differences in expansion coefficients between the resin and conductors, a major development problem was the elimination of partial discharges in voids, as it was found that the resins were susceptible to PDs of low value – perhaps tens of pCs – possibly leading to service failures. Good quality control is essential, in particular the monitoring of partial discharges.

One major restriction was the limitation of cast resins for indoor use only. After much R&D effort, the cycloaliphatic epoxy resins with appropriate fillers were introduced for outdoor applications. A number of current transformers have been in service for many years and long-term tests have been carried out on line insulators, but the newer polymeric composites seem to be superior in this latter application.

2.1.4.7 Elastomers

Elastomers are a group of polymers that have rubber-like mechanical properties. They can be moulded into such components as insulator sheds and extruded to form medium-voltage HV cables. In all applications a wide range of fillers and chemical modifications are required to obtain satisfactory performance characteristics. This is especially important for outdoor insulators and shells (see Chapter 4). There are two major systems in use in the supply industry.

Ethylene propylene rubber (EPR). For medium-voltage cables extruded EPR is widely applied. It is flexible, does not form water trees, is resistant to internal partial discharges and has good electrical properties. Ethylene propylene hexadiene monomer (EPDM) is a preferred form for outdoor insulators because it is more resistant to UV radiation and corona than EPR, although its long-term behaviour under pollution is still being monitored. Other types are ethylidene-norbornene and dicyclopentadien [22].

Silicone rubbers (HTV, LSR, RTV). The high temperature vulcanized form of silicone rubber (HTV) is used for outdoor insulators as it has good resistance to corona, ozone, UV and many forms of pollution. The material is hydrophobic, which results in surface water forming as droplets, and consequently a high-resistance path

for leakage currents, thus minimizing the possibility of dry-band arcing. Silicone is probably the only polymer having this very desirable property.

Liquid silicone rubber (LSR) appears to be advantageous where complex shapes are required and avoidance of voids is essential [23]. Room-temperature-vulcanized silicone rubber (RTV) has been applied to porcelain insulators in order to improve their wet and pollution performance [24]. A comparison of the properties of EPDM and HTV silicone rubber is given in Reference 1. Dielectric constant values are of the order of 2.5–3.5 and 3.3–4.0 respectively.

2.1.4.8 Heat-shrinkable materials

An important development was the introduction of heat-shrinkable polymeric materials [25]. This led to changes in the techniques adopted for 11 kV (and above) cable terminations at switchgear and similar locations. Much testing has been completed in the laboratory and at outdoor test sites. Assessment included the determination of the behaviour of the shrunken material when subjected to thermal cycling, as in a cable. Air gaps must not appear between the sleeve and the cable insulation (plastic or oil-impregnated), as this could result in partial discharges with subsequent failure (see Chapter 4).

2.1.4.9 Polyethylene (including XLPE)

The use of polyethylene as an insulating material is attractive, because it has low losses and moderately high electric strength. Initially, its thermal stability was unacceptable at the temperatures required in power engineering and not until cross-linked polyethylene (XLPE) was introduced did it find wide application [1]. The material can be extruded and was found suitable for cable manufacture once a number of problems were solved. These included development of methods for curing and cooling long lengths, at the same time eliminating voids in which PDs might be initiated. XLPE is susceptible to discharges of the order of tens of pCs but is now being applied as the major insulation in cables over a wide range of voltage, a few as high as 500 kV (see Chapter 4). The dielectric constant is 2.3.

2.1.4.10 Polyvinyl chloride

Polyvinyl chloride (PVC) is used extensively for the insulation of wires and as a sleeve material for low-voltage applications. In many power situations the integrity of the secondary wiring is vital. PVC has a thermal rating of 105°C, which can be increased by suitable formulations, and a dielectric constant of 3.0–4.0, depending on the form. The material is resistant to a range of liquids but is attacked by others, in particular aromatic hydrocarbons possibly associated with migration of plasticizer from the PVC [1].

2.1.4.11 Polytetrafluoroethylene

Polytetrafluoroethylene (PTFE) extrusions, moulds and films are used where demanding dielectric, mechanical, chemical and thermal conditions are encountered. Specialist applications include insulators, cables, wires and windings where the

high cost can be justified. The material is susceptible to corona and radiation. Its dielectric constant is 2.0. Fluorinated ethylene propylene copolymer (PEP) – Teflon – has similar properties to PTFE but is not as tough and has a more limited temperature range. It may be processed by conventional extrusion and moulding methods.

2.1.4.12 Polypropylene

Polypropylene (PE) film is one of the materials used as the dielectric in power capacitors, having high electric strength and low losses. It has a low dielectric constant and the appropriate grade must be selected to minimize swelling in some dielectric liquids as used in capacitors.

In its bulk form the material is utilized for moulding of components and extruded as insulation for cables operating at less than 5 kV [1]. Polypropylene tapes laminated with paper (PPL) have been used for high-voltage cable insulation for ten years or more – for example by the National Grid in the UK.

2.1.4.13 Liquid-impregnated insulation systems

At the higher voltages it seems that liquid-impregnated systems will continue to be used successfully at extra-high voltages in cables, bushings, instrument transformers, power transformers, distribution transformers and power capacitors, although gas systems (SF_6) are now well developed and are competitive in a number of applications. Despite its apparent disadvantages, oil-impregnated paper (OIP) has proved a reliable and economic insulant in many applications. The achievement of the efficient utilization of natural materials has resulted from R&D effort over many years – in particular, the determination of conditions necessary to withstand high electric stresses for the expected lifetimes of at least 20 to 30 years. Of special interest to the design and operating engineers are moisture content, gas content of the impregnant, losses at operating stresses, partial-discharge inception stresses, the location of any PDs and the ageing characteristics.

Initial drying and impregnation conditions necessary to avoid failure are well established and form part of the production know-how. Vacuum ovens capable of pressures down to 0.1 torr or lower and temperatures of 100° – 130° are common. The processing times of 2–3 weeks for a large transformer may be shortened very considerably by installation of vapour phase heating equipment, for example by using kerosene for heat transfer in the early stages of dry out. It is common for dryness levels of less than 0.1% to be achieved in such processes before impregnation. The oil would be expected to have a moisture content of a few ppm (e.g. <2 ppm).

The losses may be related to moisture content as well as to the quality of the material: a low-loss paper is used in cable manufacture. An effect found when attempting to establish breakdown criteria for new OIP is indicated in Figure 2.4. It is essential that low moisture contents be maintained in the practical systems if thermal runaway conditions and PDs are to be avoided (see Section 2.3). This is particularly important with cables in which the conductor losses pass through the OIP and add to the dielectric losses.

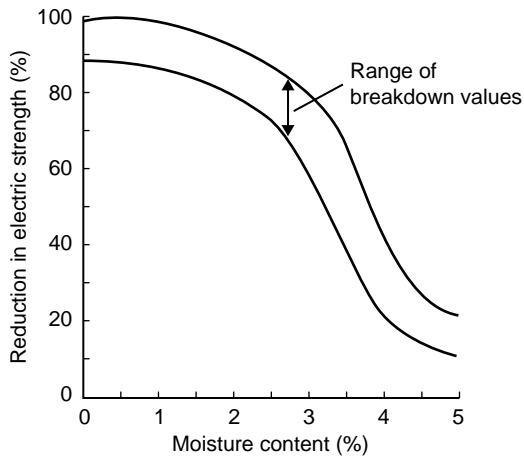


Figure 2.4 Effect of moisture on electric strength of oil-impregnated paper insulation

In high-voltage cables and some current transformers, arrangements are made to seal the system against the atmosphere, maintaining a moisture level of 0.5% or less, while in power and distribution transformers the situation is less critical, the stresses being lower and the insulation structure not so compact. This also means that gas-absorbent oils are not usually required in transformers, although there are indications that such oils are being provided as the norm. In cables, power capacitors, instrument transformers and certain regions of power transformers the existence of a gas bubble can be very significant, as it may lead to PDs that are confined, eventually leading to deterioration of the tape or sheet material. In the degradation process it appears that low-level ionization can produce a form of cross-linking in the oil impregnant resulting in the formation of the well-known X-wax compound containing carbon and hydrogen. After disassembly the presence of the compound is often taken as an indication that discharging has occurred in the paper/oil system. X-wax may be detected by magenta dye or ultraviolet light. It can be observed as a smooth cheeselike substance within the surface of the paper insulation. The effect is discussed in References 26 and 27.

A special situation in operating oil-filled power transformers is where the moisture content has risen to perhaps 2.5–4 per cent and during an overload the conductor temperatures are allowed to increase to 140° (IEC 60354) or 180°, as specified in the IEEE/ANSI standards for higher-temperature materials. Under such conditions it seems possible that gas bubbles may be released resulting in partial discharges. The effect of this will depend on their location and the electric stress values. As it was suspected that a number of transformer failures may have been due to bubble formation during overload conditions [28], the phenomenon has been investigated in some detail, including a joint project between Monash University and Electric Power Research Institute. It was demonstrated in a separate research programme

that problems in the transformer interwinding insulation might arise at the higher temperatures [29].

Extensive developments in power capacitor insulation systems included the introduction of polypropylene film in conjunction with the more traditional paper, the latter acting as an impregnating interface. However, for a number of years, all-film capacitors, in which a ‘hazy’ or similar polypropylene film is used to enable impregnation to take place, have been in service. Capacitor insulation is very susceptible to impurities because of the thickness of only 10 micrometres (μm) and the very high stresses (tens of $\text{V}/\mu\text{m}$) used. The dielectric losses in the new designs are very low and no longer a major limitation in design, giving low DDF values. The development of insulating materials for high-voltage capacitors continues to be active.

2.2 Characterization of insulation condition

A number of measurable parameters can be employed – directly or indirectly – to characterize the condition of insulating materials when built into system equipment. The predominant electrical characteristics are the values of permittivity and capacitance, resistivity and insulation resistance, insulation time constants, dielectric dissipation factor and partial discharge status, all of which are defined in Subsections 2.2.1–5. In oil-insulated apparatus the levels of moisture content, dissolved gas volumes and various chemical quantities are indicative of the oil/solid condition. These are discussed in Subsection 2.2.6 and in later chapters.

2.2.1 Permittivity (ϵ) and capacitance (C)

The relative permittivity, ϵ_r , is the ratio between capacitances of identical electrode systems with and without a dielectric present. The relationship is the capacitance $C = k \epsilon_r \epsilon_0$, where k is a constant representing the geometrical structure of the system and $\epsilon_0 = 8.854 \times 10^{-12}$. The values of ϵ_r range from 1 for air through to 5.5 or so for porcelain. Capacitance values range from a few pF (10^{-12} farads) for cap-and-pin insulators through to μF (10^{-6} farads) for cables, generators and power capacitors. In addition to the requirements of measurement systems (see Chapter 6) relative permittivity magnitudes are important in the alternating voltage design of multiple dielectric structures (see Chapter 3). At power frequencies little variation occurs in the value of ϵ_r with applied stress or temperature for the materials used in power system practice. The presence of moisture ($\epsilon_r \approx 80$) or trapped gas might be expected to increase or decrease respectively the measured values.

2.2.2 Resistivity (ρ) and insulation resistance (IR)

Volume resistivity, ρ , is defined as the resistance between opposite faces of a 1-metre cube of the insulation.

The resistance $R = \rho L/A$, where L is the spacing between electrodes and A is the area of the electrodes. The unit of volume resistivity is the ohm-metre, the

absolute values of which range from 10^9 to 10^{10} for oils through to the order of 10^{14} for materials such as XLPE.

Surface resistivity may be defined as the resistance between two opposite edges of a unit square of material. It is an important quantity for assessing the state of surfaces used in air and gas systems.

For a given material the values vary widely depending on impurity content (especially moisture for hygroscopic dielectrics) and temperature. In addition the initial insulation resistance will change with time of application for a constant direct voltage stress. This property is related to the time constant (see Subsection 2.2.3 and Chapter 6). The relative values of ρ are important in the design of direct-voltage multiple-dielectric systems such as transformers, bushings and cable terminations/joints. The difference between direct-voltage electric stress distributions and those with alternating voltages can be very significant during testing of equipment.

2.2.3 *Time constants*

Another parameter that can be related to some aspects of the insulation quality is the **time constant**, as measured by applying a direct voltage pulse to the system, measuring the rise time required to reach a predetermined value, discharging the sample (or equipment) for a known time and measuring the recovery voltage. Such characteristics are influenced by the complex impedance and frequency response of the equivalent capacitance and resistance network. The effect was studied in the 1950s, being designated the *dispersion effect*, and was applied to the determination of moisture content in insulating materials – in particular power transformers. More recent work has resulted in the development of improved techniques as discussed in Chapter 6.

The time constant changes also become apparent when measuring the **insulation resistance**.

2.2.4 *Dielectric dissipation factor*

An ideal dielectric or insulating material may be considered as a non-conductor of electricity acting as a pure capacitance when built into equipment. However, in practice conduction occurs and finite losses are produced that may be of great importance during test and operating conditions. Under alternating voltages the losses are represented by a slight change in the current phase in relation to the applied voltage as depicted in the phasor diagram of Figure 2.5.

Angle ϕ represents the usual power factor value, $I_R/I = \cos \phi$, while angle δ is designated the *loss angle*. I_R represents the losses and I_C the charging current. Both of these can be measured as described in Chapter 6. The ratio of $I_R/I_C = \tan \delta$ and is defined as the *dielectric dissipation factor* (DDF).

For good insulation, $\tan \delta$ is of the order of $1-3 \times 10^{-3}$, even for dry oil-impregnated paper at room temperature. The value for XLPE is much lower, perhaps 0.3×10^{-4} . Within this range of values, $\tan \delta \approx \delta$, enabling the DDF magnitude to be conveniently quoted in milliradians (mR) as measured. The cosine of the dielectric

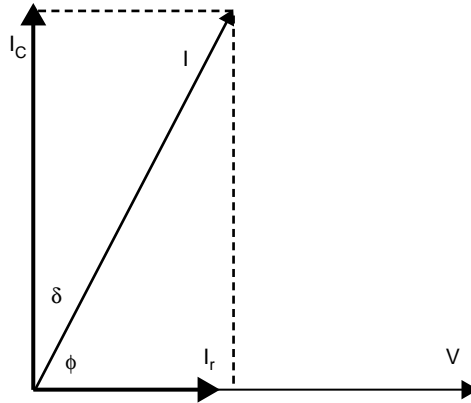


Figure 2.5 Phasor diagram for practical (lossy) dielectric

phase angle (or the sine of the dielectric loss angle) may be designated as the *dielectric power factor* by some authorities.

2.2.5 Partial discharges (PD)

According to IEC Publication 60270 [S2/9], a partial discharge may be defined as localized electrical discharge that only partially bridges the insulation system between conductors, and that may or may not occur adjacent to a conductor. The Standard states that PDs are usually due to local electrical stress concentrations in the insulation or on its surface, the pulse discharges having durations of much less than $1 \mu\text{s}$ in most cases. The ‘pulse-less’ discharges in gases are of a more continuous form and would not be detected by the techniques described in IEC 60270. The latter also notes that corona PD disturbances are associated with conductors in a gaseous medium away from solid or liquid insulants. The term is not to be applied to other forms of PDs. It is observed that sound, light, heat and chemical reactions are often produced by partial discharges.

In electrical terms PDs manifest themselves at the terminals of samples and equipment as very small-magnitude pulses (μV to volts) of rise times in the ns to μs range. The intensities of the PDs are usually represented by the charge level in picocoulombs (pC) or nanocoulombs (nC) but other parameters are also of significance in estimating possible damaging effects (see Subsection 2.3.3).

Acceptable magnitudes producing minimal deterioration in service range from a few pCs (10^{-12}C) in XLPE and GIS through to tens of pCs in oil-impregnated paper and resins, to several thousands in mica-based configurations. Higher values may be allowed in short-duration overvoltage tests.

2.2.6 Physical and chemical changes

Many deteriorative processes take place during the operation of insulation. Some of these result in by-products, which may be used for identification and monitoring of

degradation. This is especially the case for oil-immersed systems, where detection of combustible gases and of furans in the oil has resulted in the development of specialized techniques for assessing the condition of the materials. The methods utilize DGA and the application of liquid chromatography (HLPC).

An important practical insulation condition indicator associated with oil-immersed equipment is the analysis of the gases and their relative concentrations as produced by particular types of fault in the structure. Possible diagnoses are quantified in the revised IEC Publication 60599 [S2/10] and discussed by Duval (see Chapter 6). The analyses give signatures indicating the presence of low-energy partial discharges through to high-energy faults due to arcing. Interpretation of the data obtained by such techniques is considered in Chapters 9 and 10.

The physical ageing of paper as represented by the reduction in the degree of polymerization (DP) has been related to the amount of furanic compounds produced at hot-spot temperatures and absorbed in the oil of transformers in service [30]. A reduction in the magnitude of the DP from a value of >1000 (2-Furaldehyde 0–0.1 ppm) when new to 250 (2-Furaldehyde >10 ppm) is considered to be the end of life for oil-impregnated cellulose by some authorities. (See also Reference 39 of Chapter 6.) Much work is being carried out in this field, including studies for assessing the characteristics of naturally aged oil-impregnated materials aimed at estimating probable life times – for example, Reference 31. The formation of water under certain conditions, such as in sealed units, may be of considerable importance in the prediction of the rate of ageing in oil – paper systems.

Conventionally, oil acidity, interfacial tension and sludging tendency are used as physical and chemical guides for monitoring the condition of transformer oil [S2/6].

Determination of the physical changes associated with the various forms of treeing and tracking in XLPE and resins has been the aim of much research. The understanding of the mechanism of water treeing in XLPE is of considerable practical significance and remains an important research topic. This work requires the removal of samples from equipment suspected of deterioration and no longer suitable for normal service and therefore is only an indirect monitoring technique.

2.3 Modes of deterioration and failure of practical insulating materials

The concept of insulating materials having an intrinsic breakdown strength was postulated many years ago. It was found that, for thin specimens of certain pure dielectrics and by minimization of edge effects in the test configuration, the impulse breakdown stresses could be increased to perhaps ten times that achievable with normal materials. However, in practice, impurities and manufacturing variations prevent exploitation at a large scale of these purely electronic processes.

The major deteriorative and failure modes associated with power equipment insulating materials, which often comprise combinations of solid and gas/air or solid and liquid, are listed below. This is followed by consideration of some of the processes

involved. In the case of the physical and chemical changes, the present treatment is limited to mention of those aspects considered helpful in understanding the condition monitoring requirements.

- (a) Dielectric losses causing thermal instability, or runaway, in the bulk of the solid material.
- (b) Partial discharges representative of
 - partial breakdown in voids and gaps enclosed within the solid insulation producing local erosion of adjacent material;
 - partial breakdown in the ambient medium (oil, gas or air) at an interface between an electrode to dielectric or a dielectric to dielectric, thereby initiating flashover or creep and, perhaps, localized puncture through an adjacent surface.
- (c) Ageing due to thermal, electrical and mechanical stressing, including the effects in (a) and (b).
- (d) Long-term chemical changes produced by incompatibility between materials, resulting in the creation of dangerous by-products. The changes are also related to (c).
- (e) Deterioration of surface material by external pollutants, leading to reduction in tracking strength.

2.3.1 *Dielectric losses*

The failure of insulating materials due to high dielectric losses is a well-known phenomenon. In practice the effect is due to the use of, for example, unsuitable resins and often to the presence of moisture. The latter may be produced by chemical ageing, in some cases because of poor equipment sealing and, in others, by incorrect processing procedures in the factory. Additionally, the summation of the effects of energy dissipated by any high-value partial discharges can contribute significantly to the overall dielectric losses.

2.3.1.1 Determination of loss relationship

A measure of the total losses may be obtained by considering the relationship between the applied voltage and the current flowing in a simple capacitor. The relevant phasor diagram is given in Figure 2.5 as defined in Subsection 2.2.4. Assuming an angular frequency of ω the loss under alternating voltage conditions is

$$\begin{aligned}
 W &= VI_R \\
 &= VI_C \tan \delta \\
 &= V^2 \omega C \tan \delta \text{ watts}
 \end{aligned}
 \tag{2.2}$$

where V is the voltage in volts (RMS) and C is the capacitance in farads.

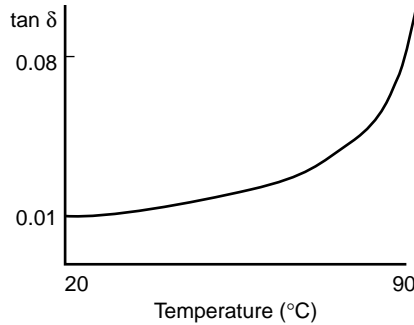


Figure 2.6 Possible variation of $\tan \delta$ with temperature for multi-layer clamping board

If C is assumed to be a cube of metre length sides then $C = \epsilon_r \epsilon_0$ farads and equation 2.2 becomes

$$\begin{aligned} W &= V^2 \omega \epsilon_r \epsilon_0 \tan \delta \text{ watts/cu. metre} \\ &= E^2 \omega \epsilon_r \epsilon_0 \tan \delta \text{ watts/cu. metre} \end{aligned} \quad (2.3)$$

where $E = \text{volts/metre}$, $\epsilon_0 = 8.854 \times 10^{-12}$ and $\epsilon_r = \text{relative permittivity}$.

In a stable direct-voltage system the losses would be simply represented by the I^2R values. Loss effects can be determined from calculations similar to the following.

2.3.1.2 Example of loss calculation

The relationship given in (2.2) may be applied for determining possible thermal instability in equipment. In studies related to the operation of oil-impregnated-paper power cables it was shown many years ago that the conductor losses, added to the dielectric losses, could lead to a continuous increase in the paper temperature. The calculation assumes a reference temperature on the conductor, e.g. 90° , an imposed outer screen temperature, knowledge of the variation of $\tan \delta$ with temperature and the dielectric thermal conductivity. An allowance is made for the logarithmic variation of stress (E) through the insulation [26].

A simpler calculation has been made for an oil-filled transformer with wooden laminated winding clamping boards. In this case it was required to determine the order of magnitude of electric stress that would be expected to produce thermal instability in 5 cm- and 10 cm-thick boards, with the oil at a temperature of 90° . The variation of $\tan \delta$ with temperature was assumed to be of the form in Figure 2.6. The calculated temperature distributions through the boards for a range of electric stresses for the two cases are indicated in Figure 2.7. The temperature rise due to a known loss in the dielectric may be determined from (2.4).

$$\Delta\theta = (1/\sigma_T)(d/A)\Sigma\Delta W \quad (2.4)$$

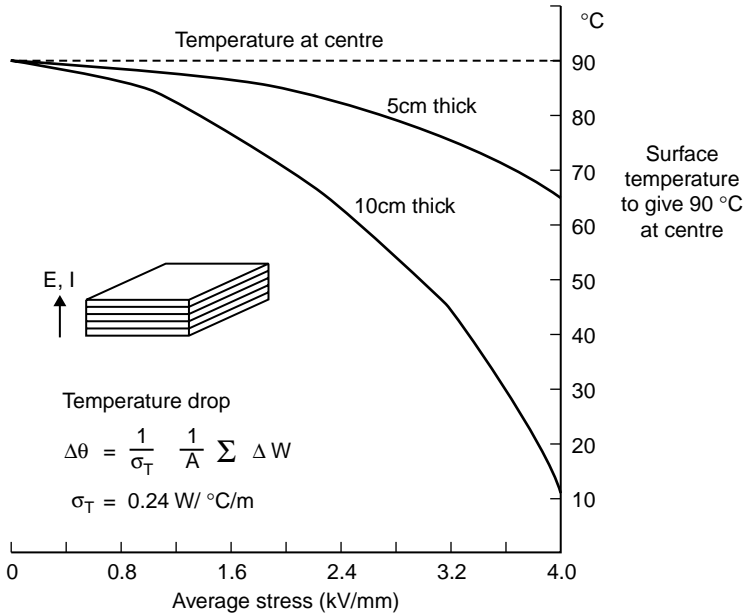


Figure 2.7 Calculated temperature distributions through insulation boards for variation in electric stress

where $\Delta\theta$ = temperature drop through a dielectric with thickness of d metre and cross-sectional area of A square metres. A thermal conductivity of $\sigma_T = 0.24$ watts/ $^\circ$ /metre is assumed.

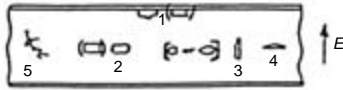
As an example, the dielectric may be divided into ten sections for the calculation and the magnitude of $\Delta\theta$ determined for each using the value of internal loss dissipated and that due to thermal flow through the section.

2.3.2 Partial discharges – sources, forms and effects

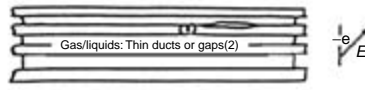
In order to appreciate the significance of partial discharges and how they can influence the life of the insulating materials it is necessary to understand where and how they might occur and the manner in which they can lead to deterioration and ultimate failure. These factors are considered briefly in the following.

2.3.2.1 Sources of partial discharges

Under alternating voltage conditions the PD sources are usually associated with trapped gas or the ambient medium. Such components of a combined insulation system have lower permittivities and breakdown strengths than the solid materials and therefore tend to be the initial location of the local partial discharges. This aspect is considered in Chapter 3 together with descriptions of some of the insulation configurations in various equipment. Despite the differences in the structures it is



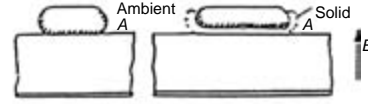
(i) Types of internal discharges in solid materials
() = Idealised shapes



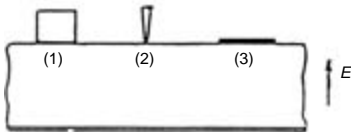
(ii) Internal discharges in laminated materials and barriered structures



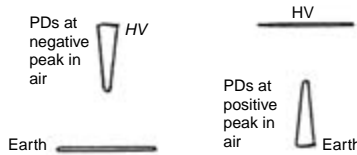
(iii) Internal discharges due to metal surface/particles embedded in insulation structures



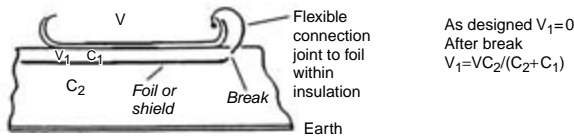
(iv) Discharges in conductor/surface and dielectric/surface wedges (A)



(v) Surface discharges due to sharp electrodes at dielectric



(vi) Discharges (corona) from uninsulated highly stressed conductors



(vii) Discharges created by changes in potential differences e.g. bushing outer foil and transformer winding shield

Figure 2.8 Examples of some partial discharge sources

possible to identify a number of common situations where electrical overstressing might occur resulting in the initiation of partial discharges. In Figure 2.8 are depicted some possibilities. These examples cover internal voids or cavities in solid and laminated insulation, relatively high stressing in ambient media at electrode or support interfaces, sharp edges at surfaces and in free space (gas/air or liquid) and conditions where a potential difference might be created due to a broken or poor connection. It should be noted that PDs can exist at earth as well as at high voltage. In air-insulated systems, such as overhead lines, discharges are usually designated *corona* or even *radio interference*, and include those from hardware components in, for example, substations.

Under direct-voltage conditions the potential distributions across insulating materials are governed by the relative values of the resistivities that in oil-impregnated systems can result in the overstressing of the solid insulants and not the liquid. The complex charging states with direct voltages may produce partial discharges that need to be monitored.

2.3.2.2 Forms of partial discharges

The model normally used for partial-discharge analysis is depicted in Figures 2.9(a) and 2.9(b). The cavity, the insulation between the cavity and the electrodes and the remaining bulk insulation are represented as capacitances C_c , C_b and C_a respectively – the a, b, c representation. The configuration was suggested by A. Gemant and W.V. Phillippoff in 1932 and analysed further as discussed by Whitehead [32] and others [33, 34].

The representation is oversimplified, as it does not allow for such factors as the existence of by-products, the finite leakage resistances (especially in the cavity), the changes due to pressure build-up and the variation of discharging surfaces within the cavity. However, the concept is helpful in understanding the pulse changes produced. Following breakdown of the gas in the cavity due to the instantaneous applied voltage, a steep pulse is produced across C_c and may be detected at the electrodes (or terminals). In Figure 2.9(c) is shown the effect of multiple discharges. The distribution of pulses within the power-frequency cycles will depend on the value of the instantaneous inception voltage (V_i) in relation to that of the applied voltage (V_{pk}). Thus if inception is near the peak, the pulses occur only on the rising quadrants, or near the peak; but, if the applied voltage is raised above the inception value ($V_i \ll V_{pk}$) – as is often the condition in practice – they would be expected to spread across the zeros as indicated in Figure 2.9(c). This concept was described earlier by Austen and Whitehead [33] and is discussed in, for example, Reference 34. However, the results of practical measurements often do not support these hypotheses as noted by Whitehead when observing that, although internal discharges tend to congregate towards the zeros with increase in voltage, they do not readily extend into the preceding half-cycle. An example of this tendency is given in Figure 2.10, which is the output of a computer-based partial-discharge measurement system [35].

The effects do not develop similarly with highly stressed electrodes (see Figure 2.8 (vi)) located in self-sealing dielectrics such as air and liquids. Under these conditions the pulses are often very distinctive, tending to cluster at the voltage peaks. The special case of corona in air where disturbances occur at the negative peak for a high-voltage point may be explained by considering the gaseous ionization conditions around the highly stressed electrode [34]. An equivalent diagram in which the air gap is assumed to be resistive and in series with a capacitance, C_c , associated with the space charge at the point electrode, is suggested by Kind [36]. This hypothesis represents the pulses and their phase shift in relation to the power-frequency voltage peak. The difference in form and location in the 50 Hz cycle of the partial discharges may assist in discriminating between external and internal discharges.

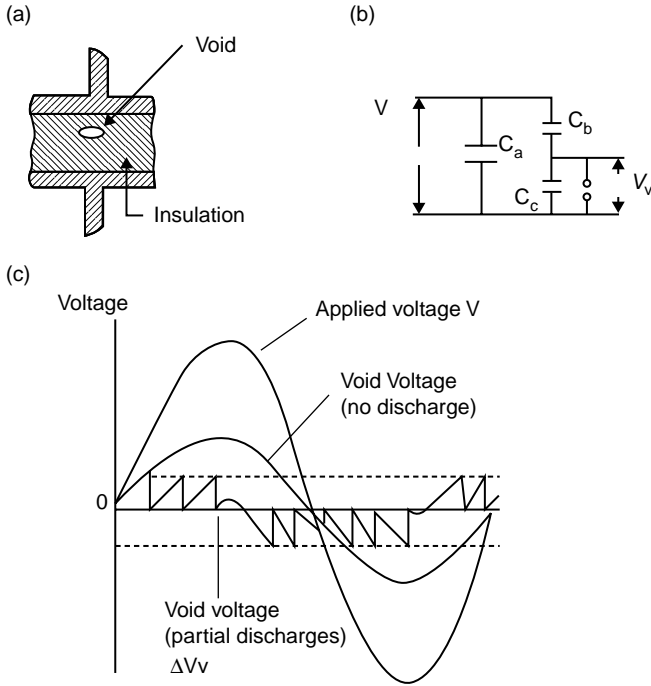


Figure 2.9 Simplified model of sample containing partial discharges [32, 33]. (a) Physical model; (b) Equivalent capacitance network; (c) Sequence of PDs for inception well below alternating voltage peak

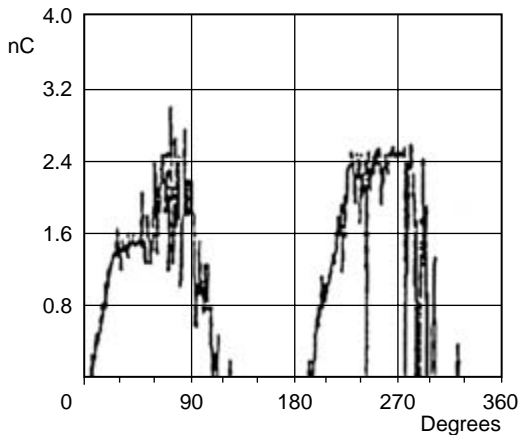


Figure 2.10 Typical PD pattern from a 'wet' pressboard sample

In Figure 2.9 the magnitude of the terminal pulse, ΔV_x , depends on the relative values of the capacitances C_c and C_b , which are usually unknown, and that of C_a . The apparent charge transfer (partial discharge) is normally the parameter measured at the terminals. The relationship between the cavity charge transfer and that at the terminal may be determined.

Referring to Figure 2.9b the change of charge across the void

$$\begin{aligned} \Delta q_c &= \Delta V_c \cdot \{C_c + C_b C_a / (C_a + C_b)\} \\ &\approx \Delta V_c \{C_c + C_b\} \text{ as } C_a \gg C_b \text{ (volume of } C_b \text{ is small)} \\ &\approx \Delta V_c C_c, \text{ as } C_c \gg C_b \text{ (area of } C_b \text{ is small and is length of sample)} \end{aligned}$$

The terminal voltage pulse due to the discharge in the cavity is

$$\Delta V_x = \Delta V_c C_b / (C_a + C_b) \text{ (capacitive division)}$$

The apparent discharge Δq_x detected at the terminals is

$$\begin{aligned} \Delta q_x &= \Delta V_x C_x = \Delta V_x \{C_a + C_b C_c / (C_b + C_c)\} \\ &\approx \Delta V_x (C_a + C_b) \text{ as } C_c \gg C_b \\ &\approx \Delta V_c C_b \end{aligned}$$

$$\text{Thus } \Delta q_x \approx \Delta q_c C_b / C_c \tag{2.5}$$

which is the quantity normally measured at the terminals. It will be noted that it would be expected to be much less than that discharged in the void as, in general, $C_c \gg C_b$. However, for a given system and approximately known location the value of Δq_x is a good measure of potential damage. It is often described as the *apparent partial discharge*.

The partial discharges that can occur within the ambient near insulation surfaces – as in regions A of Figure 2.8 (iv) – are often of larger values than disturbances within the bulk material. In air-insulated systems it may be possible to calculate the order of magnitude of the inception stress containing a wedge adjacent to the surface [37]. For a sharp-edged electrode on a surface in oil or air (Figure 2.8(v, 1) and (v, 3)), Kind [36] quotes the empirical relationship

$$V_i = K(s/\epsilon_r)^{0.45} \tag{2.6}$$

where V_i is in kV, s is the spacing in cm, and the value of K is approximately as follows:

For ‘corona’ discharge inception $K = 8$ for metal edge in air

$K = 12$ for graphite edge in air

$K = 30$ for metal or graphite edge in oil

For ‘brush’ discharge inception $K = 80$ for metal or graphite edge in air or oil

2.3.2.3 Other characteristics

Because of the unknown differences in the relative charge values and the physical changes occurring, it is considered by many investigators that energy values have a greater significance. It can easily be shown (for example, in Reference 34) that for the idealized capacitive network and a single pulse the energy dissipated in the cavity is approximately equal to the measured terminal value of $0.7 \Delta q_x V_i$, where V_i is the RMS value of the terminal inception voltage. In order to obtain a better estimate of the energy being dissipated, it is necessary to make a cumulative measurement of $\Delta q_x v_i$, where Δq_x is the terminal partial discharge value and v_i is the instantaneous value of the applied high voltage. Such measurements are possible using specially designed instruments or a general computer-based measurement system with appropriate software analysis programs.

These newer techniques allow more accurate determination of such significant PD characteristics as time of occurrence within the power-frequency cycle, repetition rate, polarity, cumulative energy dissipation and various statistical analyses of the data. The measurements are an extension of many earlier studies using less sophisticated equipment aimed at recognizing partial discharges under particular conditions. Modern digitized systems have also enabled the detection and analysis of the individual pulse wave shapes, which may have rise times of a few ns and a duration of tens of ns. In some cases with the presence of an insulation surface these times can be of the order of a microsecond. Research in such areas is now being pursued in many laboratories worldwide. Reference should be made to published papers, for example the publications of the DEIS of the IEEE and those of the International Conference on High Voltage Engineering (ISH) conferences.

In the traditional measurement systems (see Chapter 6), which are still widely applied in industry, and assuming the inception values recorded are near the peak of the high-voltage wave, energy levels tend to be comparable. This is especially so if the results are for tests on similar plant.

2.3.2.4 Damage due to partial discharges

It is apparent that certain combinations of stress and contamination are required for the onset of partial discharges under operating conditions. During overvoltage tests PDs may be initiated by incorrect design and/or manufacturing errors. Any damaging effects will depend on the materials involved and, in many cases, whether or not the by-products, especially gases, are contained locally in the structure.

In solid materials such as resins and polyethylene a form of internal tracking or treeing occurs, the stress at the tips of the trees tending to determine the progress of the branches. This effect is well documented with dangerous levels being as low as tens of pCs in some cases. With micaceous-based resin systems internal PDs are probably associated with the organic material but treeing is restricted by the mica flakes, which are able to withstand thousands of pCs for many years at operating stresses.

In laminated materials – resin- or oil-impregnated – containing gas-filled voids tracking tends to develop along the sheet, or tape, material and may exist for long

periods of time if the direction of the primary component of stress is across the laminations of the built-up structure (Figure 2.8 (ii)). Experience indicates that erosion can develop without failure with hundreds of pCs present when the stress is normal to the laminations or barriers. However, failure would be expected as the effect of the trapped gases increases and high values of several thousand pCs develop at operating stresses. Numerous 132 kV synthetic-resin-bonded paper (SRBP) bushings have survived for many years under such conditions. In some oil-impregnated systems moderate values of PDs of, perhaps, 1 000–2 000 pC can be withstood for many months.

A situation of practical importance is where discharges are initiated on a creep surface due to the stress through the material as indicated in Figure 2.8 (iv) and (v). In such cases flashover may take place along the surface as a track develops. PD values can vary from tens of pCs to thousands of pCs on oil-immersed pressboard and on polluted air surfaces in outdoor substations.

With very intense fields as in Figure 2.8 (v, 2) tens of thousands of pCs can be withstood for long periods at an oil-impregnated pressboard surface with average stresses as high as 7–8 kV/mm. The concentration of energy produces pitting and degradation of the fibres [38]. The energy required to produce a given volume of gas from oil-impregnated pressboard was estimated in the experiments by Fallou *et al.* [39].

The condition shown in Figure 2.8(vi) is unlikely to exist under oil unless some extraneous metal object, frayed lead, perhaps a gross error in design or a manufacturing fault is present. PD levels of 100 pC or so may be detected at near inception rising to several thousands at higher stresses, depending on the configuration. If remote from ground, such disturbances can continue without failure, because the oil is self-sealing. This is also the case for air where the initial values may be as low as 10–20 pC but can be many thousands of pCs at higher stresses – as in air-insulated equipment of the power system. The difference in PD polarity between oil and air at inception is notable and sometimes useful in interpretation. Air corona in an enclosed space – such as a high-voltage machine – can have a deteriorative effect due to the creation of ozone.

Although an unusual source of partial discharging, the consequence of bad connections can be very significant. Figure 2.8 (vii) indicates the effect of a broken connection where discharging occurs across the break due to capacitance coupling to the high-voltage electrode. The magnitude of the PDs will be partly dependent on such coupling and may be of the order of thousands of pCs under adverse physical conditions.

Much of the earlier work related to identification of PDs and associated possible damage was developed following the introduction of commercial discharge detectors in the 1950s. Many of the results were collated and presented in the report by CIGRE [40].

The manner in which the discharge sources might be identified using modern measurement techniques is an area of active research, some of which is detailed in CIGRE papers and in particular a brochure prepared by WG D1.11 [41].

2.3.3 Ageing effects

The various long-term changes that occur in service are often described generically as *ageing*. It is reasonable to consider ageing as a composite process including voltage stress in addition to the degradation caused by thermal stresses only. A possible methodology aimed at determining the condition of materials naturally aged in service is described in Reference 31. The results of such techniques may indicate the most appropriate in-service monitoring procedures for the particular operating conditions.

Mechanical stress effects, especially for machine insulation, are important but are not included in detail in the present discussion.

2.3.3.1 Electric stress ageing

Earlier breakdown voltage v time test results reported by, for example, Montsinger (Figure 1.9) indicated the manner in which the strength of insulation depends on the duration of the applied voltage. Presumably, such data contributed to the choice of impulse and 50 Hz test levels as related to the operating voltages – relative levels that are still applicable.

Results obtained by a number of investigators led to the establishment of the life/voltage (stress) relationship, especially applicable to dry-type insulation.

$$\text{Life}(L) = K/V^n \quad (2.7)$$

where K is a constant for the material, n is the inverse slope of the life-line on log-log paper and V the applied voltage.

In a particular investigation, the value of n was found to be between 9 and 20 for older stator bars but for other insulations it may be much smaller. The interpretation of the data from experimental tests is not simple, particularly for plastic cable samples where the scatter of results can be large. In such cases Weibull statistics [42] have been applied for estimating the probability of failure after a given time. Allowance can be made for the length and diameter of the practical cable system assuming care is exercised in the use of the statistics as discussed in Reference 43. Evaluating the results of voltage endurance tests on insulating materials is discussed in IEC 61251 [S2/4] together with explanations of the factors involved in such tests. Below certain values degradation due to electric stress would not be expected for good-quality materials within normal equipment lives. If this is a correct assumption it must be considered in the statistical analyses of test results [43].

2.3.3.2 Thermal stress ageing

The degradation due to high temperatures on the life of insulation was appreciated in the very early days of electrical engineering. This led to proposals for classifying materials according to their expected performance at particular temperatures, irrespective of electric stressing. In IEC standard 60085 [S2/1] reference is made to IEC 60216-6 [S2/2], in which procedures for the determination of the Relative Thermal Endurance Index (RTE) of a material are given. The material is then classified according to the value of the RTE interval and its thermal class. For example an RTE interval

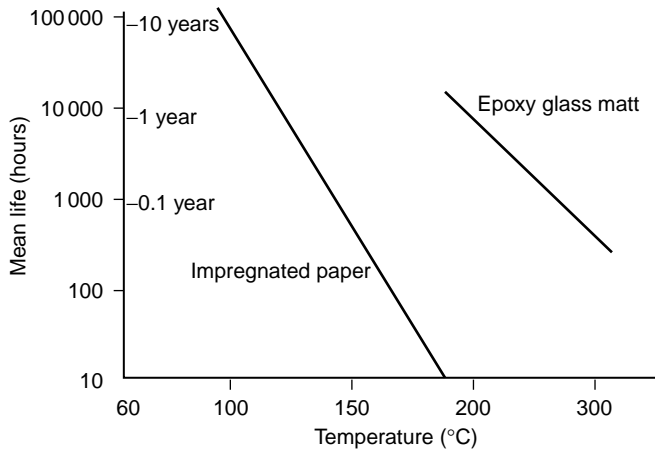


Figure 2.11 Examples of the form of thermal ageing lines

of 105–120° is allocated a thermal class of 105°, equivalent to the previous designation of Class A. An RTE of 130–155° corresponds to 130° and Class B. The standard tabulation covers the temperature range of 70° to 250° and includes a bibliography of relevant IEC and ISO standards.

The earlier experimental tests indicated that material life = $A \exp(-mt)$ where A and m are constants characteristic of the material and t is the temperature in degrees Celsius. This work formed the basis for the well-known ‘rule’ of an 8–10° rise halving the expected life of an insulating material.

These empirical results were later shown to be explainable by application of the Arrhenius description of a rate of chemical reaction

$$K = C \exp(-E/RT) \quad (2.8)$$

where C is a constant, E the activation energy, R is the gas constant and T the absolute temperature. The theory was developed by Dakin (1948) and gave the equation

$$\text{Life} = A \exp(B/T) \text{ or } \ln(\text{Life}) = \ln A + B/T \quad (2.9)$$

where A and B are constants determined by the activation energy of the particular reaction and T is the absolute temperature. A brief review of the developments is given by Brancato [44].

Strictly, the relationship applies only to conditions where one first-order chemical change determines the ageing process. Plots of $\ln(\text{Life})$ v $1/T$ should be linear for this condition. A hypothetical example is given in Figure 2.11. Results for estimation of life are often presented in this form. Statistical analyses for interpretation of measurements are included in IEC Document 60216 [S2/2].

2.4 Electrical breakdown and operating stresses

An indication has already been given in Figures 2.1–2.3 of the breakdown stresses in gases and transformer oil for simple electrode configurations. It is difficult to define or specify the electrical breakdown strength of individual materials, although this quantity is clearly of major interest for design purposes. The differences in strengths between materials are large with the values for similar samples of a particular type of dielectric varying for a specified test condition. This variation requires the introduction of probability concepts when choosing test and operational safety factors. Figure 1.9 is an example of how the mean breakdown strength of some materials might be expected to reduce with increase of the duration of the applied voltage.

In Table 2.1 are listed the order of magnitude of the 50 Hz operating stresses for some of the materials utilized in the various items of power-system equipment. Precise values cannot be quoted, as these are usually confidential, often depend on the local insulation configuration and vary according to the practice of the particular manufacturer. A number of typical sample breakdown stress values are also included in the table. The majority of such results are obtained from short-term tests on thin materials using the methods specified in a series of standards – for example IEC and ASTM. Usually these test configurations are not representative of the overall working conditions, although a particular parameter may be simulated. The tests comprise part of the quality-control process of the materials as manufactured by the supplier. The sample breakdown results are quoted in the specification for the particular material (or liquid) but must not be used as such in the design of full-scale equipment.

The electrical stress magnitudes at failure for new materials are influenced by many parameters, including the thickness of the material, the type of electrode system and the form and duration of the applied voltage. The relationship between the breakdown stress in a simple test sample and that in a full-scale structure of similar materials is difficult to determine. Also, the ratio of the power-frequency short-term equipment-test value and the much lower operating stress necessary to give an acceptable probability of life is not easily estimated. The various equipment manufacturers and users have established ratios through the relevant national and international standards committees. Ratios have also been selected to include associated lightning and switching impulse test levels. Some details of test procedures are discussed in Chapter 7.

It should be noted that the operating stresses are often 50 per cent, or even lower, of the values applied during the short-term power-frequency tests and much less than those in the impulse tests when these are required. The estimated breakdown stresses for a practical configuration installed as part of power-system equipment must be significantly higher than the test levels. This is necessary in order to maintain a safe margin during high-voltage routine and type tests. The value chosen is based on experimental tests with statistical analyses of the results if sufficient information is available, possibly supported by the use of advanced condition monitoring techniques. The choice of safety factors is influenced also by the experience and know-how of the manufacturer and user, especially in respect of the long-term operating stresses. An important factor is the need to appreciate that breakdown testing of full-scale partial structures may not necessarily allow for problems associated with the manufacture and assembly of the final equipment. For items manufactured in large quantities a lower safety margin may be acceptable.

Table 2.1 Examples of operating stresses and breakdown values of associated samples of insulating materials used in power-system equipment

| Equipment | Type of insulation | Range of 50 Hz operating stresses kV(RMS)/mm | Selected sample 50 Hz short-term breakdown stresses (average) | |
|----------------------|---|---|--|--|
| | | | kV(RMS)/mm | Reference |
| Rotating machines | Resin-mica tape | 3–4.5 | | |
| Power transformers | OI paper | 3–3.5 | 75 (ramp), 300 μm 37 (40 min), 1 mm | [45], [46] |
| | OI pressboard | 3–4.5 | 40 | IEC 60243 [47] |
| | Oil | 3 (5 mm) <1 (large) | 12 (5 mm), 3.9 (15 cm) | Figure 2.3 [13] |
| | Oil-solid creep surface | 0.4–2.0 | 7–8 (6 mm) | [46] |
| | Inter-phase air | For ex.300 kV Class 0.133 (2.250 m) | 50cm. SG @300 kV 2.35 (180 mm) Rod-plane @ 530 kV 0.265 (2.00 m) | IEC 60076-3 IEC 60052 Figure 2.1 |
| Bushings | OI paper | 3–4.5 | | |
| | SRBP | 2 | | |
| | Resin-impregnated paper | 3.5 | | |
| | Cast resin | 3 | | |
| | Porcelain – radial | | 4–16 (3 mm) | |
| | – surface (oil) – surface (air) | 0.5 0.2 | | ASTM D149 [1] |
| Current transformers | OI paper | 3.5–4 | As above | |
| | Cast resin | 3 | | |
| Capacitors | Oil–paper Film type | 10–25 50 | | |
| Cables | OI paper (pressure) | 12–15 | | |
| | – joints | 7 | | |
| | XLPE | 10–15 (new types) 4–8 | 48 (XLPE) | [48] |
| | EPR Polypropylene paper-fluid (PPL) | 3.5 10 | 20–32 (EPR) | ASTMD149 [1] |

Continued

Table 2.1 Continued

| Equipment | Type of insulation | Range of 50 Hz operating stresses kV(RMS)/mm | Selected sample 50 Hz short-term breakdown stresses (average) | |
|-----------------------------|--------------------|--|---|------------|
| | | | kV(RMS)/mm | Reference |
| Insulators | Porcelain (creep) | 20 mm/kV with medium pollution | | |
| | Composite (creep) | 0.5 (near termination) | | |
| OH lines and air clearances | Air – small gaps | | 2.1 (10 mm UF gap) | Figure 2.2 |
| | Air – long gaps | $\ll 1$ | 1.06 (1.50 m \approx UF gap) | IEC 60052 |
| | Air - non-uniform | | 0.28 (1.50 m gap) | Figure 2.2 |

2.5 Development of insulation applications

In conclusion of this chapter it is interesting to note that there appears to be an upsurge in activity related to the application of insulating materials in power-system equipment, especially in respect of the most efficient use of present plant and the incorporation of modern insulations in new equipment.

This ranges from attempting to estimate the remnant life of existing materials through to applications of the newer materials, e.g. XLPE high-voltage cables (up to 500 kVRMS or higher), SF₆ for insulation of highly rated transformers, low-loss and less hazardous liquids, metallized films for power capacitors and materials for use at superconductivity temperatures.

As discussed in later chapters, many techniques are available or under development for monitoring the critical insulating materials as installed in power-system equipment.

2.6 Summary

The review of insulating materials includes traditional and new forms as applied in power-system equipment. The electrical and physical properties of significance in characterizing and assessing the condition of the materials are introduced. A number of the deteriorative and failure mechanisms associated with practical insulating materials are described, including an indication of the magnitude of the electrical breakdown stresses of samples/prototypes compared with the actual operating stresses. An understanding of these various factors and the expected behaviour of

the materials enables the most appropriate techniques for insulation-condition assessment to be selected and assists in interpretation of the complex data recorded by the monitoring systems. The latter are considered in later chapters.

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2.8 Standards related to insulating materials

S2/1 IEC 60085 (Ed. 3.0, 2004): Electrical insulation – Thermal classification

S2/2 IEC 60216: Electrical insulating materials – Properties of thermal endurance (thermal endurance properties)

Part 1 (Ed. 5.0, 2001): Ageing procedures and evaluation of test results

Part 2 (Ed. 4.0, 2005): Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria

Part 3 (Ed. 1.0, 2002): Instructions for calculating thermal endurance characteristics

Part 4-1 (Ed. 3.0, 1990): Part 4-2 (Ed. 1.0, 2000) and Part 4-3 (Ed. 1.0, 2000): Ageing ovens

Part 5 (Ed. 2.0, 2003): Determination of relative thermal endurance index (RTE) of an insulating material

Part 6 (Ed. 1.0, 2003): Determination of thermal endurance indices (TI and RTE) of an insulating material using the fixed time frame method

S2/3 IEC 60505 (Ed. 3.0, 2004): Evaluation and qualification of electrical insulation systems

S2/4 IEC/TS 61251 (Ed. 1.0, 1993): Electrical insulating materials – AC voltage endurance evaluation – Introduction

S2/5 IEC 60156 (Ed. 2.0, 1995): Insulating liquids – Determination of the breakdown voltage at power frequency – test method

S2/6 IEC 60296 (Ed. 3.0, 2003): Fluids for electrotechnical applications – unused mineral insulating oils for transformers and switchgear

S2/7 IEC 60247 (Ed. 3.0, 2004): Insulating liquids – measurement of relative permittivity, dielectric dissipation factor ($\tan \delta$) and DC resistivity

S2/8 IEC/TR 61249 (Ed. 1.0, 1993): Insulating liquids – Determination of the partial discharge inception voltage (PDIV) – Test procedure

S2/9 IEC 60270 (Ed. 3.0, 2000): High-voltage test techniques – partial discharge measurements

S2/10 IEC 60599 (Ed. 2.0, 1999): Mineral oil-impregnated electrical equipment in service – guide to the interpretation of dissolved and free gases analysis

2.9 Problems

1. How can moisture and/or air (gas) affect the electrical properties of extruded XLPE, oil-impregnated paper and resin mouldings as applied in high-voltage equipment? Outline the principal methods that might be used to determine the presence of such contaminants.
2. Determine the AC breakdown stresses in a simple uniform field insulation system with an overall spacing of 12 mm and an insulation resin covering of 2 mm thickness on one electrode when immersed in (a) air, (b) SF₆ (both at atmospheric pressure) and (c) dry transformer oil. Calculate stress in each ‘ambient’ medium and the resin. $\epsilon_{\text{resin}} = 3.5$, $\epsilon_{\text{oil}} = 2.2$
3. An air-filled cavity of 3 mm diameter and thickness of 1 mm is suspected of existing within the laminations of an insulating board of 40 mm thickness and large area. Estimate the magnitude of partial discharges that might exist in the cavity on application of a high voltage, V, across the board. What value of PD should be detectable at the electrodes? Determine the value of the applied voltage V required to initiate discharges in the cavity. $\epsilon = 4.5$

Chapter 3

Introduction to electrical insulation design concepts

- Basic requirements for insulation design
- Electric stress distribution in insulation systems
- Electric stress control

During the process of choosing an appropriate insulation monitoring or assessment system it is of value to be aware of the design, manufacturing, electrical testing and operating requirements of the power equipment to be monitored. In this chapter an indication is given of some of the more important generic factors to be considered when selecting insulating materials for practical designs. The applications of suitable materials for a range of plant items are described in Chapters 4 and 5. The materials are reviewed in Chapter 2.

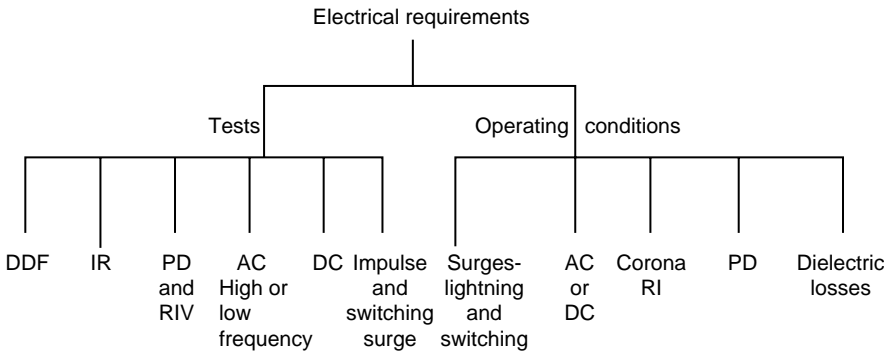
The interpretation of recorded data generated by potential faults and changes in the characteristics of the insulating materials may be aided by analysis of simple electric field configurations representing the original system. For complex arrangements it is often possible to simplify an area of interest to assist with a preliminary analysis. Several simplified cases are described in this chapter. Detailed analyses involve computerized field determinations based on accurate knowledge of the particular design. A special feature of electric field design is the use of stress-control techniques a number of which are listed together with reference to examples included in other chapters. The incorrect application of these methods can result in insulation problems detectable by appropriate monitoring systems.

3.1 Overview of insulation design requirements

The following presentation aims at giving an overview of the complexities involved in producing a satisfactory insulation structure capable of operating reliably for 25 to 40 years or more. Such lifetimes can be achieved only if efficient maintenance programmes, including insulation monitoring, are rigorously implemented.

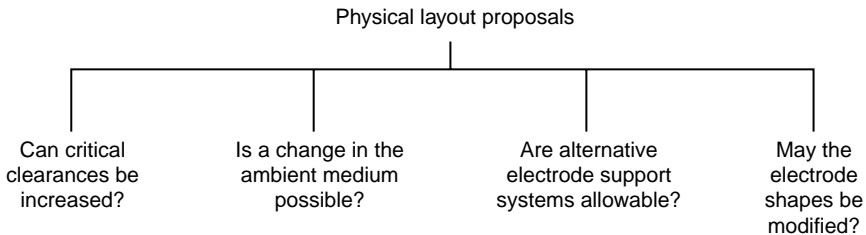
3.1.1 Electrical requirements

The electrical test voltage/operating voltage ratio varies according to the system's basic insulation level, type of equipment and its location. The value is specified by the user, guided by the data in IEC 60071-1 (Chapter 1). Depending on the particular circumstances, partial discharge, radio interference voltage and dielectric loss levels must be below specified values as manufactured. To ensure these requirements are met, appropriate tests are applied as included on the diagram. Special arrangements may be required for in-service monitoring of, for example, PDs and DDF.



3.1.2 Physical limitations

Awareness of the physical limitations imposed by non-insulation factors is important. There are many occasions when such restrictions exist and only minor modifications are possible to improve the overall dielectric performance. Some of the physical changes to the initial overall design proposals that might be considered are indicated below.

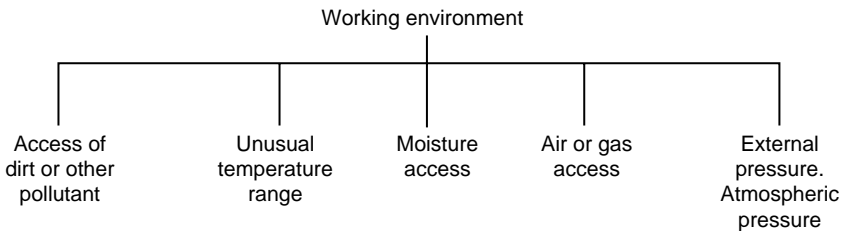


3.1.3 Working environment

No matter how well designed the structure and how satisfactory the test laboratory results, these measurements are of little value unless attempts have been made to

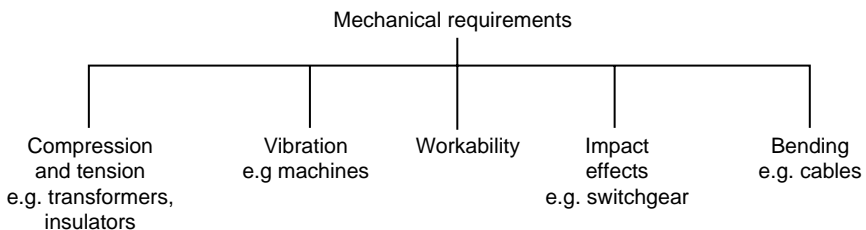
simulate and/or allow for possible insulation deterioration due to poor working conditions. If the environment results in control equipment becoming covered with dust in a damp atmosphere, or a rotating machine contaminated with grease and dirt, or an overhead line insulator polluted with salt and industrial fumes, then these factors must be considered at the design stage.

A major deteriorative effect is due to the trapping of air or the build-up of gas leading to partial discharges and ultimate failure. This can occur in oil-insulated transformers due to poor impregnation, failure to 'top' up correctly, or not following specified procedures when installing a bushing. The ingress of moisture over a long period can increase the dielectric losses in many materials, again resulting in breakdown. This applies to solid materials such as epoxy resins and XLPE as well as oil-impregnated paper, pressboard and wood. Acceptance and monitoring measurements have been devised to cover the various conditions. These techniques are described in later chapters.



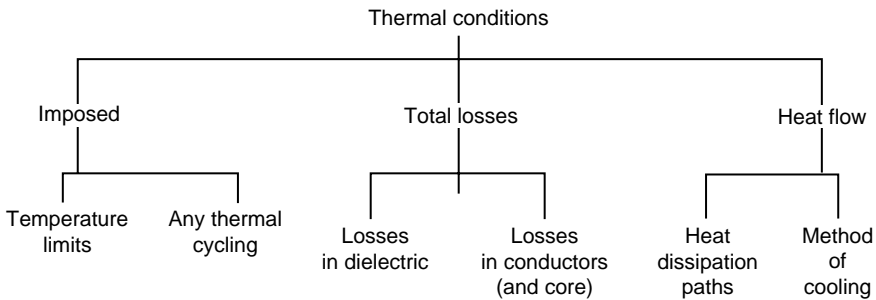
3.1.4 Mechanical requirements

As in much of electrical engineering, it is important to appreciate that allowance for the mechanical requirements in the application of insulation is essential. This is often the prime factor in ancillary low voltage systems including coaxial cables, wiring, plugs and sockets and some windings. At high voltages, in such items as rotating machines, suspension insulators, switchgear, transformers, compressed-gas or vacuum equipment and cables the mechanical performance of the insulation is of major consequence.



3.1.5 Thermal conditions

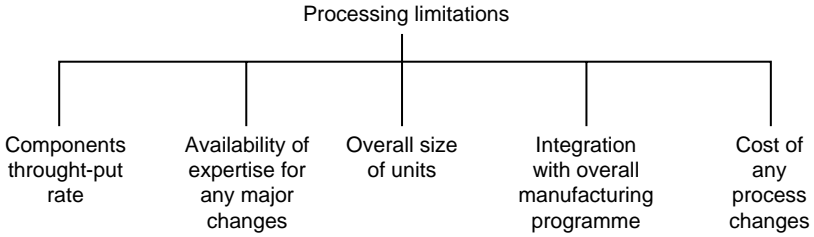
In addition to knowledge of the thermal performance of the chosen insulations, the design must allow for the imposed thermal conditions and any built-in cooling systems that exist or might be added. Thermal conditions in some cases limit the application of large amounts of insulation and structures have to be devised to allow the heat from an inner winding or conductor, and the losses in the dielectric itself, to be dissipated satisfactorily in order to avoid overheating of the insulating materials. An outstanding example of such a problem is a high-voltage power cable using oil-impregnated paper as its insulation where a ‘runaway’ condition is possible. Such conditions have also occurred in power and current transformers in which the insulating materials were not correctly dried. The use of ‘internal’ cooling of conductors has eased the thermal problem considerably in certain cases, as demonstrated in large generators and in a number of highly rated cables.



3.1.6 Processing

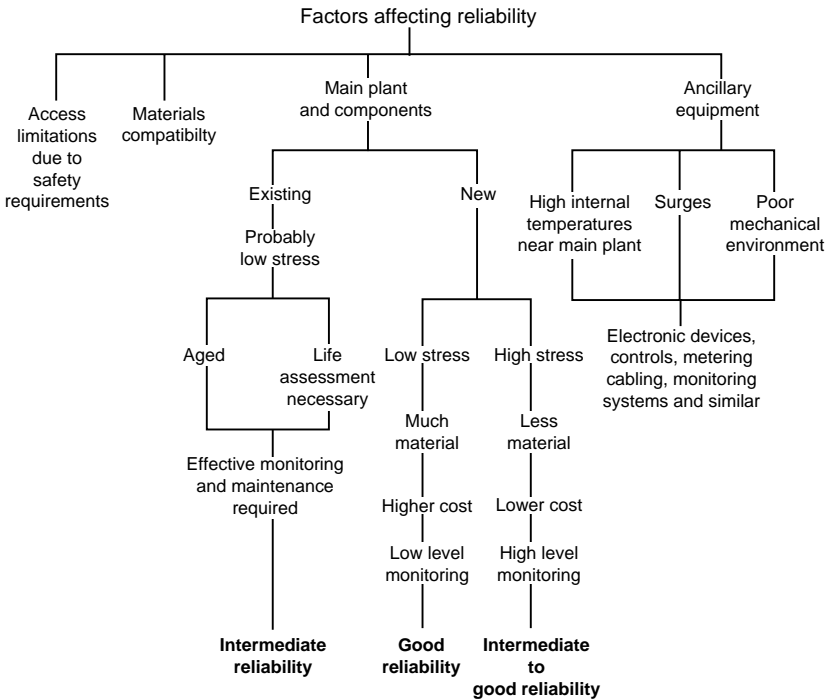
The behaviour and expected life of the insulation structures depend critically on the processing procedures adopted in the factory. These include large vacuum drying ovens through to small resin vacuum-pressure-impregnation (VPI) systems. In all cases the requirements and possible limitations must be clearly defined. An insulation change from a traditional material to a new plastic or resin may appear attractive technologically but prove uneconomic because of the cost of investment in additional manufacturing plant. For example, such decisions were necessary in the cable industry when introducing plastic systems, in transformer manufacture during development of cast-resin-type distribution units, in overhead line insulator developments, replacing conventional assembly methods with VPI processes for some larger rotating machines and replacement of oil with SF₆ in a number of plant items.

The consequence of manufacturing changes or application of new techniques must be carefully assessed following an unexpected insulation problem.



3.1.7 Reliability

The above factors influence, directly or indirectly, the ultimate reliability of the insulation structures and, therefore, of the high-voltage equipment, components and associated systems. As reliabilities of possibly better than 99 per cent – based on average times of outages over the whole system – are being claimed by some utilities, and are expected by customers, periodic maintenance and monitoring of the insulation is becoming of major importance. In the diagram, ‘stress’ includes electrical, thermal and mechanical conditions. An attempt is made to show how reliability might be related to condition (age), cost and the level of monitoring which might appear necessary.



The interpretation of some of the above factors affecting reliability is very simplistic and is intended as a guide in relation to the insulation aspects.

3.2 Electric stress distributions in simple insulation systems

There are many difficulties in applying the data available concerning the dielectric characteristics of insulation, particularly the results from small sample tests where the concepts involved in volume, area and thickness effects must be considered. Allowance needs to be made for any variations with time of electrode voltages, as can occur when a transformer winding is subjected to a lightning impulse or, sometimes, where direct and alternating voltages are applied simultaneously.

Because of the many conflicting factors it is often impossible to configure the materials to obtain an optimum insulating system. In such cases it is necessary to prepare a compromise arrangement within the overall equipment design and production limitations, as well as the customer specification. Considerable expertise is required in the layout of insulation to enable a proposed electrode system of high-voltage and earthed components to withstand the various test and operating conditions. To this end knowledge of the electric field distribution is essential together with information regarding the application of sample test results to the practical configuration, electric strength data and, perhaps most importantly, previous experience accumulated by the organization.

Design of insulation structures is often assisted by consideration of simple configurations, which can be helpful in simulating the region of interest. For some arrangements it is difficult to interpret a field determined by an advanced three-dimensional computer program unless prior knowledge as to the weakest region in relation to the local stress is known. The highest stress may occur in an inherently strong insulation structure but elsewhere a dangerous lower stress might exist in a location that is basically very difficult to insulate. Such features are more obvious in the well-established, but now rarely used, analogue techniques set up for the plotting of capacitive fields in conductive media, the commonest two being a resistive paper sheet or an electrolytic tank [1]. The choice of an appropriate method will depend on the particular circumstances including the experience and knowledge of personnel available, complexity of the problem, the accessibility of hardware and software, and whether the solutions are for development, design or urgent investigative purposes. There is no doubt that in large organizations computer programs are applied extensively. Due to cost, however, the simpler techniques may still be preferred in some cases, especially for two-dimensional problems.

Programs for solving symmetrical 3-D problems by the Finite Element Method have been in use for many years. More recently the Boundary Element Method seems to have been developed for truly 3-D asymmetric conditions. In this technique a mesh is required only at the electrode boundaries and dielectric interfaces. This reduces the storage and memory needed and usually gives stress values directly as well as the equipotential distribution. The latter is often of value in the initial design of complex insulation systems. Large computers and costly programs involving many hours of running time are still necessary for the solution of practical problems such as the GIS components discussed, for example, in Reference 2.

Because a significant number of insulation failures are related to the electric stress distributions – magnitudes and spatial rates of change – consideration is now given to

a number of common field conditions. Such analyses and associated PD/breakdown data can be helpful in interpreting the results of monitoring and testing of specific designs, including some complex configurations. Stress-enhancement factors – maximum stress ÷ average stress – have been determined for a number of simple electrode systems containing one dielectric, usually air or SF₆. A summary of a few of these factors is given in Reference 3.

3.2.1 Multiple dielectric systems

The simplest multiple dielectric configurations occur in uniform (parallel) and concentric fields.

3.2.1.1 Parallel electrodes

In Figure 3.1 is shown the condition where dielectrics are located between parallel electrodes. By neglecting the edge effects this arrangement can be used to determine the stress distribution in a parallel field in which several dielectrics are located in series, including liquid and gas layers as in laminated structures.

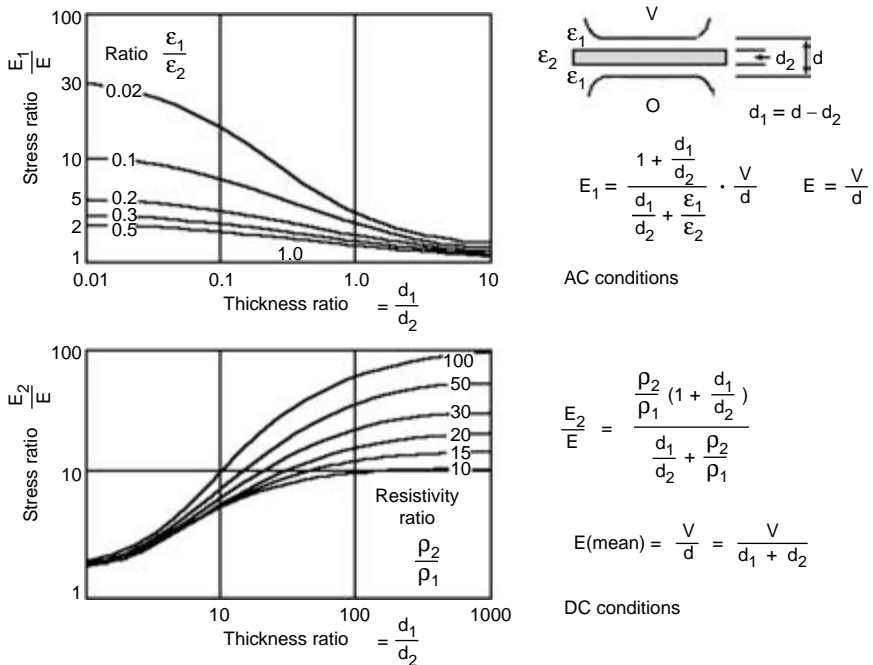


Figure 3.1 Multiple dielectrics in a parallel field (variation of stress for two dielectrics ($n = 2, d_1, d_2$))

If n dielectrics are represented then the stress in layer i is

$$E_i = \frac{V}{\varepsilon_i \left(\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2} + \dots + \frac{d_n}{\varepsilon_n} \right)} \quad (3.1)$$

and the capacitance

$$C = 2\pi \varepsilon_0 \frac{1}{\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2} + \dots + \frac{d_n}{\varepsilon_n}} \text{ farads/metre}^2 \quad (3.2)$$

For the particular case of two dielectrics ($n = 2$) – for example gas (air)/porcelain, gas (air)/pressboard, gas (air)/resin, oil/pressboard (or paper), paper/resin – nondimensional curves giving the ratio of the stress (E_1) in dielectric n_1 and the average stress (E) may be calculated as in Figure 3.1. These cover the range of permittivity ratios of 0.02 to 0.5 and resistivity ratios of 100 to 10 for a range of dielectric thickness ratios of d_1/d_2 . Applications of these simple but useful concepts may be demonstrated quantitatively as follows.

- (a) If the electrode spacing $d = d_1 + d_2 = 10$ mm, the air gap $d_1 = 3$ mm ($\varepsilon_1 = 1$), the barrier thickness $d_2 = 7$ mm ($\varepsilon_2 = 3.5$), the applied voltage V , then from (3.1) the air stress $E_1 = 0.2 V/\text{mm}$.

From Figure 2.2 the breakdown of a 3 mm-thick air gap in a uniform field is 2.59 kV/mm, thus the configuration would be expected to discharge when $E_1 = 2.59$ kV/mm or $V = 13$ kV(RMS). The calculation is an indication of how the introduction of a barrier of inappropriate thickness between HV and earth – or even between phases – may produce corona (partial discharges) in service for certain field conditions, thereby reducing the strength of the system. Failure by puncture may occur due to erosion of the surface by corona or, possibly, a flashover around the barrier even though the stress across the barrier is low – 0.74 kV/mm at corona inception in this case.

With a barrier of 4 mm thickness placed centrally between the electrodes the air space $d_1 = 6$ mm is divided into two 3 mm gaps and $d_2 = 4$ mm. The air stresses compute as 0.14 V/mm, giving a discharge inception voltage of 18.5 kV (RMS) assuming the stresses in the gaps are 2.59 kV/mm.

Although the inception voltage is increased by reducing the barrier thickness it is still below that of 21.9 kV for a gap of 10 mm without a barrier. The latter would be unstable with a near-uniform field containing particles, moisture and other pollutants as in a practical system – for example, bus-bar arrangements in metal-clad switchgear. Equipment test stresses would be chosen to be much lower than those deduced from the Paschen curves (see Figure 2.2), but the data are of value in choosing the optimum configuration and in analysing failures.

- (b) For the above condition, where the duct or gap is filled with oil ($\varepsilon_1 = 2.2$, 3 mm thick), the barrier is pressboard ($\varepsilon_2 = 4.4$, 7 mm thick), (3.1) gives the value of $E_1 = 0.153$ V/mm. From Figure 2.3 a 3 mm-thick oil gap would be expected to break down at approximately 14 kV/mm (RMS) corresponding to an applied voltage of $V = 91$ kV (RMS) with a stress of only 7 kV/mm in the solid and an average stress of 9.1 kV/mm (RMS). This average stress can be increased by

reducing the barrier thickness and forming, for example, two 3 mm-thick ducts. By a procedure as in (a) the voltage for inception becomes 112 kV (RMS), although the gap still limits the overall strength. These stress values may not be achieved in practice in transformers where the allowable interwinding oil stress during short-term testing might be of the order of 10 kV/mm. This is well below the uniform field conditions represented in Figure 2.3. If the stress-v-volume graph in Figure 2.3 had been applied for a large volume, a lower voltage would be expected to produce partial discharges. Such considerations are taken into account when designing large insulation structures as in power transformers.

It will be noted that as $d_1 \rightarrow 0$ (or $d_1/d_2 \rightarrow 0$) the stress $E_1 \rightarrow E \cdot \epsilon_2/\epsilon_1$.

Similar calculations may be carried out for DC conditions in oil. In such cases the stress in the solid material will be higher than in the oil. For example, with a resistivity ratio of 100 (oil – $10^{11} \Omega\text{m}$, impregnated paper/pressboard – $10^{13} \Omega\text{m}$) and $d_1/d_2 = 1/9$ the stress in the oil is very small (see Figure 3.1). If the oil gap is relatively large the solid may be overstressed. During the application of direct voltage tests to AC equipment this condition must be recognized when choosing levels to be applied. With an air gap (high resistivity), partial discharges can easily be induced but are usually of a low repetition rate. The ‘hissing’ from high-voltage DC test sets and charging units is typical.

3.2.1.2 Concentric electrodes

Another simple configuration that can often be of assistance in interpreting test results is that of concentric cylinders, Figure 3.2 (a).

In this case the field distribution is logarithmic, the magnitudes depending on the radial location and the value of the permittivity (for AC conditions) or conductivity (for DC conditions). The stress at radius r_1 is given by the following, where ϵ_x is the

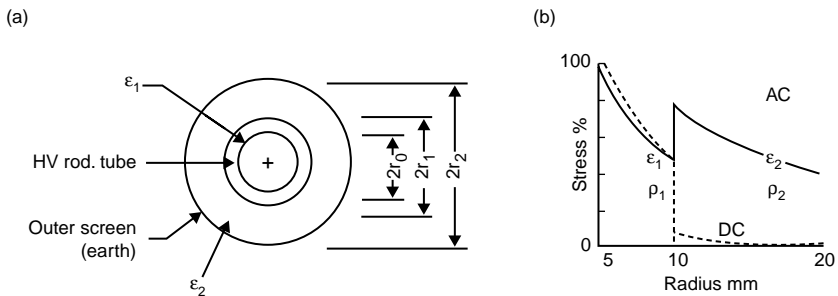


Figure 3.2 Multiple dielectrics in a concentric field. (a) Configuration for two dielectrics; (b) Variation of stress across two dielectrics

$$r_0 = 5 \text{ mm}, r_1 = 10 \text{ mm}, r_2 = 20 \text{ mm}. \epsilon_1 = 3.5, \epsilon_2 = 2.2$$

$$\rho_1 = 10^{13} \Omega\text{m}, \rho_2 = 10^{11} \Omega\text{m}$$

permittivity of the particular section:

$$E(r_i) = \frac{V}{\varepsilon_x r_i \left(\frac{1}{\varepsilon_1} \ln \frac{r_1}{r_0} + \frac{1}{\varepsilon_2} \ln \frac{r_2}{r_1} + \dots + \frac{1}{\varepsilon_n} \ln \frac{r_n}{r_{n-1}} \right)} \quad (3.3)$$

for a capacitive distribution. Note that the total capacitance

$$C = 2\pi \varepsilon_0 \frac{1}{\frac{1}{\varepsilon_1} \ln \frac{r_1}{r_0} + \frac{1}{\varepsilon_2} \ln \frac{r_2}{r_1} + \dots + \frac{1}{\varepsilon_n} \ln \frac{r_n}{r_{n-1}}} \text{ farads/metre} \quad (3.4)$$

Substituting conductivities for permittivities gives the equivalent DC conditions. The stress distribution across a two-layer system for particular values is indicated in Figure 3.2(b).

The sudden change in electric stress due to different permittivities and conductivities at the insulation interface is apparent. The possibility of maximum stress reduction is sometimes exploited in high-voltage oil-impregnated cables by using higher-density papers at the inner conductor.

The significant difference in the AC and DC stress distributions can introduce problems when testing power frequency equipment with direct voltages – in particular cable sealing ends and through joints.

3.2.2 *Edge effects*

Edge effects at the interface or terminations of the electrodes and the insulating materials can introduce problems requiring special arrangements to prevent PDs and avoid breakdown. The determination of the electric stress distribution in such cases is essential in order to ensure optimum performance on test and in service.

A condition that can arise in bushings, some current transformers, possibly in capacitors, in incorrectly terminated cables and on the stator bars of high-voltage machines is indicated in Figure 3.3 (a). Here the thin foil or screen end is not stress-relieved. Although some stress relieving by inclusion of a curved electrode may be effected as in Figure 3.3(b), partial discharges might still occur in the ambient medium within the wedge at test and operating voltages. Some indication of the voltage levels allowable can be determined by calculation of the stresses in the ambient insulation of air/gas or insulating oils within the wedge formed at the surface.

By assuming a capacitive division across distances d_1 and d_2 with a common localized area, the inception voltage $V_i \approx V_1 \{ \varepsilon_1 \cdot d_2 / \varepsilon_2 \cdot d_1 + 1 \}$ where V_i is the inception voltage to earth. For a range of values of d_1 the expected inception voltages (V_1) may be estimated from the Paschen curves in Figure 2.2 for gases and the data in Figure 2.3 for oil.

This approach for determining the inception voltage in the gap, and therefore that of a system containing such a wedge, was described by Mason [4] and is analysed further by Kreuger [5].

The position of the PD source in the oil or air next to the electrode surface may be transferred to a ‘safer’ region by addition of insulation on the electrode in configurations as shown in Figure 3.3 (b) – see also Figure 2.8 (iv, b). This is a form of stress reduction along the insulation surface. The particular case of a sphere touching

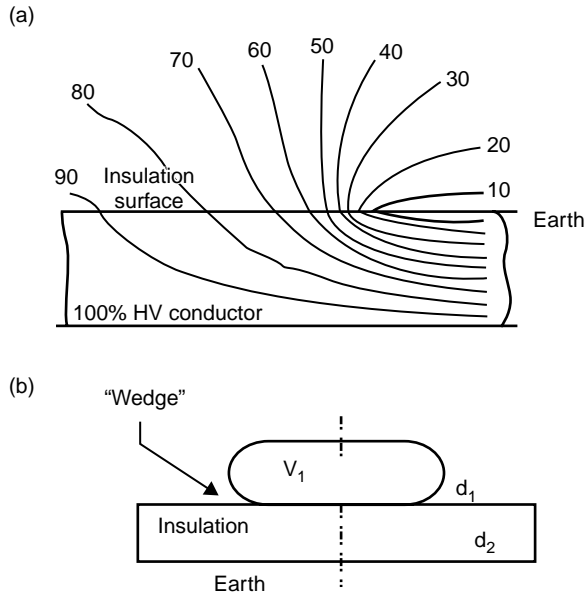


Figure 3.3 Effects at edge of electrodes located on an insulation surface. (a) Voltage distribution at edge of thin earthed electrode; (b) Model for determination of PD inception at a curved electrode

or being embedded in an insulation for a range of permittivity ratios was analysed by Binns [6]. This includes determination of maximum stresses and tangential values at the interface between the two insulating materials. Equipotential plots showing how the field along the insulation surface adjacent to a partially embedded electrode is influenced by the permittivity ratios of the solid ($\epsilon = 4$) and ambient medium ($\epsilon = 1$) are given as an example in Figure 3.4. The reduction in stress for condition (b) is significant. A number of practical applications, in particular for GIS, are given in References 2 and 3.

The supporting of insulated high-voltage leads in oil adjacent to a plane earthed surface often requires a creep surface between the two, as in Figure 3.5(a). In order to reduce the maximum tangential stress (at the paper surface) along the supporting board to an acceptable value it may be possible to increase locally the diameter of the paper on the lead. If the overall spacing is large, an indication of the diameter required can be estimated by assuming a concentric cylinder configuration even though the earth electrode is a plane. This is a case where the insulation is being used to effect AC stress control in a critical region as well as providing increased puncture strength. For more accurate estimates, a field analysis would be required. The voltage distribution across the system is of the form in Figure 3.5(b). As in a previous example, for a paper/oil configuration the direct voltage distribution is primarily across the paper and not the oil. This is not the case for a gas/air system, in which the conductivity of

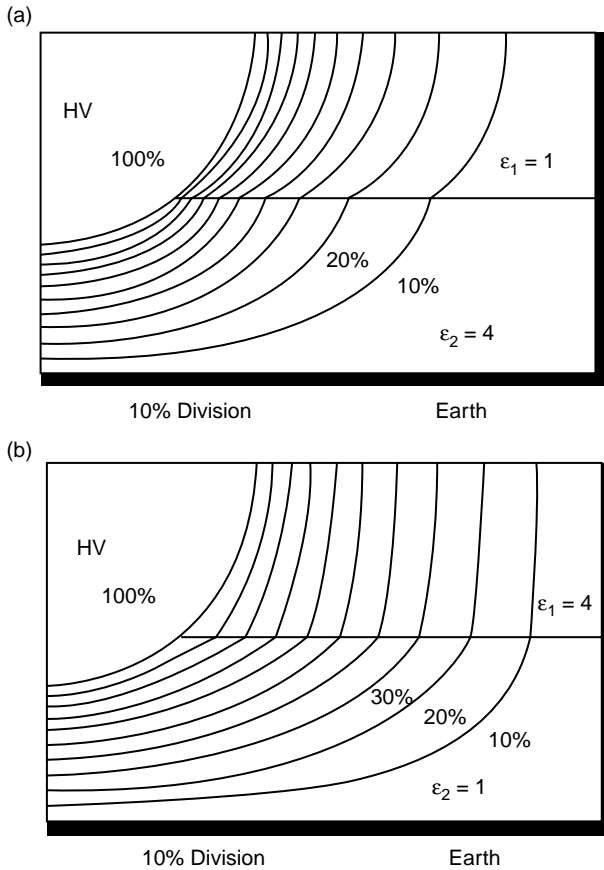


Figure 3.4 Equipotential plots for partially embedded electrode. (a) $\epsilon_1/\epsilon_2 = 1/4$; (b) $\epsilon_1/\epsilon_2 = 4/1$

the ambient is very low. The concepts also apply if the ambient is a gas as in GIS, dry-type transformers, air-insulated switchgear and high-voltage machines.

The curves in Figure 3.5(b) for the main gap are based on permittivity, conductivity and spacing values for practical systems. The principles can be applied to other insulation arrangements incorporating different materials.

3.2.3 Multiple electrode configurations

During the investigation of certain types of fault it is often unclear as to why a particular tracking or flashover/puncture path was followed. Such a situation can arise where three or more electrodes are involved. Stressing in a well-insulated direction can produce PDs that may cause a failure along an unrelated path. This has been demonstrated experimentally at high voltage with the electrode system represented

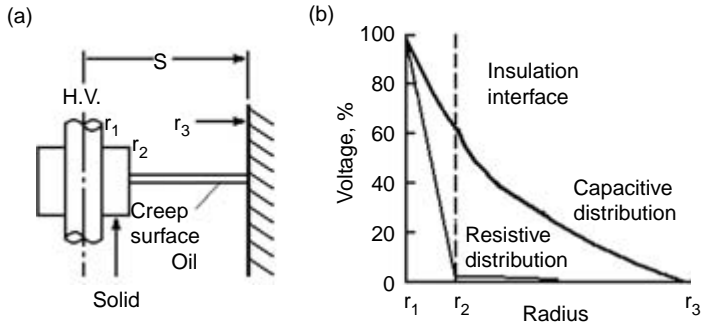


Figure 3.5 Insulation support for insulated high voltage lead. (a) Basic configuration; (b) Voltage distribution in main gap for AC and DC conditions (solid/oil system)

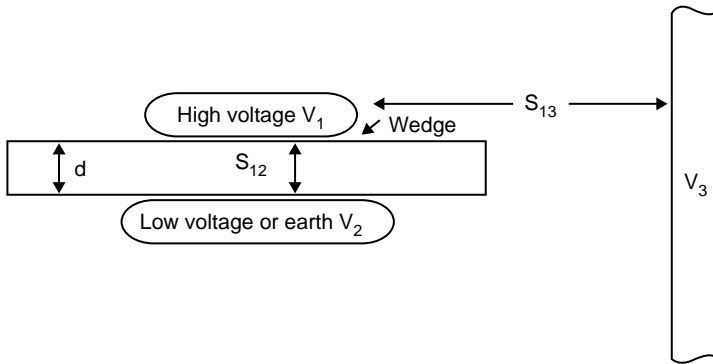


Figure 3.6 Effect of normal and tangential stressing in a multiple electrode system

in Figure 3.6. This is an example of a practical test in oil in which the flashover voltage strength along the insulation board was reduced by an increase in the stress value across the insulation thickness.

Although paths S_{12} and S_{13} may be considered independently, the initiation of PDs in the oil wedge due to the ‘normal’ stress between V_1 and V_2 can reduce the breakdown strength along the ‘tangential’ path S_{13} between the electrodes at voltages V_1 and V_3 . Similar situations can occur in dry-type equipment. Such a scenario requires careful analysis of the electric field in relation to the original design and how this may have influenced the failure pattern. A more complex situation exists in transformer windings, where each turn may be treated as a separate electrode at a different potential from the others and from adjacent windings. In dry-type configurations, where discharges in the wedge may be induced more easily, such stress conditions can be very significant.

Simultaneous testing between phases and to ground in three-phase equipment may produce similar situations.

3.3 Electric stress control

In order to ensure the most economic use of space and materials, insulation designers have employed a range of techniques effectively to reduce the maximum to average stress ratio in the configurations utilized in high-voltage equipment. Under some conditions such methods may not be helpful. For example, during tests with insulated rods to a plane in oil it was found that the more uniform fields gave lower average stresses at breakdown. This was due to the ‘volume’ effect associated with the tendency for particles to be uniformly distributed throughout the oil space. In the case of the less uniform systems it can be postulated that the particles are attracted to the more highly stressed regions, thereby producing an overall oil gap of greater strength in series with the insulated high-voltage electrode.

The outstanding examples of stress control are in cable terminations, bushings, instrument transformers, insulator strings, stator bars, switchgear and power transformers. In many situations these insulation systems must be designed to withstand impulse voltages of twice or more the magnitude of the RMS value of the corresponding power frequency test voltage.

Many methods of stress control are practised as described in numerous papers and books. A number of areas of application of the techniques are summarized below and, where appropriate, reference made to diagrams in this book.

- (a) Reduction of stress at high-voltage external terminations by
 - use of rings and similarly shaped electrodes in substations on support structures, surge arresters, circuit breakers, disconnect switches (isolators) and other devices (Figures 1.4–1.6);
 - application of continuous shields, or possibly ‘cages’, for bushing (Figure 5.11) and sealing end terminations.
- (b) Reduction of stress at high-voltage conductors in air by
 - configuring two or four conductors in parallel as on transmission lines.
- (c) Reduction of stress at internal support structures by
 - shaping of cast-resin spacers to improve the equipotential distribution at the conductors of SF₆ busbars;
 - dimensioning of insulation to reduce critical stress at HV lead supports (Figure 3.5).
- (d) Reduction of stress at the edges or corners at earthed exits by
 - contouring earthed foils in bushings (contoured or part of capacitor foil system), and in sealing ends (Figures 4.9 and 4.12);
 - adding semiconducting tapes or similar compounds to plastic cables (Figure 4.12) and to stator bars (Figure 5.2).
- (e) Reduction of stress external to oil-immersed transformer windings by
 - including metallized end rings in disc-type windings (Figure 5.10) and outer shields in layer-type windings (Figure 5.5(c)).

- (f) Reduction and control of stress within the main structures of devices by
- winding in foils within current transformers (Figure 4.4) and in capacitive type bushings (Figure 4.3);
 - adjusting the turns arrangement to give capacitive control of surge voltage stresses in transformer windings (Figure 5.4);
 - fitting of metallic shields around line-end tap changers;
 - inclusion of shields in through joints of high-voltage cables (Figures 4.10 and 4.13) and dry-type terminations.

Some of the above aspects will be highlighted in Chapters 4 and 5 during the description of possible faults in particular equipment and components.

3.4 Summary

The chapter reviews many of the factors involved in the design of electrical insulation as applied in power-system equipment – ranging from physical, mechanical and ageing aspects through to the determination of electric stress.

Stress analyses of simple insulation configurations are presented. Such concepts are helpful in the determination of the order of magnitude of electric stresses, perhaps after a failure on test or in service, and in choosing the most appropriate computer-based program to investigate details. These basic analyses also assist in understanding the adverse conditions that can be present or arise. A number of electric stress-control methods as applied in practice are listed at the end of the chapter.

An appreciation of the problems associated with the insulation design of particular power equipment is desirable when choosing or developing a condition monitoring system.

3.5 References

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5. Kreuger F. H., *Partial Discharge Detection in High-Voltage Equipment* (Butterworth & Co., London, 1989)
6. Binns, D.F., and Randall, T.J., 'Calculation of potential gradients for a dielectric slab placed between a sphere and plane', *Proc. Inst. Electr. Eng.*, 1967; **114**:1521–8

3.6 Problems

1. Identify the major electrical, thermal, mechanical and manufacturing requirements for electrical insulating materials as applied in the following AC power-system equipment. Indicate possible materials for each case.
 - (i) Outdoor insulators (6.6 kV and above).
 - (ii) HV power transformers (132 kV and above).
 - (iii) HV cables (11 kV and above).

Refer to Chapters 2, 4 and 5.

2. For the cases in Q1 suggest the insulation parameters that might be monitored in service.

Refer to Chapters 2, 4 and 9.

3. A piece of oil-impregnated pressboard is placed between two parallel plate electrodes in transformer oil. The effective area of the electrodes is 10×10 cm and the spacing 1 cm. The thickness of the pressboard is 3 mm and its area $\gg 10 \times 10$ cm. The relative permittivities of the oil and pressboard are 2.2 and 4.4 respectively. Assume the corresponding resistivities are 10^{11} and 10^{12} ohm-metres. Calculate the electrical stresses in the oil and board:

- (i) For a voltage of 100 kV (RMS) applied between the electrodes. Assume a parallel field.
- (ii) Repeat (i) for a direct voltage of 100 kV applied.

What are the practical implications of the difference in the field distributions?

4. For the conditions in Q3 determine the capacitances of the oil and pressboard thicknesses and the total capacitance. Calculate the corresponding resistance values. Assume a 10×10 cm area. ($\epsilon_0 = 8.854 \times 10^{-12}$)
5. For the dimensions in Q3 determine the expected terminal voltage at onset of partial discharges or breakdown in the oil with the pressboard located (i) at one of the electrodes and (ii) in the middle of the gap.

Refer to Figure 2.3 of Chapter 2.

Chapter 4

Insulation defects in power-system equipment: Part 1

- Insulators and bushings
- Capacitor voltage transformers
- Power capacitors
- Surge arresters
- Circuit breakers and gas insulated systems
- Power cables

In this chapter are discussed the insulation configurations of a number of power system components that may be considered as behaving predominantly as capacitances. Rotating machines and transformers are reviewed in Chapter 5. Descriptions and examples are given of insulation conditions that might result in deterioration and possible failure.

4.1 Suspension and post insulators

4.1.1 *Suspension (string) insulators*

The construction of one form of conventional cap-and-pin-type suspension insulator as used in strings is depicted in Figure 4.1(a). The units consist of porcelain or glass as the major insulation and are connected in series according to the particular line voltage. For example, a 330 kV line may require 20 individual units depending on the expected pollution at the tower site. It is notable that in 1996 glass insulators represented in cost terms 19 per cent of the world's exports of porcelain and glass units [1]. The surface profiles of the insulator sheds are designed to minimize the effect of pollution, rain, fog and ice as specified for the local application. In extreme conditions such as near the coast, in dust or desert areas and in locations adjacent to some industrial installations, flashovers may occur due to the creation of conduction paths. A particular electrical discharge phenomenon is associated with the formation

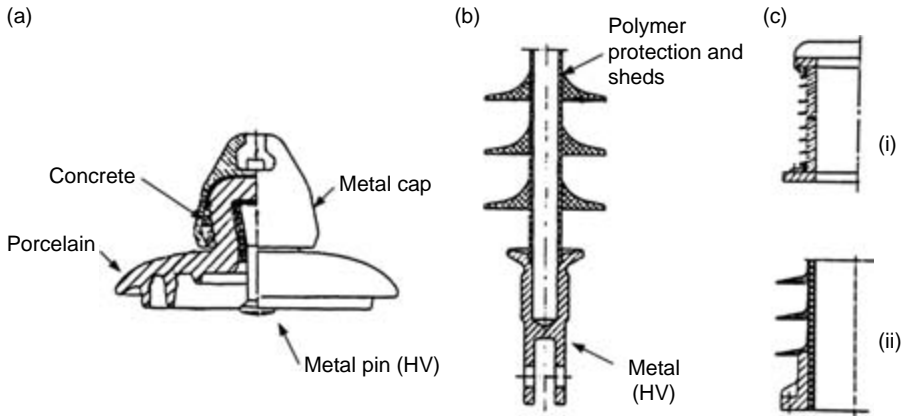


Figure 4.1 Examples of suspension and post insulators. (a) Porcelain suspension insulator; (b) Composite polymer suspension insulator; (c) Insulator shells (i) porcelain (ii) composite

of ‘dry bands’ on the porcelain surface. The bands are created by the electric stress in localized regions on the surface being of sufficient magnitude to produce losses in the pollutant, which may dry out because the ambient condition (e.g. the moisture evaporation rate) does not allow dissipation of the heat. This can result in a build-up of voltage across the band with subsequent discharges or arcing [2].

Another fault that may or may not be troublesome with ceramic insulators is the presence of partial discharging (corona). Although the PDs, usually associated with the metal work, rarely cause damage to the materials, they can result in unacceptable radio and TV interference.

Failures of insulators were caused by excessive deposition of ice and snow during storms in the USA and Canada. These types of failure are surveyed in a 2005 CIGRE report [3], which contains a number of references related to the condition. EPRI investigations have indicated that a number of cap-and-pin insulators would be expected to lose much of their insulating properties after 60 years in normal service [4]. Despite the excellent performance of the older units, cases have been reported of catastrophic mechanical failures of recently manufactured ceramic insulators.

Long-rod composite polymeric insulators are increasingly being applied despite the naturally cautious approach of utilities. The advantages include reduction in weight – giving easier handling – and somewhat improved performance under heavy pollution conditions. However there is still some concern regarding chemical changes due to dry-band-arcing, corona and weathering. Laboratory and field tests have been carried out for many years but there appears to be a wide range of opinion and experience as to the long-term effects. In the United States a high percentage of all new insulators are composites, while in other countries the introduction of polymer units is being carried out with caution or possibly on a trial basis.

The principle of the construction of long-rod composite insulators is shown in Figure 4.1(b) – a stress ring at the lower end is not included. The load-bearing inner rod consists of fibreglass-reinforced polymer (FRP) – epoxy resin probably being the most used polymer – terminated with metal ends. These are shaped to minimize corona, whose presence can contribute to brittleness and cracking of the glass–resin composite. The polymer seal must be maintained in order to prevent access of moisture. The complex processes associated with ‘brittle’ failures have been studied for many years. Part of the research in the USA supported by the Electric Power Research Institute (EPRI) is reported in some detail in Reference 5. The catastrophic failures develop radially across the glass fibres, probably in the high-voltage region, and appear to be due to the combined influence of the working mechanical stress, acidic attack due to the interaction of the materials (resin and glass), the electric stress, corona effects (ozone) and moisture ingress/diffusion. The use of polyester resin is considered to be unsuitable by the EPRI investigators. Although the number of failures is low (200) compared with those now in service ($> 10^6$) [5] the long-term effects are not known. However, various design and manufacturing changes have been made based on the studies so far, including recommendations regarding correct handling procedures.

In composite insulators, the weather sheds are formed over the rod and usually consist of silicone rubber (SIR). Chemical bonding is effected between the sheds and the rod and between the sheds themselves. As the electric stress acts along the rod fibres and the longitudinal interface, it might be expected that any manufacturing or service problems in these regions could result in electrical as well as mechanical weaknesses [4].

SIR is probably the preferred material at the present time, because its hydrophobic properties (minimum affinity for water) are good and it has a higher resistance to UV radiation than some other materials and also to dry-band arcing. After exposure to intense discharges, SIR forms silica, which is non-conducting. Other materials that have been used and are in service include ethylene propylene rubber (EPR) and cycloaliphatic epoxy.

For many years room-temperature-vulcanized (RTV) SIR high-voltage coatings have been used by some utilities for improving the pollution performance of porcelain insulators. The behaviour of such systems is discussed by Cherney *et al.* [6], where it is emphasized that, unlike the case with porcelain, low-energy corona from end fittings can degrade the RTV–SIR coating. This can be a significant problem if the original source of corona is not removed by modification of rods, end rings and similar.

The monitoring of potential faults associated with insulators may be detected by thermal (or acoustic) scanning, as discussed in Chapter 9.

4.1.2 Post insulators

Post insulators may consist of a solid core, a shell of porcelain or, in the case of composites, an inner, fibre-wound epoxy cylinder with metal terminations and a protective polymer covering. For the last of these, sheds are provided of a compatible

material – e.g. silicone rubber. Identical faults to those for the suspension units have not been reported [4], although it is possible that high crimping pressures of the terminations may have caused apparently similar mechanical failures at the earthed end, as well as at the high-voltage connection. Larger-size shells are also used in bushings, instrument transformers and surge arresters.

4.2 High-voltage bushings

Bushings in their various forms are used wherever it is necessary to pass a live conductor through a metal plate or tank at a different potential – usually at earth potential. The basic requirements are indicated in Figure 4.2(a). A bushing consists of a metal rod (or tube) supported by a simple insulation structure at the lower voltages through to higher-voltage units containing many stress-grading foils within the insulation. Commercial bushings are classified in Standards such as IEC 60 137 [S4/1].

The method of improving stress control by means of isolated conducting foils is shown in Figure 4.2 (b), where a comparison is made between an ungraded and graded configuration of a hypothetical bushing. It is apparent that the voltage distributions axially along the insulation surfaces and radially through the structure are much more uniform in condition (ii) than in the uncontrolled case (i).

In practice it is not possible to achieve the ideal of uniform distribution in both axes by adjusting the relative capacitances [7]. Computer programs are utilized for solving the complex calculations required to determine the number and dimensions of foils necessary to give acceptable stresses within the structure. The values are related to the puncture and creep strengths of the various solid insulations and the associated

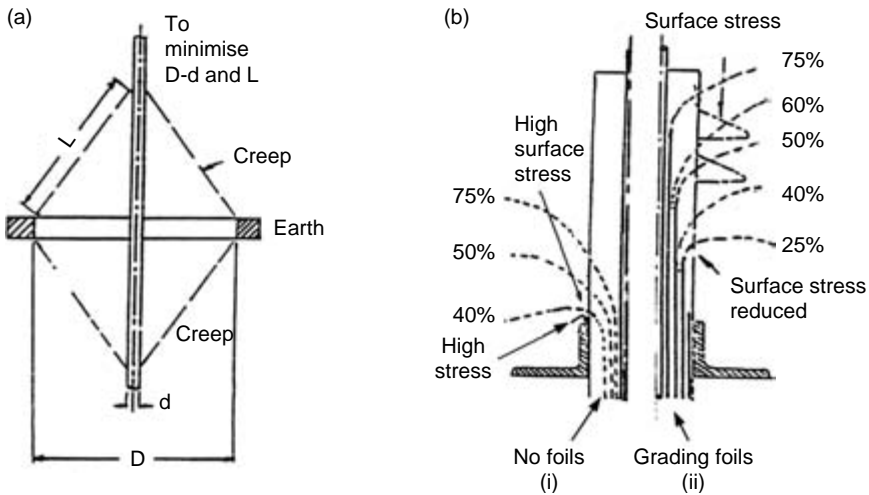


Figure 4.2 Basis of high voltage bushings. (a) Design requirements; (b) Equipotential distribution (i) No foils (ii) Grading foils

ambient medium of air, SF₆, or oil. According to the voltage class the number of foils varies from zero at 11 kV to two or three at 33/66 kV through to perhaps one hundred or more at the highest levels. Care must be taken that overstressing does not occur at the foil terminations. The outer foil of the majority of high-voltage bushings of 72 kV class and above may be 'floated' in order to provide a means of monitoring the insulation condition in the factory and in service. It is normally earthed. If not earthed, or connected through an appropriate impedance, the foil will rise to a high voltage and probably cause an insulation failure.

The types and forms of the insulating materials in bushings depend on the manufacturer's practice, the voltage class and, to some extent, the age of the product. Older units were insulated with SRBP and the solid structure immersed in oil within a porcelain shell. Such designs can operate successfully up to 300 kV but there have been problems regarding partial discharging within the resin paper wraps. Both loss angle and PD measurements are applied to assess the state of, for example, SRBP 66 kV and 132 kV bushings, many of which of the older units have internally eroded insulation, often produced over long periods of time. In some cases replacement programmes of up to 30-year-old units have been instituted based on such measurements [8]. Some of these bushings have been operating with PD levels of several hundred pC. High-voltage resin-vacuum-impregnated paper bushings have been produced for a number of years including units up to 500 kV. However, it appears that the oil-impregnated paper type is still preferred for many applications at the higher voltages.

Oil-impregnated paper bushings are built into, for example, power transformers, shunt and series reactors, switchgear and enclosures at substations up to the highest voltages. In these designs it is essential that the multi-foil paper structure be well dried and efficiently impregnated with dry oil under low vacuum when mounted in the porcelain housing (shell). More recently, composite shells – possibly with silicone sheds and protection – have been manufactured. Low partial-discharge levels must be achieved in all high-voltage bushings in order to prevent problems in service. Also low values are necessary in any bushing type installed in equipment in which PD levels of tens of pCs or less are required to be measured. A state of dryness must be maintained during operation, otherwise the dielectric losses may rise significantly, resulting in thermal deterioration of the insulation and possibly the initiation of high-level PDs (hundreds/thousands of pCs). Both changes can result in failure and internal explosion. Such events have resulted in intense fires and widespread damage within large power transformers. The application of composite shells reduces the damage and danger to personnel should an explosion occur.

An example of external flashovers of wall bushings due to salt pollution is described in Reference 9. The failure resulted in the outage of a complete power station. The bushings were replaced with another design and a leakage-current-monitoring system installed having an initial sensitivity level of 13 mA. Automatic washing equipment was also installed as a trial.

Typical equipotential distributions around the oil end of a conventional and a re-entrant high-voltage transformer bushing mounted in a turret are depicted in Figure 4.3 [10]. The manner in which the field is controlled by the capacitive grading (foils) and the stress distributor at the point of entry of the high-voltage lead is apparent for

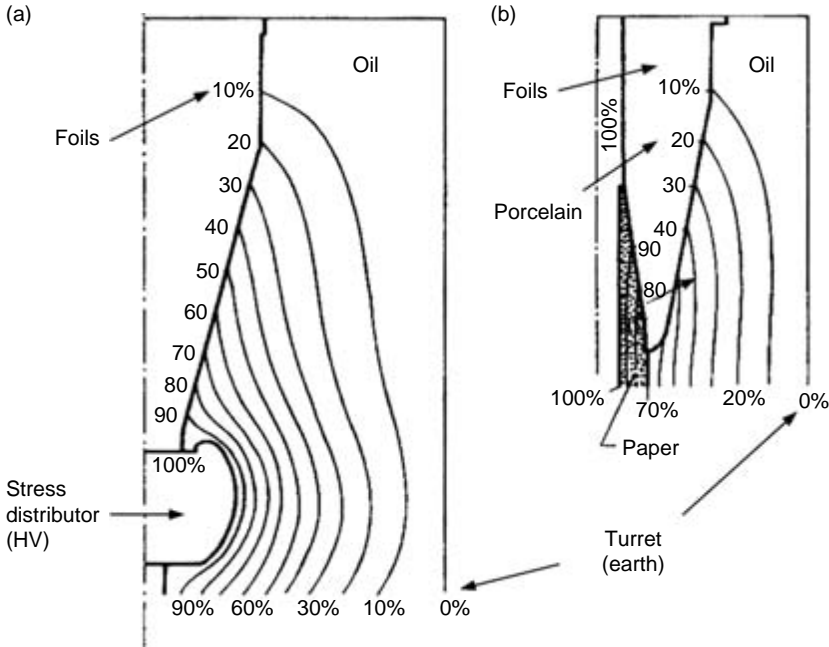


Figure 4.3 Typical equipotential field plots around the oil ends of high-voltage bushings within an earthed turret [10]. (a) Conventional type; (b) Re-entrant type [Reproduced by permission of CIGRE]

the conventional arrangement. The field is more uniform for the re-entrant design and requires less space within the turret but reduces the allowable movement when installing the bushing. During testing of this type it is essential to provide a 'tail' to ensure the field distribution is correct along the inner surface of the lower porcelain. In earlier types failures have occurred due to gas becoming trapped between the lead and the re-entrant section of the porcelain. Methods are now incorporated to prevent such a condition. Failures have been reported in conventional-type bushings due to defects in the foils and poor connection of the internal stress shield at the lower end terminal. The latter condition can produce PD disturbances of hundreds of picocoulombs in service.

In the case of bushings for direct-voltage applications, the field plots are significantly different from those in Figure 4.3 because of the effect of the high resistivity of the solid compared with that of the oil – see Chapter 3. The differences within a bushing are discussed in Reference 10. It is shown how the increased electrical stresses under DC conditions may be controlled by the judicious application of insulation barriers around the end of the lower porcelain and paper insulated shield as, for example, in converter transformer practice.

At the lower voltages extensive use is made of casting resins, especially for switchgear applications. In such units it is possible to improve the electric field

conditions at the outer diameter by modifying the contour of the earth electrode or including an earthed foil of appropriate shape, both within the body of the insulation. However the production of these bushings must be of high quality, as any voids or trapped air can result in partial discharging and subsequent failure in service. PD levels of below 200 pC are known to have caused failures in service. Values for new components are in the tens of pCs. Acceptance levels are specified in IEC Publication 60137 [S4/1]. User measurements are essential before commissioning critical equipment containing bushings of this type, particularly where unusual materials are incorporated in the structure.

With some of the older 11 kV bushings difficulties have arisen during the PD testing of high-voltage power transformers because of internal discharging within the LV conductor to porcelain radial oil, or even air, gap. Also, problems have been experienced due to corona around the unshielded earth clamping system (see Figure 4.2(b, i)).

It should be appreciated that some of the electrical faults associated with insulators can also occur with porcelain and resins/polymers utilized in bushings. In all cases this applies to any attached hardware – particularly rod gaps.

4.3 High-voltage instrument transformers

Insulation problems associated with instrument transformers have assumed considerable importance during the past ten to twenty years. This applies particularly to high-voltage current transformers (HVCT) of the ‘hairpin’ design. Much effort has been devoted to developing efficient and economic instrument-transformer site-monitoring systems. Although the cost of an individual transformer is relatively small, the failure of such a unit can result in a violent explosion with high consequential damage. This is in addition to the risk of injury to personnel due to fractured porcelain, sections of which can be projected many metres. Valuable information was collected through international surveys by CIGRE WG 23.07 (1970–85) and WG 12.16 (1985–95). In the latter the HVCT (>60 kV) sample size was approximately 89 200, including 24 000 combined CT/VT units. Of this total 95 per cent were oil-paper insulation systems, 3 per cent resin and the remainder SF₆. The overall major failure rate *per year* for oil–paper HVCTs was 0.035 per cent (60 kV to >380 kV) of that population, averaged over the ten-year period; the corresponding value for resin-insulated units (60 kV to 200 kV) was 0.175 per cent and 0 per cent for SF₆ designs up to and above 380 kV. Major *yearly* failure rates for magnetic voltage transformers (MVT) and capacitor voltage transformers (CVT) were of the order of 0.044 per cent and 0.026 per cent respectively. Although these major failure rates are low, each event represents a potentially catastrophic situation and, therefore, they are of considerable concern to the industry.

The problem is being addressed in many ways, in particular by design changes in new units, including the application of polymer composite housings in order to reduce the dangerous consequences of an explosive failure, the use of SF₆ insulation systems and, in the longer term, the limited application of fibre-optic-type units [11,14].

However, many thousands of existing oil–paper-insulated instrument transformers will continue to operate for many years to come [8]. It is important that users be aware of possible failure scenarios, especially for the oil-impregnated units, and of the site-monitoring methods now available or under development (see Chapter 9).

4.3.1 *Oil-impregnated current transformers*

The constructions of HVCTs vary considerably, as indicated in Figure 4.4. These may be designated (a) hairpin, (b) eye bolt and (c) bar primary. Earlier designs were reviewed in a report prepared for Study Committee SC 23 of CIGRE by WG 23.08.

In cases (a) and (b) the oil–paper insulation structures are equivalent to electrostatically graded bushings with the inner electrode at high voltage and the outer foil at ‘earth’, adjacent to the earthed core around which are located the secondary low-voltage windings. A 330 kV CT might incorporate 30 main foils and a 66 kV unit, only two or three, each with end rings. In some very high-voltage designs short intermediate foils may be used between the ends of the main foils in order to improve the end stresses without incorporating local stress rings. The structures are enclosed in a housing mounted on a metal tank, the whole being dried at temperatures of up to 120°C and vacuums of less than 0.02 torr and then filled with processed oil under vacuum. Because of the large diameters required, each leg of some hairpin designs is accommodated in its own housing. It is noted that in Japan a porcelain bushing housing (shell) of 1.5 metre diameter and 11.5 metres length has been developed for 1 000 kV AC operation but such sizes are very expensive.

The bar primary arrangement (c) is, in effect, an inverted bushing with the inner electrode tube containing the connections from the secondary windings, which are mounted on the earthed core, also insulated from the high-voltage primary bar at the line end. The major internal insulation from the high-voltage outer to the inner

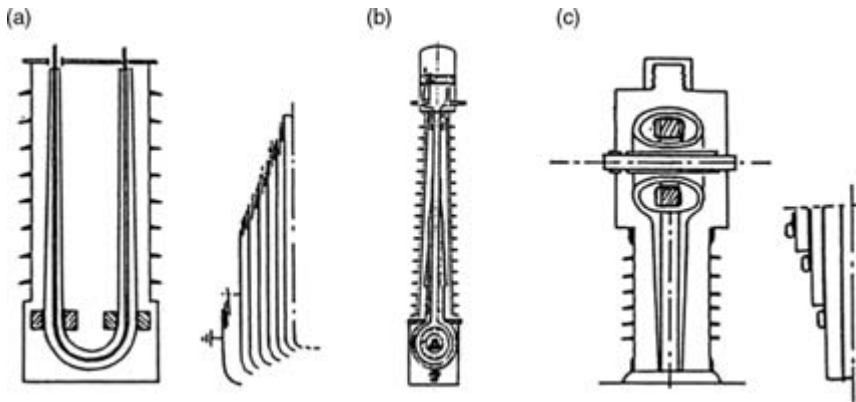


Figure 4.4 Examples of current transformer (HVCT) configurations. (a) Hairpin type; (b) Eye bolt type; (c) Bar primary type

grounded tube is provided by an axially and radially voltage-graded insulation system. A housing is provided for containment of the oil and for supporting the overall structure. The head of the type in (c) may be metal or of resin. Such units are available for operation in 765 kV systems. The capacitances of the various HVCTs are in the range of a few hundred to possibly a thousand picofarads.

Most of the major HVCT failures have been associated with paper/oil hairpin units. The breakdown modes are difficult to identify but probably involve one or more of the following:

- (a) Degradation of the paper system due to ingress of moisture through leaking seals. A fault could develop as the dielectric losses increase, resulting in thermal instability at the operating stresses of 3–4 kV/mm. This, together with surge effects, may explain failures after relatively short periods of 10 to 15 years.
- (b) Development of trapped gas in the body of the insulation during the process in (a) resulting in the inception of partial discharges, initially of low levels and increasing to values of thousands of pCs before failure by puncture. ‘X-wax’ and small black spots in non-failed regions are indicative of long-term thermal instability followed by partial discharging. Such effects may arise due to poor dry out and impregnation during manufacture.
- (c) Overstressing at a foil termination produced by deterioration or physical damage could result in PDs leading to puncture.
- (d) Inconsistencies in the taped paper structure allowing partial discharges to develop due to reduction in thickness and, also, the creation of oil gaps (see Figure 4.5).

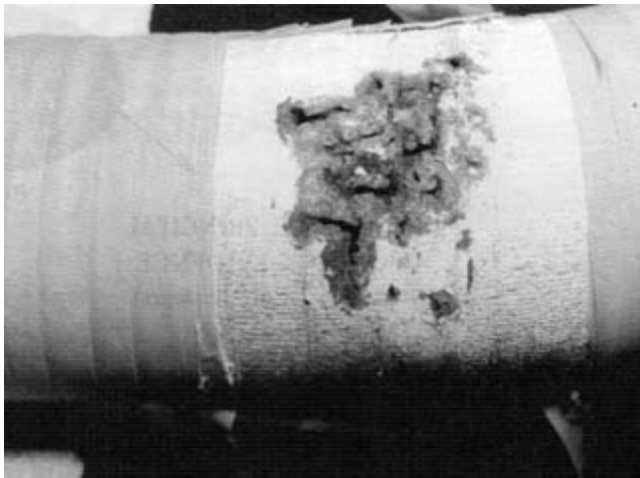


Figure 4.5 Failure of HV current transformer oil–paper taping due to dielectric overstressing and partial discharges [26] [reproduced by permission of CIGRE]

- (e) Long-term disintegration of the connection between the internal DDF terminal (normally earthed) and the first foil used for the measurement. This may produce gas, which results in axial flashover through the oil. The fault could be due to a cumulative effect produced by the surge currents and associated arcing created during switching of local air isolators. An optional special test is included in the revision of the instrument transformer standard [S4/2, Annex B] requiring the application of a minimum of 100 chopped waves.
- (f) Bad connections or floating metal at the DDF tap, which may result in a condition as in (a) (Figure 2.8(vii)).

Condition (d) may explain some failures after less than a year's service. The failure mode probably involves paper burning between several foils and the production of PDs – possibly increasing to ten nCs or more near failure. A common feature seems to be that the final scenario develops quickly – perhaps in days or even hours – making prediction of breakdown by means of the commonest monitoring technique of periodic oil sampling of DGA ineffective. Also, it has been found in some cases that a significant change in the DDF value would not necessarily arise if, for example, considerable burning between two foils was present [13]. In other instances low partial-discharge values have been recorded, even though tracking was established. Nevertheless, continuous monitoring of DDF and, where practical, PDs is highly desirable for critical installations. It is noted that in these types of failure a high internal pressure is built up due to arc gases being produced within the small volume of the CT housing. This can, and does, result in explosions, causing the shattering of the porcelain with dangerous consequences. Other anomalies are described in Reference 13.

Partial-discharge levels may range from hundreds to many thousands of pCs in a 'dielectric stress' type failure. DDF values possibly increase to hundreds of mRs in a 'thermal runaway' breakdown mode.

4.3.2 *Dry-type current transformers*

In the surveys quoted above it was reported that major failures of cast-resin CTs in the voltage range >60 kV to <200 kV were 0.175 per cent of their population. It is not known whether there is a dominant cause for these failures. However, with such components good quality control is essential in order to ensure that no voids are produced during processing. An example of such a problem was a 33 kV/ $\sqrt{3}$ bar primary unit that, on receipt from a reputable manufacturer, was found to have a PD level of 200 pC at operating voltage. Due to operational pressures the CT was installed and failed after one year's service. Pre-service and, perhaps, periodic PD measurements may be justified for this type of construction. Another example of a poor-quality product was an 11 kV CT designed for mounting on a bushing. In this case a low-quality plastic insulating tube and associated compounds were used, resulting in an unacceptably high DDF value. The excessive dielectric losses could have produced a service failure. Again, the unit was from an established manufacturer.

At the higher voltages, live tank dry-type units are now common, utilising SF₆ gas as the insulant between the primary bar and the earthed components located inside the head. The support structure may be of porcelain or polymeric material. An appropriate gas pressure must be maintained during the life of the CT and its level monitored in service.

4.3.3 Capacitor-type voltage transformers – CVT

There are two basic forms of voltage transformer for use at high voltage: the capacitor divider type (see Figure 4.6) and the magnetic type – MVT (see Chapter 5).

The cheaper, but possibly less accurate, capacitor-type (CVT) design is effectively a voltage divider with a tuned low-voltage arm. The voltage across this arm would be approximately 19 kV with a capacitance ratio of, for example, 3 800/38 000 pF for a 330 kV unit and, possibly, 12 kV (5 600/30 000 pF) for a 132 kV CT. The capacitors consist of many series elements subjected to a slight positive pressure with a steady-state voltage of, typically, 2 kV across each. The design of the elements and the operating stresses (20 kV/mm) are similar to those used in paper/oil power capacitors. Where paper is included, the insulation system is dried and vacuum impregnated with processed oil.

In the case of the capacitor units (Figure 4.6) major failures have been related to discharging at the end of foils of individual elements (Figure 3.3), thermal runaway and oil leakage exposing the upper elements. It is possible for two or three elements to be shorted and a major failure not to occur immediately. Some operators consider that physical inspection, e.g. for oil leakage, can be a very useful indicator of the internal state of an instrument transformer. Such a procedure is labour-intensive and may be hazardous in the case of suspect units. Because the loss of elements will vary the output voltage, the inspection of CVTs can be minimized by continuously monitoring any small changes in the output voltage.

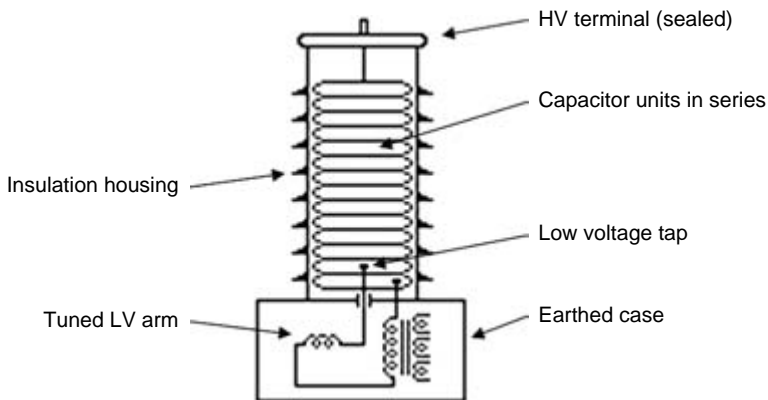


Figure 4.6 Capacitor voltage transformer (CVT) configuration

4.4 High-voltage power capacitors

The application of capacitors for power-factor correction at high voltages is becoming more extensive with the incorporation of static VAR compensators (SCV) into the supply systems. The usual design is to mount outdoors in the substation a large number of individual units in a series/parallel configuration at the LV side of a step-down coupling transformer. The capacitance values of the units range up to hundreds of microfarads and 10 to 20 kV, depending on the particular internal design and application.

There are various forms of power capacitor, the simplest of which comprises a series/parallel arrangement of elements mounted within a metal tank or case having dimensions of perhaps the order of $500 \times 200 \times 750$ mm high, but these values are very dependent on the particular application. In a particular design, each element consists of a compressed roll of continuous lengths of two metal foils – the capacitor electrodes – separated by thin sheets of paper, paper/plastic film or special film only, acting as the insulation. The whole is dried and filled with an insulating liquid – natural or synthetic – under high vacuum. A simple layout is indicated in Figure 4.7.

The foils of the various elements are interconnected within the tank before processing in order to give the required capacitance at the terminals, which are usually outdoor-type bushings. The older units were impregnated with low-viscosity mineral oil but, later, PCB liquid was also used (see Chapter 2) because of its high permittivity ($\epsilon_r = 5$) and, incidentally, its higher flashpoint. However, capacitors containing PCB are unacceptable for environmental reasons and they have now been replaced by units impregnated with one of the many other synthetic dielectric liquids developed over the past twenty years or more. The foil–foil operating voltages are of the order of 2 kV, giving stresses of 13–18 V/ μm for paper, 40 V/ μm for mixed dielectrics and

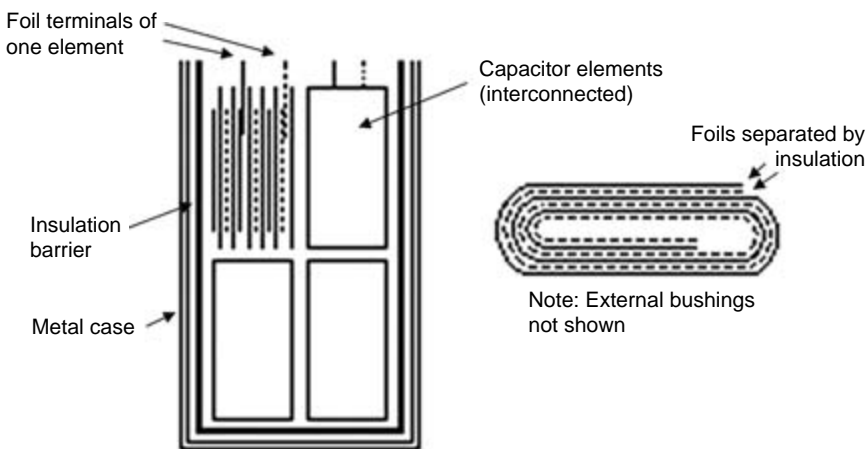


Figure 4.7 Possible configuration of foils and insulation in a power capacitor

$>50 \text{ V}/\mu\text{m}$ for all film. In the last case special materials are necessary to ensure efficient vacuum impregnation and to minimize swelling. Research is continuing in this area.

Because of the thin insulating materials used in the capacitors, great care is required to ensure no particles become trapped during manufacture and that the foil ends are located correctly with reliable connections. Also, at these high stresses it is essential that the processing eliminates the possibility of voids, otherwise PDs will cause failure. This applies particularly with the film materials, where 'dry' areas may be created. Ultrasonic monitoring devices have been applied as a quality check during production. Some problems in service have been associated with deterioration of the insulation between the capacitor elements and the tank side. Suspect units with the older paper/oil system were found to have PD levels of several thousand pCs after removal from the high-voltage structure. These were detected by direct observation of distortion of the tank due to gas build-up or offline checks of units from a suspect capacitor bank. Other difficulties have involved the bushings and internal fuse mountings. The detection of partial discharges in power capacitors tends to be insensitive because of the large capacitance values and, possibly, the resonant effects of the connections. Traditionally, capacitors are monitored by DDF measurements but this technique tends to be less useful, because the losses in the all-film units are very low. It is noted that the failure rates for the non-paper designs and the mixed insulation types are significantly lower than for the paper/oil systems. A number of standardized requirements are given in IEC Publication 60871, Parts 1 and 2 [S4/4].

4.5 High-voltage surge arresters

Surge arresters are used for limiting the magnitude of lightning and switching surge voltages on overhead lines and equipment operating in the range 6.6 kV up to 500 kV AC and above, and on DC transmission systems. Their application as part of system insulation coordination is defined in IEC 60071, Parts 2 and 5 [S4/5].

The major components are nonlinear silicon carbide discs with series gaps and metal oxide without series gaps [S4/6] and an appropriate housing of porcelain or, more recently, polymer. The layout for a low-voltage unit is shown in Figure 4.8. High-voltage arresters are included in Figure 5.11(a).

These devices are an essential part of the insulation coordination design of the power system and therefore must be reliable under steady-state as well as surge conditions. Failures have occurred that are suspected of being due to, for example,

- (a) ingress of moisture – good sealing is essential; this is a problem with the older gap type units;
- (b) localized losses and discharging caused by poor inter-disc contact;
- (c) deterioration of grading resistors in the gapped type, leading to sparking at operating voltage;
- (d) housing deterioration (or pollution) changing the voltage distribution along the stack;

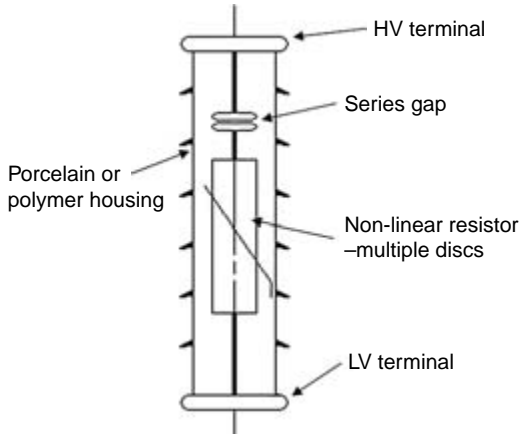


Figure 4.8 Layout of a single-stage gap-type surge arrester

- (e) mechanical fractures in the metal-oxide material (gapless type) due to thermal runaway after a high current surge; also damage due to surge current concentration at the edge of the electrode can result in failure [15];
- (f) resultant damage to the discs created by previous multiple-stroke lightning surges; this is a condition not covered by routine or type tests and may be very significant [16].

Metal-oxide arresters are inherently faster-acting than the gapped type, since there is no time delay due to series air gaps extinguishing the current. It seems that the metal-oxide units are proving more reliable than the previous designs.

In critical locations, e.g. adjacent to a major transmission or generator transformer, it may be justifiable to monitor arrester conditions continuously – see Chapter 9.

4.6 High-voltage circuit breakers

There are many types of circuit breaker installed in power supply systems. These range from 11 kV air break metal-clad or resin-insulated systems, bulk oil units from 11 kV up to 275 kV, low-oil-content live tank designs, air blast of dead and live tank configurations up to 400 kV and, in recent years, the widespread application of SF₆ units. Different designs of the last of these are applied over the whole voltage range. The majority of new breakers are of the SF₆ type and include live and dead tank types. Examples of SF₆ units produced by six manufacturers are presented in Chapter 8 of Reference 18. However, many of the existing units at the lower voltages are oil-filled and a number of air-blast types remain in service at 132 kV and possibly 275 kV, all of which will need regular periodic inspections until replaced.

For some applications 11 kV and 33 kV vacuum interrupters are installed. The switches are vacuum-sealed and should not require maintenance throughout the

specified life. These breakers can produce steep transients, as can SF₆ circuit breakers at the higher voltages. Protection of the circuits and connected plant can often be effected by correct use of metal-oxide arresters (MOA).

Insulation failures in circuit breakers would be expected to be associated with deterioration of the arc-suppressing medium or the insulation of components between high voltage and ground. According to the age and type of breaker, the components might include bushings, laminated wooden operating arms in older designs, SRBP and resin-impregnated glass-fibre operating rods, tubes of resin-impregnated glass fibre for compressed-air or SF₆ gas feeds in live tank configurations, outer shells and support insulators of porcelain or polymers.

Insulation breakdowns within SF₆ circuit breakers can be due to chemical by-products producing conductive areas on insulator surfaces, protrusions on conductors, conductive particles, faults in the solid dielectrics including voids, trapped moisture and poor adhesion of parts. Dielectric overheating produced by bad contact in the current circuit can also lead to breakdown. In practice, failure rates due to insulation deterioration are low compared with other factors associated with breaker operations.

Internal flashover due to tracking along laminated components in older bulk oil breakers can result in the production of gases and subsequent explosion and fire [17].

An interesting example of a failure to ground was due to a wooden operating rod within an oil-filled porcelain shell supporting the live-end tank of a 330 kV breaker. Due to moisture ingress and the incorrect location of the rod with respect to the shell, it was concluded that flashover had probably occurred from the high-voltage termination over the outer porcelain surface to an intermediate metal flange, across the reduced oil gap to the rod and then along the rod–oil interface to ground. In addition to visual examination the probable sequence of events was deduced from measurements of the insulation resistance (IR) values of the various paths involved.

Another case involving moisture ingress measurements on laminated components from oil-filled switchgear enabled a criterion based on IR values to be determined for the continued operation of similar equipment – thus acting as a simple condition assessment for the particular insulation system [18].

The application of unsatisfactory insulation as spacers between busbars in metal clad 11 kV switchgear created major problems in a number of substations. Following an inter-phase failure at one site, diagnostic techniques, including DDF and PD measurements with ultrasonic detectors, were applied. These procedures allowed surveillance of operating substations while others were being modified. Several years were required to update the many substations involved. The success of the project showed the value of having available a range of monitoring systems together with the necessary specialized engineers and test personnel.

The application of partial discharge testing in an open, conventional, high-voltage switchyard is often restricted by the presence of air corona from the bus-bar system. Obvious sources are rod gaps and faulty insulators. Site experience has shown that many designs of air isolators used for protection during maintenance procedures have sharp-edged guides for mechanically locating the horizontal arm as it closes onto the line. Corona from these guides can be easily identified using a handheld ultrasonic detector and may be of several thousand pCs magnitude. In many cases it would

appear possible to reduce the disturbances by modification of the configurations to allow measurements on adjacent equipment. Other corona sources noted included the corners of lugs provided for temporary earthing purposes on 132 kV busbars and, in one case, the lack of bonding between a 66 kV bar and the metal cap of the supporting insulator. This fault produced a disturbance of greater than 10,000 pC, preventing the completion of any useful PD measurements in the substation. Experience has shown that a 6 mm-diameter rod mounted on a 132 kV bushing (76 kV to ground) will produce a PD of 1 000–2 000 pC, depending on the weather conditions.

Routine periodic monitoring (DDF and IR) of circuit-breaker insulation would probably include the bushings and any associated busbars as appropriate. Under some conditions it may be possible to carry out online PD measurements utilising a high-voltage reference capacitor (see Chapter 9) or high-frequency probes (capacitive or current transformer – Chapter 8). By application of a separate source supply and a differential circuit measurement, sensitivities of 10 pC or less have been reported during site tests in high-voltage switchyards.

4.7 Gas-insulated systems (GIS)

In order to overcome the space limitations, and some environmental problems created by conventional open-type substations, gas-insulated systems have been developed in which the circuit breakers, other switchgear, disconnectors (isolators), instrument transformers, surge arresters and busbars are all enclosed in metal earthed chambers. Epoxy insulators are used for supporting the structure in the compressed SF₆ gas. The systems are designed to keep the gas dry and oxygen-free, thus minimising long-term insulation deterioration. Since no maintenance is required except for inspections after a specified number of switching operations, GIS are normally considered to be maintenance-free. Complete systems are available for voltages up to at least 765 kV. An earlier 132 kV design was installed in Sydney, Australia, in the 1970s for connecting the outputs of 330/132 kV transformers to the local distribution system. The conventional transformers were supplied from outside the city through 330 kV single-phase cables. Much information is available regarding the design and performance of GIS substations [18].

Special diagnostic measurement techniques for GIS have been developed over a long period of time but are not yet standardized (see Chapters 6 and 9). The majority of the methods are applied online and include the electrical detection of low-level PDs of less than 10 pC at very high frequencies and by ultrasonic systems. Low levels are also required at overvoltages during commissioning following assembly of the complex structures. Because of the relatively low capacitances, separate-source PD tests are practical. By-products detected during analysis of SF₆ gas samples may represent a fault as well as indicating the possibility of damage to the insulation and other materials in the chambers. The major causes of deterioration, or flashover, are associated with the presence of small metal particles, loose bolts, bad contacts, faults developing in the epoxy spacers due to decomposition of the gas, and perhaps voids that were undetectable during commissioning. Inappropriate electric field distributions

along spacers may occasionally produce surface-creep problems. Detailed computer programs have been developed by manufacturers to achieve optimum electric field conditions around the electrodes and along insulation surfaces.

4.8 High-voltage cables

Much information is available describing the many designs and insulation systems of high-voltage cables and accessories. Electrically, mechanically and thermally, the configurations are simple concentric cylinders, except for the older, lower-voltage, three-phase belted cables, where no outer screen was provided for each core. When practical, the three screened cores of a three-phase system are contained in a common cable but, at the higher ratings and voltages, it is necessary to manufacture and lay them separately.

The electric field in the body of the cable follows that given by Equation 3.3 for one dielectric and that at the end by the type of distribution in Figure 3.3(a), where very high stressing occurs at the edge of the outer sheath. In this region stress control is effected by use of one of the many terminating methods available, the components of which are critical in the design and assembly of a cable system.

The many types of high-voltage cable require highly specialized production and installation techniques. At the present time, in respect of insulation, there are three major classes of cable in service.

4.8.1 Oil-paper cables

Oil-paper cables may be classified according to the following:

- (a) Older oil-paper 'solid' systems filled with oil/rosin – operating up to 33 kV and possibly 66 kV;
- (b) Oil-paper systems impregnated with low-viscosity oil at high vacuums and sealed in service under positive pressure – installed up to the highest voltages and ratings (hollow conductors are utilized for cooling in single-phase cables and channels or a pipe-type enclosure in three-phase designs);
- (c) Oil-paper system but filled with dry nitrogen under pressure;
- (d) Oil-polypropylene-paper (PPLP) systems for very high-voltage applications – this is a relatively new technology [19].

4.8.1.1 Faults in the bodies of oil-paper cables

- (a) Sheath damage – accidental or due to chemical erosion – allowing the ingress of moisture, and in pressure cables the loss of oil, with subsequent degradation of the dielectric. Erosion problems would appear likely in distribution cables some of which are more than 40 years old.
- (b) Thermal runaway caused by overloading beyond the specified design limits or the lack of adequate heat dissipation around the cable. The latter is a major factor in the installation of underground cables. The failures in Auckland in

1998 [20] were believed to be due to a combination of these factors – unavoidable overloading in order to maintain supply and insufficient thermal dissipation. Temperature monitoring systems are now available for installation at important locations (see Chapter 8).

(c) Partial discharges leading to tracking and waxing as described in Section 2.1.3.

4.8.1.2 Faults in the oil–paper cable accessories

Faults in the cable accessories are more likely than in the main cable due to the required manual addition of insulation on site and because of the complex insulation structures in such regions.

Sealing ends (terminations): At the medium and higher voltages the sheath edge stress and longitudinal fields in oil–paper sealing ends are controlled by stress relieving cones as indicated in Figure 4.9. Such cones may be formed by paper taping on site or be preformed within a synthetic resin moulding fed over the end of the conductor. Incorrect stress distribution, moisture ingress, void formation possibly due to oil leakage, or overheating due to combination of load and excessive ambient temperatures – as produced by direct sunlight – might each create an insulation problem. In one case a bad contact problem at the top of a 132 kV sealing end was associated with the cap. The intermittent partial discharges were of sufficient magnitude to mask PD measurements being made on the cable termination. The fault was detected and located by use of a handheld remote ultrasonic detector.

Special care in the stress distribution design is necessary, especially if different insulating materials are utilized. In the non-pressurized systems the oil may drain downwards over a long period of time producing oil-dry regions that could discharge with resultant puncture of the paper or flashover along the surface. Such faults can occur in the cable boxes or similar of 11/22 kV equipment, many of which were

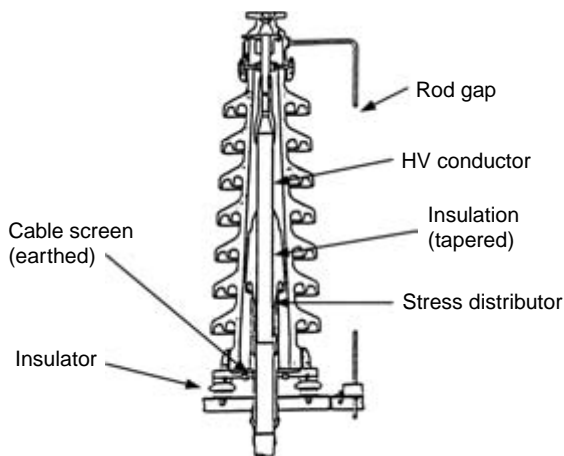


Figure 4.9 Principle of medium voltage oil–paper sealing end

filled with bitumastic material or oil. The latter system has now been replaced in many cases by the application of plastic heat-shrink coverings which may include some electric stress relief without the need for a bulk insulation filler. These newer techniques require care in order to avoid the trapping of air at the interface.

PDs in such regions may be detectable by the use of localized ultrasonic detection techniques (see Chapter 9). Except for the larger discharges this is not possible through a metal sheath.

Joints: The formation of joints in oil–paper cables is a skilled and lengthy procedure. In principle the process consists of scarfing or stepping of paper wraps on the sections to be joined and, after connection of the conductors, filling the interspace with layers of pre-dried, oil-impregnated paper tapes and wraps. For the higher-voltage cables, allowance is made for accommodation of a high-voltage stress distributor contained in synthetic resin and connected to the conductor. The paper is built up to support a stress-relieving cone at the sheath edge. This work is carried out with the system exposed to air, thereby introducing the possibility of void creation and moisture ingress. Special precautions and speed of application are essential – for example, under temporary cover and using dry air during a period of perhaps 12 hours is required for a large high-voltage joint.

The configuration for an older design of high-voltage joint with an internal oil duct is shown in principle in Figure 4.10. A later system with cone-shaped ducts for oil input failed in service due to partial discharges probably caused by the accumulation of small metal particles – from the conductor wires – which then generated gas. Failure occurred in the thin oil duct between the resin casting containing the stress distributor and the paper tape [21]. Other designs are based on similar principles [19].

The principle of a transition joint design between a ‘fed’ oil- (or gas-) filled paper cable and an extruded polymeric cable is described in Section 1.2.4 of Reference 24. At the lower voltages such a joint may have an oil–paper cable with PD magnitude levels of 200–300 pC operating satisfactorily, but the values in the extruded cable would be expected to be much less – perhaps in the tens of pCs. This measurement problem, and also how it relates to location errors, is highlighted in CIGRE Brochure 297 [22].

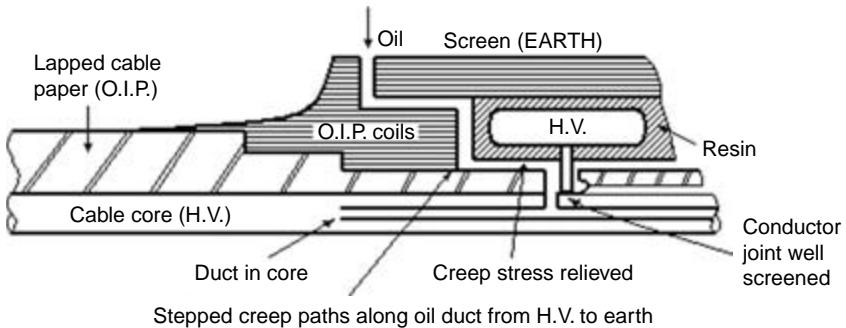


Figure 4.10 Principle of an earlier high-voltage joint with oil feed

Where a solid insulating material of different conductivity to the paper is used in such joints – and in other high-voltage components – the design must allow for the changed field distribution if direct-voltage tests are to be applied in the factory and during commissioning of the AC cable. Previous damage was suspected due to such a test following the failure of a 132 kV cable joint in service some years ago.

4.8.2 *Extruded cables*

During the past fifty years or more, extensive research into the development of plastic materials has resulted in their successful application as insulation for cables – initially for low-voltage wiring (e.g. PVC coverings) through to modern systems of XLPE, some of which are operating at 500 kV (AC). Test requirements for the various voltage levels are given in the Standards [S4/7–S4/9]. The widest application of extruded cables has been for medium to high voltages in the distribution field: ranging from 11 kV through to 33 kV/66 kV and a few systems at 132 kV and 500 kV. The production techniques have varied but the commonest, based on much experience, is the triple-extrusion method. The construction of a typical single core 22 kV cable is depicted in Figure 4.11.

During the process an inner semiconductive layer, the major insulation and an outer semiconductive layer are extruded simultaneously, thus producing, ideally, a good concentric field. In earlier methods the outer layer was added separately, which sometimes created voids at the interface and subsequent failure due to partial discharges. XLPE in particular is very susceptible to low-level PDs. The usual insulation is XLPE, although EPR is favoured by some manufacturers for specific applications.

Apart from avoiding the formation of voids during the manufacturing process, a major problem with XLPE has been the tendency for water trees to develop in the material. The effect has been minimized by replacing the earlier pressurized steam cross-linking techniques with, for example, the siloxane process or the continuous-gas-vulcanization dry-curing method in pressurized nitrogen and, when considered necessary in service, the use of a water barrier on the outside of the cable. It is noted that EPR and tree-retardant cross-linked polyethylene (TRXLPE) appear to be the preferred materials for medium-voltage (15–35 kV) cables in the USA [23]. The application does not require the use of water barriers. However, for 69 kV and above, barriers are often specified.

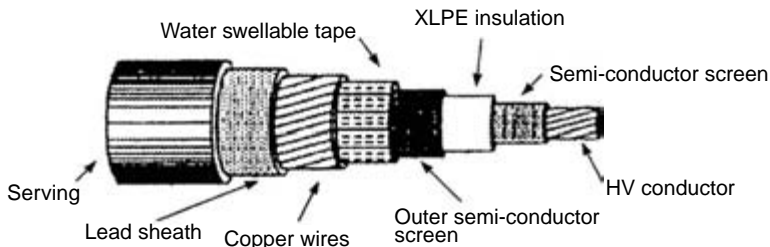


Figure 4.11 *Construction of a typical XLPE 22 kV (RMS) single core cable*

XLPE and EPR cables are now very competitive with oil–paper types at the medium-voltage range for a number of reasons including the possibility of operating at somewhat higher temperatures. At the higher voltages the application of plastic cable designs is increasing.

Although the manufacturing and acceptance tests for plastic cables are very stringent, a number of potential faults are possible in service. These include the following in the bulk of the cable.

- (a) The development of carbonized trees in the main insulation due to voids or particles introduced by incorrect manufacturing. The initial faults may not have been detectable during the factory PD measurements.
- (b) Localized separation between the main insulation and semiconductor outer layers resulting in PDs, possibly formed after manufacture due to lack of bonding and accentuated by bending of the cable.
- (c) The creation of water trees in XLPE formed during manufacture – but now less likely – and in service following ingress of moisture. Failures in the older cables were relatively frequent due to this cause [23]. The ‘trees’ cannot be detected easily in the final product and become apparent only when almost bridging the dielectric. Advanced detection techniques are being developed including dielectric response measurements (see Chapter 6).

4.8.2.1 Terminations and joints for extruded cables

Many forms of terminations and joints have been developed for extruded polymeric cables. Some of these are described in principle in the report by WG 21.06 of CIGRE [24]. This includes outlines of techniques for transition joints for connecting oil-filled and polymeric cables.

One of the special problems associated with polymeric terminations and joints is the possible creation of faults at the interface between the cable insulation and the electrical stress-relieving material or semiconductor cone connected to the earth screen. The objective is to improve the longitudinal (axial) stress along the interface and the cable insulation. The examples in Figure 4.12 indicate how this may be effected by application of (a) a heat-shrink stress control sleeve, or (b) a semiconducting stress cone, or (c) a semiconducting cone with a conical thermoset casting and compression springs. At the higher voltages the longitudinal stress can be improved by winding layers of conducting film interleaved with polymeric film around the cable insulation to form a capacitor-type bushing construction [24].

The necessity for very good physical contact between interface surfaces is analysed in CIGRE Brochure 210 [25]. Among the findings, it is concluded that (i) the surfaces must be sufficiently smooth to reduce void sizes to a micrometre or so and (ii) sufficient pressure be applied by – for example – heat shrinking (Figure 4.12a), the elasticity of the rubber material or spring pressure forcing a rubber insert against an epoxy conical casting (Figure 4.12c). The mechanical and thermal characteristics must be such that no significant gaps or voids are formed when installing on site or due to movement in service. Although the maximum electrical stress will be radial, it is the longitudinal component that may cause failure. This is especially the case if

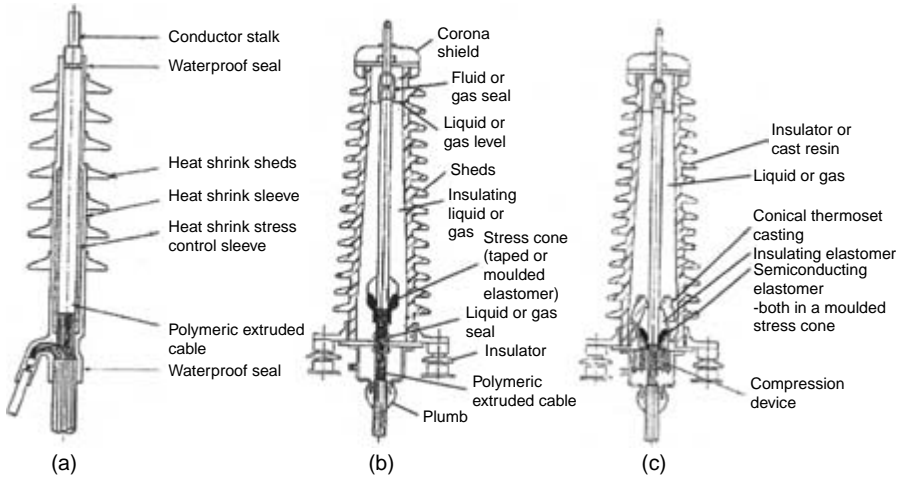


Figure 4.12 Possible outdoor terminations for polymeric extruded cables [24] [reproduced by permission of CIGRE]

voids have been formed and the radial stress value is sufficiently high to induce partial discharges. If the magnitude of the latter is of the order of only a few picocoulombs this might lead to failure within a few hours in some joint structures [25]. Outdoor terminations may have lower stresses and similar (or higher) PD values but failure would be expected to occur in the longer term. In order to minimize possible problems, emphasis is given to careful preparation of the surfaces, the precise following of the accessory manufacturer's instructions and the employment of skilled joiners.

In older designs a failure due to arcing can occur if the semiconductor elastomer of a cone is incorrectly assembled over the earthed screen and is not making contact. Such a condition has resulted in the semiconductor rising in potential above earth with subsequent discharge to the screen and failure.

The principles discussed above for terminations are applicable to the numerous forms of joints [24, 25]. In many respects the installation and the long-term condition of the joints are more critical because of their complexity and difficult access. A particular design of joint is shown in Figure 4.13 [24]. In Reference 26 the separation or relaxation of the stress-control materials in service was found to be a significant cause of failure.

Much attention is being given to the development of techniques for the condition monitoring of extruded cables and, in particular, their accessories (Chapter 9).

4.8.2.2 Gas-insulated transmission lines (GIL)

Gas-insulated transmission lines have been developed over many years for installation in locations where access, for example, to a city centre by a high-voltage supply is required. The lines comprise a rigid metal outer tube with an inner conductor mounted on specially designed epoxy resin insulators. The lines can be buried, above ground

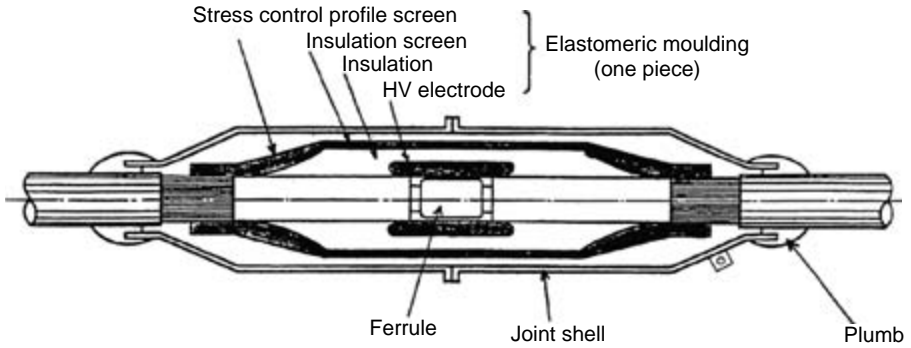


Figure 4.13 Example of dry-type pre-moulded joint [24] [reproduced by permission of CIGRE]

or mounted in existing/new tunnels. An overview is presented in *Electra* [27], in which systems of up to 550 kV and 3 km in length are described. The gas mixture used is quoted as 80 per cent N₂, SF₆ 20 per cent at a pressure of 7 bar, thus reducing the quantity of SF₆ required.

In an earlier 275 kV system of 3.3 km length the diameter of the outer aluminium tube is 420 mm and that of the high-voltage conductor tube 170 mm with an SF₆ gas pressure of 0.44 MPa. These systems would be expected to require minimal maintenance. The commissioning checks include partial-discharge measurements, probably utilizing UHF technology [27] (Chapter 9).

4.9 Summary

The chapter reviews how the various insulating materials are applied in a range of power-system equipment excluding rotating machines and transformers. Although the number of examples of possible failures is limited, those chosen indicate where problems might arise. Knowledge and understanding of the behaviour of new and aged insulation structures is essential when considering the need or otherwise for a particular condition-monitoring system. The values of the partial discharges expected for the different operating conditions give an indication of the sensitivity required for the condition monitoring systems.

4.10 References

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4.11 Standards related to Chapter 4

- S4/1 IEC 60137 (1995): Bushings for alternating voltages above 1000 (AS 1265)
- S4/2 IEC 60044-1 (2003): Instrument transformers – Part 1: Current transformers, Annex B (Informative)
- S4/3 IEC 60044 (2004): Instrument transformers – Part 5: Capacitive voltage transformers (AS 60044.5, 2004)
- S4/4 IEC 60871-1 (2005): Shunt capacitors for AC power systems having a rated voltage above 1000V (AS 2897)
- S4/5 IEC 60071-2 & 5: Insulation co-ordination (AS 1824)
- S4/6 IEC 60099-1: Surge arresters Part 1: Non-linear resistor type gapped surge arresters for AC systems (1999). Part 4: Metal-oxide surge arresters without gaps for AC systems (2004)
- S4/7 IEC 60502-2 (2005): Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1.2$ kV) up to 30 kV ($U_m = 36$ kV). Part 2: Cables for rated voltages from 6 kV ($U_m = 7.2$ kV) up to 30 kV ($U_m = 36$ kV). See also AS/NZS 1429.1:2000

S4/8 IEC 60840 (2004): Power cables with extruded insulation and their accessories for rated voltages above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) – Test methods and requirements (AS1429.2:1998)

S4/9 IEC 62067 (2001): Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test methods and requirements

4.12 Problems

1. Capacitive grading is to be included in an oil impregnated bushing ($\epsilon_r = 3.5$). The details are as follows:

Length of foil adjacent to HV conductor = 400 mm (l_1).

The radial spacings between conductor/foils/earthed flange are 6 mm.

The conductor radius (r_o) = 20 mm. The earthed flange inner radius (r_4) = 44 mm.

The maximum radial stresses in the OIP of each layer are to be equal.

Determine

- (i) the foil lengths (l_1, \dots, l_4)
- (ii) the capacitance values between foils (C_1, \dots, C_4) and that between HV and earth (C)
- (iii) the maximum radial stresses
- (iv) the maximum radial stress without foils

The test voltage is 60 kV (RMS)

Assume $Q = CV = C_1(V_0 - V_1) = C_2(V_1 - V_2) = \dots = C_4(V_3 - V_4)$.

2. What are the limitations when measuring the partial-discharge characteristics of an AC extruded power cable on site (a) using a separate-source high-voltage supply and (b) under operating conditions? Assume a termination and a joint are in the section under test. Refer to Chapters 6, 7 and 9.
3. An extruded cable is terminated with a semiconducting stress cone. By assuming a radial operating stress at the cone and cable insulation of 2 kV/mm (RMS) calculate the thickness of a void/air gap within the interface that might discharge under this condition. Also, determine the maximum gap thickness allowable to avoid partial discharges during a test voltage application of $1.5U_o$. Refer to Chapter 3 (Section 3.2.1) and Chapter 2 (Figure 2.2). Assume the insulation thickness \gg the air gap and that parallel field conditions are applicable $\epsilon_r = 2.2$.

Chapter 5

Insulation defects in power-system equipment: Part 2

- Low- and high-voltage motors
- Large generators
- Power, distribution and magnetic voltage transformers

This chapter considers the construction of rotating machines and transformers in sufficient detail to identify a number of possible failure modes. Several examples are included.

5.1 Electrical rotating machines

In the supply systems, a wide range of rotating machines is utilized in addition to the power generators. This is especially the case in the power stations where motors from ratings of less than a kW at 415 V through to those for blower and pump drives of up to the order of 10 MW or more at 11 kV might be installed.

5.1.1 Low-voltage motors

With the wider application of power electronics for adjustable speed drives, there seems to be a need for more careful design of the insulation systems even for the lower-voltage motors. The presence of partial discharges has been detected in random wound stators operating at 440 V supplied from PWM converter circuits [1]. In this area specialized tests are required to prove the turn-to-turn strength. A differential $0.2 \mu\text{s}$ rise-time surge test [2] as defined for formed wound machines may be applied for assessing the inter-turn wire covering. However, this does not necessarily prove the integrity of a winding subjected to less steep pulses but of much higher repetition rate. The complexity of the conditions as imposed on the insulation are considered in Reference 3. Following failures of motors supplied by PWM control systems, investigations were made of the effects of voltage/frequency variations,

pulse rise times, pulse width/duty cycles and overshoot/resonance voltages on the electrical insulation. It is possible for partial discharges to develop during the pulses under adverse conditions. The incorporation of sine-wave output filters may result in improvements but their size and cost can be prohibitive [4]. The work of IEC TC2 WG27 in preparing the new IEC Specification IEC 60034-18-41 [5] is presented by Wheeler in Reference 4.

5.1.2 High-voltage machines

In principle, the electrical insulation systems of the stator windings of the majority of high-voltage machines may be considered to be similar [6]. Insulated conductors, usually of rectangular section, are assembled in the slots of the laminated cylindrical core – a process described as *winding*. As depicted in Figure 5.1(a), the connections between the active parts (straight sections) of the insulated conductors are made in the ‘overhang’ region, enabling the formation of series/parallel configurations with the appropriate coil pitch (spread) to produce the desired three-phase output voltage. The overhang is supported by various insulation structures, possibly involving large-diameter insulation rings, cords (strings) and additional insulation taping.

5.1.2.1 Motors

For motors in the range of 3 kV to 11 kV and up to tens of MWs ratings, it is possible to preform and insulate the two-sided diamond-shaped coils containing multiple rectangular turns with the appropriate pitch and overhang contour suitable for assembly

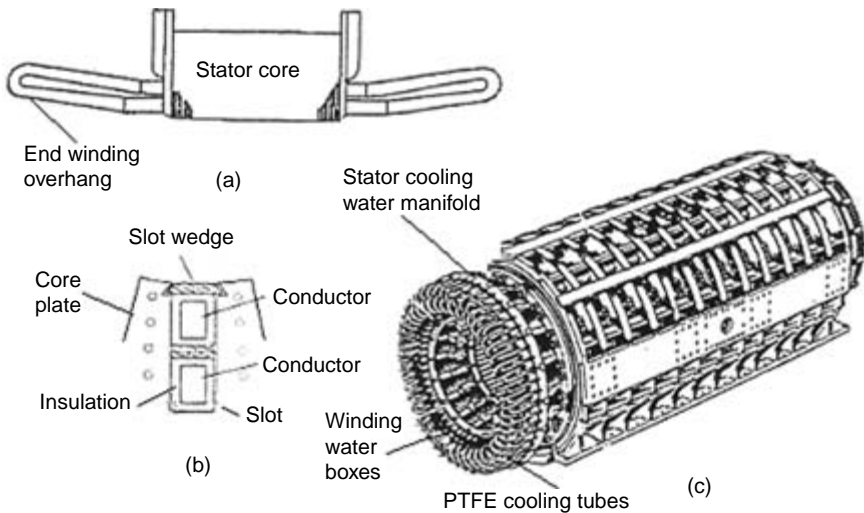


Figure 5.1 Layout of coils/bars and insulation in AC stator winding. (a) Core and end windings (overhang); (b) Turns/bars in slot; (c) Large water-cooled turbine generator stator

(winding) in the core slots. As an example, the conductor dimensions for a three-phase, 11 kV, 3 MW motor might be of the order of 5×3 mm cross-section, 4 in parallel with 5 turns/coil and 30 coils per phase having an axial core length of about 1 metre with overhangs of less than 0.5 metre. The core inner diameter might be of the order of 0.75 metre.

5.1.2.2 Generators

The large low-speed (a few hundred rpm), air-cooled, salient-pole, vertical-shaft hydro-generators may have ratings up to 500 MVA at 15 kV and the steam-turbine generators up to 1 600 MVA at, possibly, 27 kV and 1 800 rpm (60 Hz). The latter types form the major power sources for the supply systems of the utilities and more usually have outputs of 500–660 MVA operating at 3 000 rpm (50 Hz) and 22 kV. Each stator bar (two per slot) is manufactured separately with the correct overhang configuration and, after assembly in the core, is connected to its associated turn – probably by means of a flexible link. With internally cooled generators the distilled water is supplied through plastic tubes – typically of PTFE – feeding ‘water boxes’ at the ends of the bars (Figures 5.1(b) and (c)).

The conductor of an older 500 MVA, 22 kV steam turbine-generator might have an overall cross-section of 66×26 mm comprising many strands in parallel each insulated from the others to reduce eddy current losses and hollow for water cooling. The bar lengths might be of the order of 6.5 metre within the core and 0.8 metre for each overhang. Two parallel paths per phase are required with 16 bars in series in each, depending on the number of slots. Full line voltage appears between the line end bars (conductors) which may be physically adjacent in the overhang. Phase voltage to ground is present from the line end bars to the core within the slots. The whole system – core, rotor and windings – operates in dry hydrogen at a pressure of about 6 bar, the gas acting as a coolant and insulant. See Figure 2.2 for the breakdown characteristics of hydrogen.

5.1.2.3 Machine insulation systems

In the older machines, many of which are still in service, the turn insulation consisted of ‘thermoplastic’ systems. Following many years of research and development, mica paper (incorporating small mica splittings), synthetic thermosetting resins and higher-temperature backing tapes were introduced in the 1960s and continue to be the configurations now used but with improved techniques and material formulations. The three basic methods are briefly outlined in the following.

(a) Shellac/bitumen binding varnishes

Earlier systems comprised mica splittings, cellulosic paper and binders of shellac/bitumen varnish. After wrapping of the insulated conductors and forming of the coil contour – two-sided for smaller machines and half-coil/bars for large generators – the wall insulation was added, the straight sections compressed to the correct thickness for fitting in the core slots, the overhang taping added and the whole consolidated at an appropriate temperature. If not continuously hand-taped, a scarfed

joint was included between the straight section projecting beyond the slots and the evolute sections.

(b) Resin-rich systems

The conductors in multi-turn coils are insulated with enamel and glass or a mica-based tape. After formation into the correct shape and overall dimensions, ground wall insulation consisting of film- or glass-backed epoxy-resin-bonded micaceous tape is applied. The tapes are supplied with the resin partially cured to a 'B'-stage condition and contain sufficient excess resin to effect adequate consolidation during the subsequent heat and pressure treatment necessary to produce a void-free insulation configuration. Hand or machine wrapping may be used depending on the manufacturer and equipment size.

The end-winding insulation may consist of the same type of tape, therefore necessitating special heat treatment or, alternatively, a fully cured tape that will enable manipulation of the coils during winding without damage. If a scarf joint is included, additional resin may be required along the length of the joint with subsequent localized curing.

(c) Vacuum-pressure-impregnation (VPI) process

In this process the coils and bars are initially insulated with 'dry' micaceous tapes containing a minimum amount of resin. The structure – coil or bar – is fitted into a mould within a tank, subjected to a high vacuum to extract air and moisture and then flooded (impregnated) with low-viscosity resin under a positive air pressure. This procedure (VPI) should result in a void-free insulation system, which is subsequently cured to thermoset the resin. The inclusion of some flexible tapes in the evolute sections makes it possible to wind the coils or bars into the stator slots and form the correct overhang configuration. The latter is maintained by use of cords and tapes and, for the large generators (single bars), the inclusion of a supporting structure of treated wood or fibreglass.

In the case of medium-sized, high-voltage machines, this whole process can be carried out with the coils already wound into the stator and the overhang completed. Plants are now available to accommodate machines up to ratings of 200 MVA [7].

As required, insulation systems operating with Class 130 °C and Class 155 °C have been developed. More details of winding insulation and its historical development are given in Reference 7.

5.1.3 Possible insulation failure mechanisms in rotating machines

Insulation failures in high-voltage machines are predominantly associated with combinations of thermal and electrical stresses for the medium sizes and mechanical and electrical stresses for the larger units. Temperatures range from 105 °C for the older machines up to Class 155 for the newer insulations and average electrical operating stresses are in the range 1–4 kV/mm, depending on age and types of material. It is possible to identify, in general terms, the regions where insulation problems might arise, depending on the size, insulation system and age of the machine.

5.1.3.1 Main wall insulation

A simplified arrangement of the main wall insulation is shown in Figure 5.2. Voids (A) may be formed in the insulation due to delamination in the thermoplastic systems – or inefficient resin impregnation in both the resin-rich and possibly VPI processes.

The air-gap thickness between the coil insulation and the stator core may be of the order of 1 mm, allowing for assembly clearances. In such gaps partial discharges would be produced for unscreened conductor insulation as may be calculated using the parallel field relationships and Paschen's Law (Chapter 3). To prevent such PDs the wall insulation is covered with a continuous semiconducting layer of resistance of perhaps 1 k Ω /square. This surface may be described as a corona screen and if earthed at one location (the stator) should limit the voltage drop along the length to a few volts. If a screen-free area of only a few mm diameter (D) caused by mechanical vibration is formed, then discharges might occur to the core across the gas or air gap and, more significantly, along the bare insulation area (D) [8]. These surface discharges at the edge of the screen may be of high intensity. The situation is particularly dangerous for an isolated section of screen as indicated at E in Figure 5.2. An additional problem may develop if the eroded areas occur near the corner of a core cooling duct (C). Failures have occurred in such regions and much insulation and core damage found thought to be due to very large discharges or low-level arcing. Some of these effects are reported and analysed by Wilson [8] based on ten years of measurements and investigations at the National Grid R&D Centre, Leatherhead, UK. It is noted [Reference 2 of 8] that with hydrogen-cooled generators the phenomena may not be present because of the higher gas pressures, although problems might still occur.

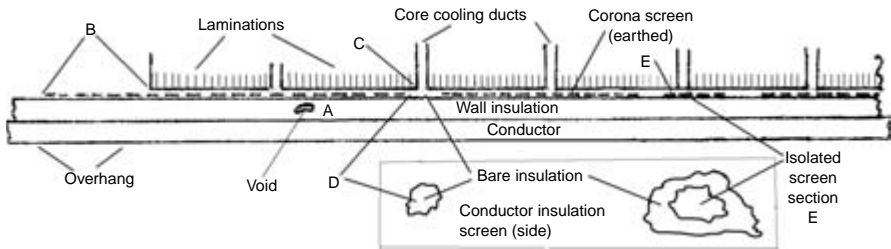


Figure 5.2 Sites of possible partial discharges related to the wall insulation of a stator winding

5.1.3.2 Inter-turn insulation

In the larger form-wound (pre-formed coils) motors the insulation systems may be subjected to steep surges produced in unprotected input circuits including, for example, high-voltage vacuum circuit breakers. This is a well-known problem but can still arise due to poorly designed motor supply circuits, including, for example, significant lengths of cable. With multiple turns, as shown in Figure 5.3, a surge at the high-voltage terminal can cause breakdown over a group of turns (Figure 5.3(a)) or

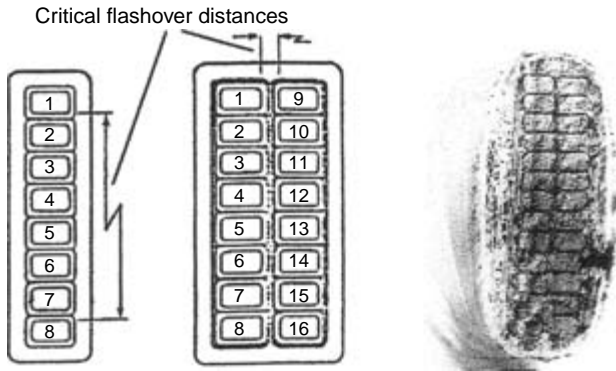


Figure 5.3 Multi-turn motor winding. (a) Single section; (b) Double section; (c) Taping in end-winding of failed 11 kV motor

between sections if wound, as in Figure 5.3(b), due to the non-uniform voltage distribution across the line-end turns. The photograph in Figure 5.3(c) shows part of the overhang section of a VPI coil the impregnation of which was insufficient. A failure occurred in a similar manner to that in Figure 5.3(a), due to switching of a vacuum circuit breaker at the end of a cable. Protective devices were added after this incident.

In large machines the interaction of the distributed capacitance and inductance is important when considering the analysis of partial-discharge measurements. The results relate to such parameters as the non-uniform pulse distribution, the winding pulse transit time and the coupling between phases. These factors also influence the designs of the test systems for monitoring the partial discharges.

5.1.3.3 End-winding insulation

The insulation of the winding overhang can be complex. This is associated with the necessary arrangement and shape of the conductors together with the asymmetrical electromagnetic forces set up by the stator winding currents. In the case of motors many starts per day are often required. Continuous vibration can lead to the spacer blocks becoming loose, resulting in fretting of the conductor insulation. Dust due to this process is evidence of insulation deterioration. Although the electrical stresses to ground are much lower than in the slots, there are locations in many designs where line-to-line conductors are adjacent and insulation-creep surface strengths must be maintained – particularly under poor environmental conditions (e.g. moisture and dust). Failures in these regions have been reported. The presence of creep surfaces can represent a design problem for large hydrogen-cooled generators, which are tested in the factory and at site in air at the $2U_N$ level. It must be accepted that the newer resin-impregnated materials (e.g. glass-fibre systems), as well as the natural types such as impregnated laminated wood, will absorb a limited amount of moisture, which could result in a degradation of electrical properties.

A one-minute test in air on a hydrogen-cooled generator at approximately $2U_N$ (AC) resulted in discharges, initiated at the semiconductor edges, flashing across the end insulation surfaces. This was probably due to localized charged areas on the high-resistivity insulating materials used. These effects are not present in hydrogen at the operating pressure of 6 bar, as the gas breakdown stresses are much higher for this condition.

To minimize surface PDs at the exit point of the coils/bars (Figure 5.2 B), a semiconducting surface is added on machines of about 6 kV and above. If deteriorated or incorrectly applied this can result in high-energy partial discharges including air-corona at operating voltages. This was observed for an 11 kV pump motor where excessive corona was located around the end windings using a handheld ultrasonic detector. The levels were too high to carry out significant PD tests. Such a state may have been causing environmental problems within and external to the unit.

Also in these exit regions it may be necessary to incorporate a scarf joint (Figure 5.2 B) for integrating the slot wall insulation and the overhang external tapes. In another type of 11 kV motor semi-cured tapes had been applied in the formation of the joint in order to assist in winding. During assembly it was suspected that undue force was applied, resulting in a lack of bonding during the final cure. A failure occurred at such a location in service. Subsequent testing of the other phases indicated partial discharge levels of several thousand picocoulombs at below operating voltage. Subsequently, failure occurred at the corresponding joint on increasing the test voltage. The mica paper was found to be poorly bonded.

5.1.4 CIGRE summary of expected machine insulation degradation

It is of value to note the summary included in CIGRE General Reports for 1998 [9].

The common opinion is that modern epoxy-mica based insulation systems will not fail for electrical reasons. What will affect the insulation is mechanical malfunction that may in time lead to electrical failure. Such failures include:

- Excessive coil end vibrations
- Loosening of the bars in the slots
- Loosening of the end winding bracing
- Water leakage resulting in delamination of the insulation of water cooled bars
- Poor manufacturing quality for earlier installations (prior to 1970)
- Failure of the semi-conducting layer of the stator bars

Thus, for modern systems, the insulation in itself cannot be expected to be a root cause of future failures. This is in contrast to the experience with many older systems where electrical problems are a common cause of failure.

As the fleet of operating generators includes many old as well as new machines, it can be expected that a lot of electrical as well as mechanically induced failures will occur in the future.

5.1.5 Future of machine insulation

The development of improved insulating-tape systems continues, as does the advancement of stator insulation manufacturing techniques for large units – for example VPI processes. A new concept utilizing high-voltage XLPE cable as the stator winding

thus allowing operation at much higher voltages is described in Reference 10. The prototype was commissioned in 1998, having a rating of 11 MVA at 45 kV and 600 rpm. The first commercial units included a turbine generator rated at 136 kV, 42 MVA and 3000 rpm and a hydro-generator of 155 kV, 75 MVA and 125 rpm rating. Applying the same principle, high-voltage motors within the rating range 4 MW to 70 MW are available.

Monitoring of the large machine insulation systems is expected to expand as the measurement techniques become more advanced. Some possibilities are discussed in Chapter 9.

5.2 Transformers and reactors

The insulation problems associated with power-system transformers and reactors are especially related to the complexity of the various windings, the methods of cooling, the need for efficient clamping techniques to resist short circuits and transportation forces, the location and mounting of interconnecting leads, the accommodation of bushings and tap changers, and the form and condition of the insulating materials themselves. All these factors influence the forms of the three-dimensional electric fields and the magnitude of stresses in the insulation structures as set up by the steady-state voltages and, critically, the surges due to lightning and switching.

Insulation deterioration in service occurs naturally but the rate can be reduced by good and well-planned maintenance. Although the situation is improving with the introduction of more extensive monitoring, transformers are sometimes treated as the ‘sleeping partners’ in the system, even though their continuous service is vital to the successful operation – both technologically and economically – and to the versatility of the networks. The latter include DC transmission schemes where converter transformers form the link with the AC generation source (Chapter 1).

5.2.1 Windings

5.2.1.1 General considerations

In principle there are two basic forms of transformer winding: (i) helical and layer types with turns wound axially in single or interconnected multiple layers; and (ii) disc (core-type transformers) or pancake (shell-type transformers) types with the turns wound radially and the discs continuous or coils interconnected if wound separately. There are many winding variations depending on the voltage and current ratings, the tapping range specified, the reactance required between windings (an important parameter in system design), any switching surge tests (see Chapter 1), the likelihood of very fast transients (VFT) associated with SF₆ switchgear and, very importantly, the lightning impulse test (Chapters 1, 6 and 7).

5.2.1.2 Lightning impulse design

The impulse test requirement has a major influence on the design of high-voltage windings as the voltage distribution between sections, layers and turns is not identical

to that for the power-frequency condition. This resulted in the use of shielding to reduce the effective shunt capacitance C_g , interleaving [11,12] to increase the effective series capacitance C_s or judicious design with large rating disc windings to increase the radial depth, thereby producing a natural increase in C_s . The effect of these parameters on the initial distribution of the surge voltage – represented as a unit function – may be demonstrated by considering the equivalent capacitance network for a uniform winding (Figure 5.4(a)). This simplification assumes the series inductances of the winding are open circuit at zero time. The final voltages are theoretically proportional to the resistive components and are thus identical to the turns distribution. In Figure 5.4(b) are plotted voltages for different values of α where $\alpha = \sqrt{\frac{C_g}{C_s}}$ in the equation $v_x = V\{\sinh(\alpha x/L)\}/\sinh \alpha$. Note that C_g and C_s are the effective total values and that the winding has an earthed neutral. By achieving a low α value a better balance between the insulation requirements for steady-state and impulse conditions is possible. At some locations special precautions are necessary to allow for the surge

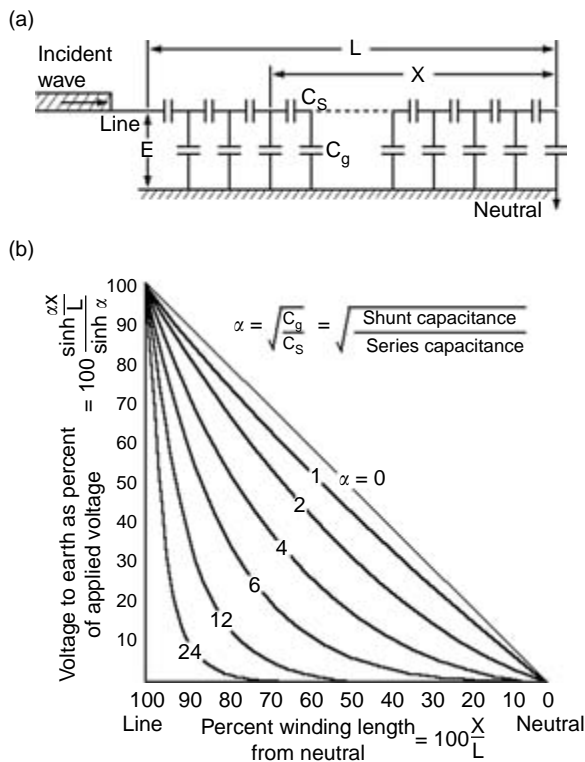


Figure 5.4 Initial distribution of impulse voltage in a uniform winding with earthed neutral. (a) Equivalent capacitance network neglecting inductances and losses; (b) Initial distributions for different values of factor α

condition – particularly along the axial insulation paths at the surfaces of disc winding stacks.

In practice the values of α range from 5 or 6 for an uncompensated winding to 1 or 2 for the high-voltage large MVA units; the power frequency distribution ($\alpha = 0$) is uniform. For a given location ($L = x$) the difference between the initial and final voltages is an indication of the possible magnitude of the overswing or oscillation occurring later in time at that position. Although these concepts are relatively simple they form the basis of the advanced computerized design programs that may include series and mutual inductance parameters. Additionally they can be of assistance when carrying out a first assessment of a failure during test or perhaps a suspected lightning strike in service.

5.2.1.3 Particular winding configurations

A number of many possible winding configurations are depicted in Figure 5.5. These range from the lower voltage (6.6 → 11 kV) low-kVA units with simple layer (wire or foil) windings through ratings of tens of MVA at 66–132 kV with disc high-voltage coils to the major generator and transmission transformers of 660 MVA or higher at voltages up to 550 kV as 3-phase units and 750 kV → 1 000 kV single-phase units.

Although many designs of core-type transformers with layer windings [13] and shell-type transformers with pancake windings [14] are in service, the core type with disc windings are probably dominant – with normal, interleaved or intershielded coils and appropriate end radial shields as shown in Figure 5.5 (e, f2, f3).

The sketches indicate also the locations of tapping windings. These are essential for voltage regulation but can introduce unacceptable reactance changes if positioned in the main gap. This restriction led to the introduction of external taps (Figure 5.5 (e, f2, f3)). The increases in MVA and load current enabled centre entry windings (two halves in parallel) to be developed economically and allowed the high-voltage input to be located away from the yoke (earthed). Such a configuration simplifies the electric stress conditions at the ends of the windings, although with outer tapping windings other clearance problems are introduced around the high-voltage lead.

Reactors are not included in the figure. High-voltage power system inter-bus couplers and filter reactors (DC systems) are series-wound, being designed to withstand a full-impulse test with an appropriate equivalent surge impedance at the non-tested terminal, and also to withstand a separate source test to ground. The latter can be a searching test for oil-insulated windings because of the large areas and volumes of oil, which are subjected to a fairly uniform stress. See Chapter 2.

5.2.2 Transformer insulation structures

An outline is given in the following of the more important aspects of transformer structures, including indications of where problems might occur. Examples are given of particular faults and how these might be detected or monitored. The configurations may be loosely divided according to their main functions, namely windings, interwinding space, winding end clearances, interconnecting leads, bushings, internal terminations and tap changers with leads and mounting boards.

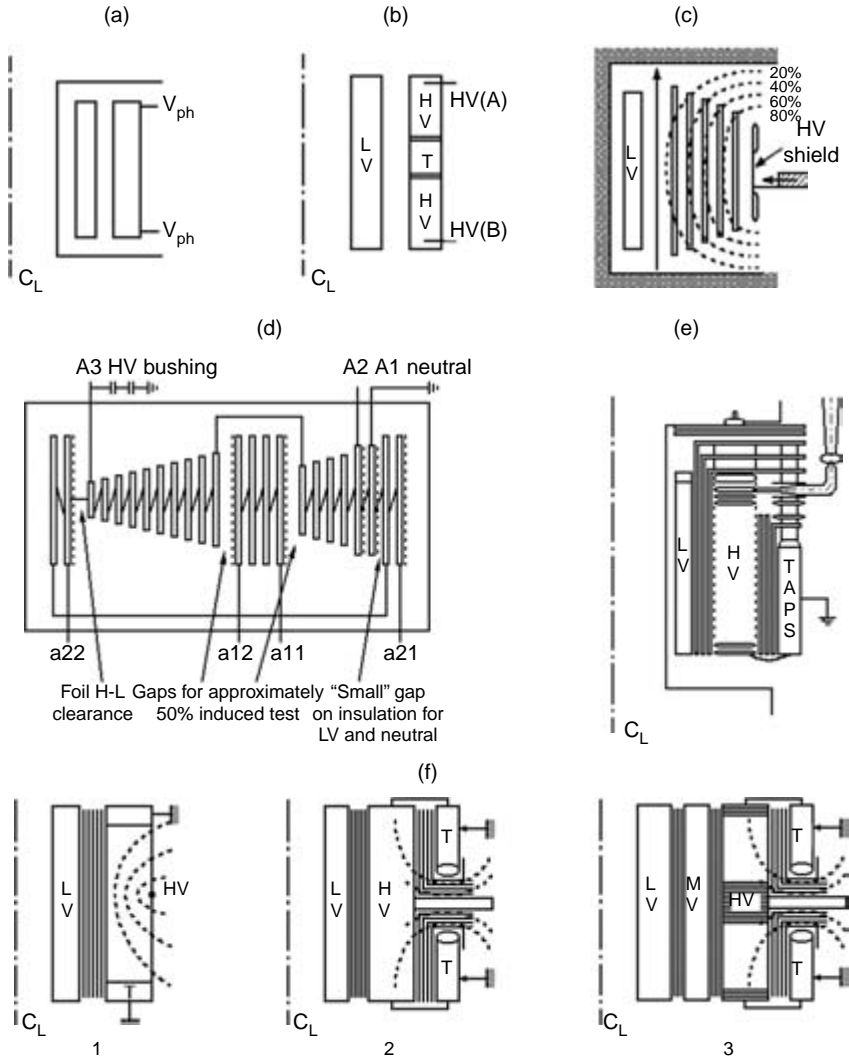


Figure 5.5 Examples of the layout of different types of transformer windings. (a) Low kVA (layer-wire or foil); (b) Medium kVA (discs and taps) – fully insulated; (c) Layer windings core-type power transformers; (d) Pancake windings–shell-type power transformers; (e) End connected disc windings – core-type power transformers; (f) Centre entry disc windings – core-type power transformers

The majority of transformers are insulated with cellulose-based, oil-impregnated materials. However, within the distribution range – possibly up to a few MVA, for example 22 kV/415 V (Δ :Y) – cast-resin high-voltage coils are in service. Units for

indoor applications in the 150–300 kVA, 17 kV/415 V range are now common. Many of the small 5–10 kVA, 11 kV/415 V pole-mounted transformers are insulated with oil-based systems but these will probably be replaced by dry-type designs.

Although not considered here, a number of SF₆ gas-insulated power transformers are in service. A notable example is the substation in the business centre of the city of Sydney (Australia), where three 400 MVA, 330/132 kV units were installed in 2003 [22].

Overall conditions that can contribute to oil-filled transformer insulation failures are (i) the presence of moisture during test caused by inadequate processing and, on site, due to inappropriate maintenance or long-term ageing, and (ii) the trapping of air caused by incorrect vacuum filling in the factory and on site, the latter perhaps after lowering of the oil for inspection purposes or a bushing change. In some dry-type designs, air clearances and termination configurations may be such as to cause corona and consequential erosion of the adjacent insulating materials.

5.2.2.1 Windings

(a) *Low-kVA oil-impregnated windings*

The high-voltage windings of the low-kVA units (11 kV systems) may consist of resin-covered, small-diameter wire wound in layers with a low-voltage, single-layer winding of enamelled rectangular strip. In some cases the LV winding comprises layers of aluminium foil separated by one or two sheets of presspaper of, perhaps, 0.12 mm thick. Although the volts/turn are very low – perhaps five – a few cases have been reported of inter-turn service failures, probably due to metal particles trapped in the rolls of foil puncturing the paper during operation but not on test. In another case, from a different manufacturer, an 11 kV foil winding of a well-established design failed during impulse test. The inter-foil (inter-turn) insulation was 0.2 mm thickness (several tens of volts/turn) specially prepared to allow resin curing and oil penetration during subsequent vacuum filling. The failure was due to unusual mechanical distortion of the foil during winding. Foil thicknesses seem to be in the range of 0.4 to 0.6 mm, depending on the current rating. A more conventional 11 kV, 7 MVA three-phase winding might have eight layers of copper, resin-coated, rectangular conductor with dimensions of the order of 11 mm × 4 mm × 4 strands in parallel and inter-layer presspaper containing vertical cooling duct(s). The system would be dried and oil-filled under vacuum.

A magnetic-type voltage transformer (MVT) consists of a bushing, a core and windings with high turns ratios. The high-voltage winding conductor is of fine wire, perhaps of the order of 0.5 mm diameter, usually wound in concentric layers. A good impulse-voltage response is achieved because of the high capacitances between layers and by the provision of inner and outer electrostatic shields. For the highest voltages a cascade arrangement is preferred.

Resin- and SF₆-insulated units are in service. Efficient resin impregnation around a large number of turns of fine wire requires very careful processing.

A number of major failures of oil–paper MVTs have been associated with the termination of the ends of the electrostatic shield on the outside of the high-voltage

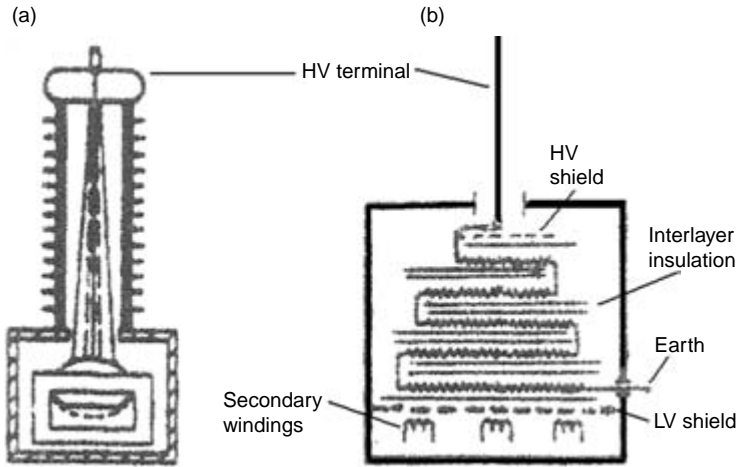


Figure 5.6 Single-stage magnetic voltage transformer (MVT). (a) Layout of dead tank design with layer winding; (b) Equivalent circuit representing many concentric layers

winding. The drying and vacuum oil impregnation of the ductless paper insulation between winding layers must be efficient to prevent voids and subsequent partial discharges. The form of a particular single-stage structure is shown in Figure 5.6. In some cases ducts and layer end insulation may be incorporated

(b) Dry type windings

Small, dry-type windings for special applications are insulated with materials such as polyester film (Class 130, e.g. Mylar and Melinex) and composites and aramid paper (Class 220, e.g. Nomex) and then impregnated or simply dipped in resins followed by curing. The latter procedures can lead to the trapping of air with resultant partial discharges of many thousands of picocoulombs in the inter-winding insulation. A number of such units failed in service due to this cause. PD testing enabled recommendations to be made for improvements in the design and processing methods. For larger ratings of, perhaps, 150 kVA (three-phase) at 22 kV, VPI techniques have been developed. This allows complete encasement of each phase of the HV windings in the resin using a mould giving a smooth outer finish with appropriate connections. Each of the windings is lowered over the particular LV winding on the core with a corona-free inter-winding air gap. PD levels of less than 10pC are achievable although connecting leads and mountings have produced much higher values – as located by ultrasonic detectors.

(c) Higher-rated oil-impregnated windings

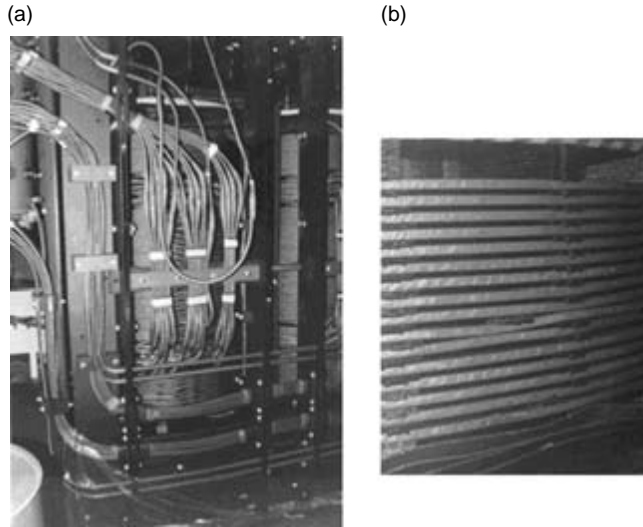
Low-voltage windings (11–22 kV) for oil/paper/pressboard-insulated transformers of higher ratings are usually of the helical form in one layer with many strands in parallel. Problems have occurred where the enamelling on the conductors was

relied upon to provide insulation between strands but after several years of service abrasive mechanical movement between the conductors produced short circuits with subsequent circulating currents and overheating. This required complete rewinding with paper-insulated conductors at considerable cost. Such faults might be detected by monitoring of gases and furans produced by overheating of the enamel, pressboard spacers and adjacent oil.

The larger layer-type high-voltage windings in core type transformers for 220 kV and above (Figure 5.5(c)) might consist of 5–7 layers of paper-insulated, continuously transposed cable. Extra layers are included for taps and the low-voltage section of an autotransformer. The turns are wound on wraps (sheets) of paper up to a thickness of possibly 12 mm and cooled by oil ducts maintained with axially located pressboard spacers of 6 to 12 mm thickness, the relative dimensions depending on the electrical and thermal design requirements for the particular unit. With an earthed neutral, the layers and insulation are graded as in Figure 5.5(c). The inter-layer paper is flanged (petalled) at right angles to form the end insulation including a continuation of the vertical oil ducts. In one arrangement the layer ends are brought out through the horizontal ducts and connected in series – ‘top to bottom’ – by the provision outside the winding shield of accurately located insulated leads of specified dimensions [13]. The inner and outer shields are necessary to ensure a good impulse distribution for the simple arrangement shown. The inner shield may not be required under some conditions. Insulation faults in these windings include deterioration of the winding-to-shield connections, blocking of ducts due to bulging of paper at the end of the layers and lead connection problems causing local overheating. Gas analysis is the major monitoring technique used, although some faults have been located ultrasonically. Tracking due to electrostatic charging in the lower inlet and cooling ducts was reported by one manufacturer. Tests on models and in-service transformers were carried out [15]. The problem was located by partial-discharge ultrasonic methods and confirmed on unwinding. It is considered that the layer-type winding has been successful with units operating for 40 years or more. However, it appears that the international mergers of manufacturers and the associated economic evaluations will see the demise of the design in favour of the more versatile disc winding.

Shell-type transformer coils (Figure 5.5(d)) have good surge response and are well supported mechanically [14]. The ducts between ‘pancakes’ are relatively thin and the cooling oil-flow rates tend to be high. Electrostatic charging effects were believed to have resulted in a number of service failures in different types of transformers in which local oil velocities seemed to be excessive. Extensive investigations in the USA and Japan and by CIGRE Study Committees 12 and 15 were carried out [16,17]. Some monitoring is possible by low-voltage DC measurements and ultrasonic detection. The advantages of shell-type transformers are being applied by some manufacturers.

The majority of high-voltage windings from tens of MVA (66 kV) up to the largest ratings and highest voltages consist of discs of paper-insulated conductors wound continuously or in pairs (coils). Horizontal and vertical ducts are formed by pressboard spacers. With directed flow units, ducts on the inside and outside diameters of the winding are formed by vertical barriers (cylinders) and insulation washers provided at critical locations in the stack in order to direct the oil flow horizontally between



*Figure 5.7 Example of the surface of a medium-size disc winding (10 MVA, 66 kV).
 (a) View of leads from tapping windings located within the 66 kV stacks.
 (b) Displacement of 66 kV winding turns due to service fault*

discs. The oil is pumped into the bottom of the winding from the external air or water coolers.

The failure rates of windings are low, as reported in CIGRE surveys and papers. Problems with the older medium-size units are probably associated with lightning strikes where the protection was inadequate or the design not appropriate. Windings may fail also due to tap changer maloperation (Figure 5.7). Occasionally, unusual faults occur as in a 66 kV winding where a nut had lodged between a disc and a vertical barrier. This probably occurred during an inspection three years previously, but was not detected by the overvoltage tests applied at that time. It was deduced that the nut was dislodged into a more critical position during service and partial discharges were set up, which eventually led to a winding failure. Such a condition may have been detectable by gas analyses or, possibly, by PD measurements on site. It would have been very difficult, or impossible, to detect by ultrasonic methods, as the fault was within the winding. The relocation of aged, moderate-size or large, transformers can produce internal movement and consequent insulation damage. This problem has been reported for new transformers, where insufficient allowance had been made for the forces produced during transport – by ship, rail and road.

The desirability of continuous online monitoring, especially for large generator and transmission transformers, is indicated by a number of failure types whose causes are difficult to determine with certainty. These include (i) manufacturing faults related to the winding insulation, which develop into a dangerous condition only after some time in service, e.g. mechanical failures of conductor joints; (ii) electrostatic charging

effects caused by high-velocity oil flows in winding ducts; (iii) contamination caused by the production of fine metal particles in the oil circuit; (iv) reduction in winding clamping pressures, allowing movement of the coils and consequential insulation damage, during high current through faults and, possibly, normal switching; and (v) the effect of high-frequency transients produced by a local GIS flashover. An example of the condition in (iv) was believed to be the cause of the shorting of the strands of a turn in a disc at the bottom of a three-phase, 400 MVA, 362 kV winding after many years in service. This fault probably produced gas bubbles, which developed into an axial flashover along the vertical surface of the high-voltage winding. The major failure of one leg of one phase of a 990 MVA, 21.45/500 kV generator transformer resulted in a detailed investigation of the possible cause as described in Reference 18. After extensive measurements, modelling and analyses it was concluded that the failure was possibly due to excessive voltage stresses across the line-end discs. These stresses were assumed to be created by several SF₆ bus flashovers at the end of the 600 m overhead transmission line connected to the transformer. It was noted that during a period of six months the transformer was not connected to the generator, thus creating a condition where the LV winding can influence the HV winding stresses under surge voltages. The paper concludes that the transformer designers require detailed information of probable service transient conditions not covered by the normal factory surge tests.

The windings – LV, HV and taps – of a 300 MVA, 400 kV, three-phase unit may have an external diameter of 2.5 metres, a height of >3 metres and weigh 8 tonnes (each phase) when assembled on the core. The total weight of such a transformer with the core and coils assembled in the tank and full of oil is more than 250 tonnes. The height of the tank might be 4.6 metres and the bushings a further 2.5 metres.

The core and coils of a 220 kV substation transformer with high-voltage disc windings in the final stages of assembly is depicted in Figure 5.8. In this unit the connections from the outside tapping windings are connected to the on-load tap changer located on the left-hand side of the structure. A series reactor in an 11 kV delta connection is mounted on the right.

5.2.2.2 Inter-winding insulation

In oil-core-type transformers the inter-winding insulation usually consists of wraps or cylinders of pressboard, the latter having a vertical split overlap with a scarfed joint to prevent radial build-up and to allow tolerances on the diameters. Oil ducts are maintained by vertical pressboard spacers in the thickness range of 6 mm or less, up to 12 mm or more. The board thicknesses are 3–6 mm with lengths of the order of 3 metres. The spacers should be attached with non-contaminating glue and in the lower electrically stressed areas where possible. Adjacent to the high-voltage winding incorrect procedures can lead to an axial failure, especially during an impulse test or lightning strike. The damage to a disc coil following an axial failure on site is indicated in Figure 5.9. An example of the equipotential distribution and possible barrier configuration at the end of a high-voltage winding is given in Figure 5.10.



Figure 5.8 Core and coils of a 225 MVA, 220/66/11 kV substation transformer with outside taps and centre-entry high-voltage leads [photograph by AREVA T&D, Brisbane, Australia]

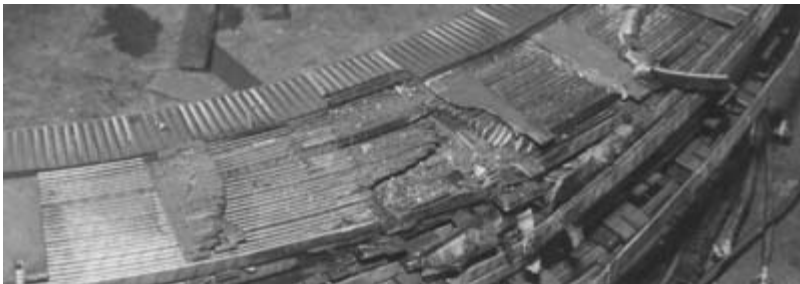


Figure 5.9 Example of winding damage due to internal insulation breakdown

It is very unusual for inter-winding insulation systems to fail, particularly in puncture. One configuration that has become a problem in a few instances after many years of operation is a structure where the interwinding insulation comprises continuous wraps of presspaper. This was introduced to produce a more economic system and exploit the advantages of a new design of winding. The units were successfully tested (300 kV class) but in service it became apparent that the materials may not have been completely dried out or efficiently impregnated under vacuum because of the large radial thickness and axial length of the ductless system. Failures developed due to high local partial discharges and associated dielectric losses. Puncture occurred from the high-voltage winding to the neutral axial shield in a few cases. Disassembly of non-failed units showed a gradual erosion into the wrappings at the inside diameter (centre entry) of the high-voltage coils. Other designs with continuous

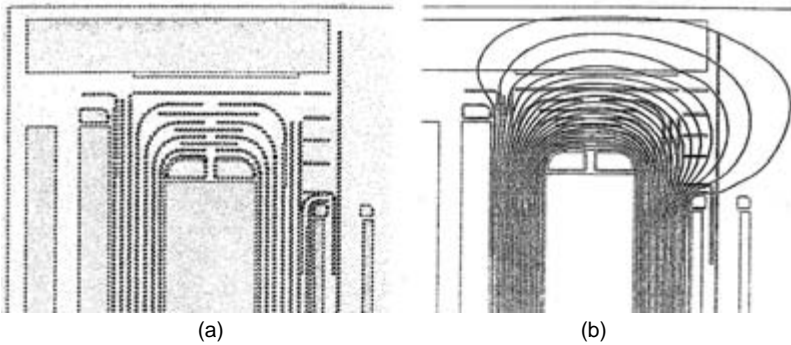


Figure 5.10 Typical insulation layout and equipotential field of an end-connected high-voltage power transformer [diagrams by Weidmann Transformer Systems AG, Rapperswil]

paper wraps have probably exhibited similar problems. By the inclusion of thin ducts (see Section 3.2.1) it is possible to achieve high average operating stresses if this is required in the proposed design. Other faults detected within inter-winding insulation include a broken connection between the inner axial shield and neutral.

A potential fault condition in a newer transformer was the presence of contamination by fine metal particles produced by a faulty cooler. This particular unit had not failed but on disassembling was found to contain pressboard and paper surfaces covered with the particulate. On-site PD tests showed no apparently significant values and, again, after a factory impulse test during which failure occurred well below the expected withstand level. Physical examination detected a fine track mark along the surface of the barrier forming the duct next to the inside diameter of the high-voltage winding (centre entry). In this case conventional electrical monitoring was unable to predict a possible service failure due to the particles or a track path created by a low-energy surge flashover [19].

Metal particles of millimetre dimensions within a structure have been detected during PD tests in the factory. Such a particle will produce PDs only if it is located and trapped in a position where its shape enhances the electric stress. PD magnitudes of the order of hundreds of pCs might be expected [19]. A number of failures in service as well as during overvoltage tests are reported in the CIGRE review [20]. These problems are more likely to be associated with long oil distances, e.g. a bushing termination to turret or the outside of a winding to ground, rather than within the coils themselves.

5.2.2.3 End insulation

With end-connected windings (Figures 5.5(e) and 5.10(a)), careful layout of the insulation is necessary to prevent flashover along surfaces to ground (including the earthed core) and to adjacent windings such as outer taps and to ensure good oil flow for cooling of the windings. The use of a radial shield connected to the line end disc

(Figure 5.10(a)) [21] and the contoured cylindrical pressboard barriers following the equipotential lines (Figure 5.10(b)) provide an efficient insulation system. In Figure 5.10(b) the equipotentials represent 5 per cent intervals. The corresponding electric stresses may be calculated by means of an associated field computer program. Ideally, the spacings between barriers may be staggered in order to prevent partial discharges in the particular oil gap (Figure 2.3) during testing. This is especially important adjacent to the maximum-stress areas at the corners of the high-voltage and low-voltage windings and the tap windings. In Figure 5.10(b) shields at the corners of the LV and tap windings are at, or near, earth potential. At the position of connection of the HV lead the configuration becomes more complex. Preformed barriers and components for lead insulation are available from specialist manufacturers. The figure's plot is for a separate source test. During an induced or impulse test conditions in the end insulation do not change significantly except, perhaps, at the lower corners of the radial shield.

In a particular case omission of horizontal pressboard washers above the cooling gap through the radial shield (Figure 5.10(a)) resulted in an impulse test failure along a tortuous pressboard path to earth.

A problem that has arisen is the production of partial discharges at the edges of the metal (earthed) winding clamping studs where these were not of correct dimensions and insulated. An unsatisfactory arrangement can result in PDs of many thousands of pC leading to flashover to an adjacent high-voltage lead or similar during factory tests (see Figure 3.6). Discharges at the surface of earthed clamping studs have been detected by DGA on-site and located using ultrasonic methods. During maintenance, the upper insulating board (laminated wood or pressboard) may be exposed when lowering the oil, thus allowing ingress of moisture if precautions are not taken. Failures due to dielectric losses in such boards are possible as considered in Chapter 2.

5.2.2.4 Insulation to tank and core

It is usual in the larger transformers to provide pressboard barriers in order to break up the long oil paths between the windings and tank, between phases (three-phase) and to the outer core leg (5-limb designs), especially where particles might be present [20]. The distances involved are possibly in the range of 50–250 mm depending on the test voltages and the chosen safety factor. In older transformers tracking on barriers has been found although no 'direct feed' point was involved. The effect is probably due to moisture development or ingress and would not be detectable by existing electrical monitoring [19]. Some change in DGA sample values may be measurable.

5.2.2.5 Bushing internal terminations and leads

Bushing designs have been discussed in Section 4.3. The method of connection of a conventional bushing within a power transformer at high voltages is indicated in Figure 5.5(e) and the associated field plots for both conventional and re-entrant types mounted in a turret in Figure 4.3. Plots are also presented in Reference 13, including the equipotential distribution for a re-entrant bushing without a high-voltage lead in place. Bushings installed in transformers are shown in Figure 5.11.

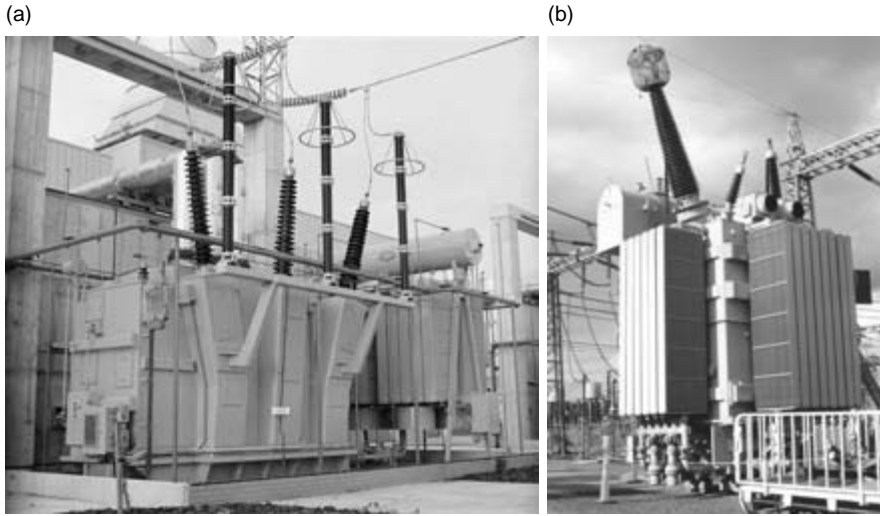


Figure 5.11 Bushings installed in high-voltage power transformers. (a) 100 MVA, 11/230 kV generator transformer [photograph by Wilson Transformer Company]; (b) 133 MVA, $330/\sqrt{3}/138/\sqrt{3}$ kV auto transformer [by permission of Transgrid NSW]

Flashovers have occurred between bushings and turrets due to contaminated oil and particles and where a local barrier has been exposed for too long during installation. In a number of cases the stress distributor (Figures 5.5(e) and 4.3(a)) has become loose, resulting in discharging (sparking) and gas production, which might have triggered an axial flashover. Such discharging has been detected by DGA measurements and successfully located by ultrasonic techniques. Problems in re-entrant bushings can arise due to incorrect location of the paper-insulated lead within the porcelain (Figure 4.3(b)). For example, air might be trapped within the paper–porcelain gap in some configurations when topping up the oil on site.

The design and insulation of leads from bushing ends to the windings require special care to ensure safe stresses at the paper surfaces. By use of prefabricated pressboard systems, concentric cylinders and angles can be built in as shown in principle in Figure 5.5(f, 2/3). A critical region in such structures is where a scarfed joint is required at the exit point. Creep along an incorrectly made scarf can lead to a major flashover with pre-discharging of thousands of pCs during AC tests. The discharges may be detected by PD measurements and located by ultrasonic methods. Failures to the top of unshielded tap windings without barrier protection have also occurred on test, the condition being exacerbated by the ‘radial’ stressing produced by the adjacent high-voltage winding (Figure 5.5(e) and (f, 2/3)).

The location, the thickness and the diameter of insulation around high- and low-voltage leads are determined by the local field distortion as well as the oil and creep paths. Field analyses are necessary to ensure the stresses are acceptable.

5.2.2.6 Tap changers

Although most tap-changer failures can be traced to mechanical maloperation, some are related to tracking along the insulation surfaces or a direct oil flashover perhaps associated with contamination created by incorrect wearing of the metal contacts.

In a particular 66 kV transformer, distortion of the tap windings in the centre of the high-voltage winding (Figure 5.5(b)) was due to a flashover along the inner cylinder of the 20-year-old tap changer. Some damage was also present in the main windings, thus requiring a rewind of the complete leg.

As conditions within a tap changer are quite onerous, monitoring of the gas levels and regular maintenance are essential. New techniques are being developed to improve surveillance. Care is necessary when interpreting transformer DGA results if the tap changer is in the main tank or there is a possibility of leakage from the tap changer/diverter enclosures.

5.2.2.7 Core and magnetic shields

Overheating due to circulating currents in cores and laminated magnetic shields caused by low-level interlaminar insulation degradation has been detected by DGA sampling. The temperatures produced can result in breakdown of the oil. The locations have been identified using ultrasonics and units subsequently kept in service until remedial action could be taken. If allowed to build up, the deposits at the fault are difficult to remove as experienced in an old 275 kV, 120 MVA transmission transformer. With magnetic-shield faults, continued operation may be possible at reduced load current.

5.2.2.8 Major transformer failures

Service failures of oil-filled transformers can result in complete destruction of the system by fire and irreparable damage to core and tank as well as expensive outages. For example, see Figure 5.12. If the supply-system protection operates quickly, damage may not involve the whole unit, although carbon contamination can be extensive, especially if pumped oil coolers are installed. It is anticipated that development of continuous monitoring systems will help eliminate such catastrophic failures.

5.2.2.9 Power transformer summary

The situations described are typical of some of the insulation faults that might develop in power transformers. Although a particular failure can be very significant it should be appreciated that the problems involve a small percentage of the total number of units in service. However, it is probable that the percentage will increase as the assets age, full-load (or more) currents are demanded for longer periods and higher electric stresses tend to be applied in new designs to meet economic demands. It is essential, therefore, that testing, insulation-condition assessment and monitoring continue to be improved, especially for the generator transformers and the medium- to large-size transmission transformers. It would be expected that if large SF₆-insulated units [22] become more common some of the existing operational problems will be reduced.



Figure 5.12 Fire following failure of a 330 kV transformer in a transmission substation [photograph by Brendan Esposito/Sydney Morning Herald]

5.3 Summary

A number of possible insulation problems associated with the largest units of equipment – generators and power transformers – are discussed in the chapter. Although faults are infrequent, their influence on the operation of the power system can be very significant, both economically and technically. The prevention of lengthy major outages as well as damage to critical plant items justifies consideration of the application of the new condition-monitoring techniques as they are developed. This applies especially to online methods but also includes the continuation and improvement of offline procedures. An understanding of the equipment insulation configurations as considered in this chapter assists in interpretation of failure scenarios [23] and in applying the most appropriate monitoring system.

5.4 References

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5.5 Problems

1.
 - (i) Differentiate between the conventional insulation and cooling systems of a large steam turbine generator and that of a hydro-generator.
 - (ii) How are the surface discharges controlled at the exit of the stator bars from the core slots?
 - (iii) Describe techniques suitable for the monitoring of possible partial discharges in the two types of machine (refer to Chapter 9).
2. In an air-cooled, medium-size rotating machine the outer earthed conducting layer on a stator bar has been eroded by vibration within a core slot. Determine whether air discharges would be expected for an insulation thickness of 3 mm, a spacing to the core laminations of 0.5 mm and a voltage of $11/\sqrt{3}$ kV. If similar dimensions were used in a hydrogen-cooled machine at a pressure of 5 bar, at what voltage might PDs be initiated for a similar condition? Refer to Figure 2.2. Assume a pressboard permittivity of 3.5.
3.
 - (i) Describe the major differences between the insulation systems of large core- and shell-type transformers.
 - (ii) The spacing (duct) between adjacent discs (7 per cent of winding turns) at the line end of a uniformly wound core type transformer is 8 mm of oil and the two-side conductor insulation thickness is 1.5 mm. Calculate the theoretical lightning impulse breakdown strengths of two windings of similar configurations with α values of 4 and 1. Assume a uniform field (a big approximation) and that failure would be expected to occur in the oil at the line end to the adjacent disc. The permittivities of the oil and conductor paper are 2.2 and 3.2 respectively. Determine for which voltage class each winding would be suitable assuming a minimum test safety factor of 1.3. Refer to Equation 3.1, Figure 2.3 (c), Figure 5.4 and Table 1.2.
4. From a transformer DGA results it was found that the oil hydrogen level was 1 200 ppm and the total combustible gas 3 000 ppm. This indicated a source of PDs within the unit. Describe methods for detecting and locating the site as well as confirming that the disturbance was probably a partial discharge. Refer to Chapters 6, 9 and 10.

Chapter 6

Basic methods for insulation assessment

- High-voltage test supplies
- Electrical non-destructive test methods
- Physical and chemical assessment techniques

In this chapter an overview is given of the more important methods employed in the supply industry for assessing the condition of insulation in power-system equipment – before leaving the factory, on commissioning, during service and when undergoing major maintenance or repair. The particular requirements for equipment of different insulation structures are described in Chapter 7, including reference to Standards where appropriate. More advanced recently developed methods are presented in Chapters 8–10.

The earliest methods for determining whether or not an insulating material was suitable for a particular usage included the application of steady-state voltages for, perhaps, one minute at twice or more the operating stress. Later, this was followed by the development of surge voltage tests to simulate lightning and system-switching effects. Much research was necessary in the design and construction of high-voltage test equipment and associated test/laboratory areas.

In recent years there has been a tendency to close high-voltage laboratories in those countries with developed power systems. However, this may be a short-sighted policy, since it is essential to provide local reference measurement systems and capabilities for checking and proving ageing equipment, as well as new items of plant in which unproven insulating materials may be included.

In the following, the various methods of assessment are grouped according to whether the application is:

- (i) an overvoltage withstand test;
- (ii) a non-destructive electrical measurement; or
- (iii) a physical/chemical determination that may require access to a sample of the insulating material.

6.1 Generation and measurement of test high voltages

The form of the source and method of voltage measurement are briefly described for each type of test voltage. More detailed treatments will be found in the books by, for example, Kuffel and Zaengl [1], Schwab [2], Kind [3] and Hylton-Cavallius [4].

6.1.1 Power-frequency voltages

Power-frequency voltages for insulation withstand testing are produced by specialised transformers with outputs within the range of tens of kV to a few hundred kV in a single unit and up to a million kV or more in cascade arrangements. The voltages required for routine testing are tabulated in Chapter 1. The current ratings vary according to the capacitances of the particular equipment to be tested and the kVA ratings from 10 kVA (e.g. 0.1 A at 100 kV) up to 500–1 000 kVA at the higher voltages. The ratings quoted are maxima and the current values must not be exceeded – for example, a 100 kV, 10 kVA transformer can only operate at 5 kVA (0.1 A) at 50 kV unless otherwise specified. Such transformers are often designed for short time ratings at full-load current and are not overvoltage-tested at the same margins as power transformers. Usually they are not subjected to lightning and switching type surges. Modern units are supplied with a low partial-discharge guarantee, typically less than a few pCs at full voltage. In addition to units produced by test equipment specialists, a number of power and distribution transformer manufacturers have built their own testing transformers.

6.1.1.1 Single-unit testing transformers

The simplest testing transformer consists of a closed core with a low-voltage winding (240/120 V), over which is wound a graded layer winding of many turns, the major insulation comprising oil-impregnated paper. The high-voltage winding is provided with an outer shield (see Figure 5.5(c)) in order to ensure a ‘uniform’ voltage distribution following a flashover at the HV terminal due to breakdown of a test object or a measurement sphere gap. The core and coils are mounted in a steel tank with a high-voltage bushing (Figure 6.1) or in many applications, for indoor use, in an insulating cylinder with a spinning as the HV terminal mounted on the top of the cylinder. The unit in Figure 6.2 has a diameter of 1 metre. In one case a centre-entry design with an ‘open’ core and outer insulating cylinder was successfully used for separate source testing up to voltages of 70 kV. Single units for production of a million volts were built in the 1930s but some eventually failed, probably due to partial discharges. The more common single-unit designs are probably in the range of 200 to 600 and a few up to 750 kV [4].

6.1.1.2 Multiple-unit (cascade) testing transformers

Production of voltages above 350–500 kV is probably achieved more reliably by cascading transformers of lower voltages, as indicated in Figure 6.3. The individual units are similar to single transformers but have an exciting winding supplying an upper transformer, which is insulated from earth for the output of the lower unit.



Figure 6.1 200 kV testing transformer – metal tank



Figure 6.2 250 kV testing transformer and capacitor divider – insulation cylinders as shells

An insulating shell with the individual units stacked above one another to form a composite transformer may be used – for example the 2.4 MV unit at IREQ [1,4] or, more commonly, stand-off insulators supporting the tanks of the upper units. It is important to allow for the different operating currents in the units – the lower unit supplying the power for the other transformers – and also for the non-uniform voltage distribution created across the various windings on flashover at the output terminal. Compensating reactors are sometimes included in parallel with the windings when testing large capacitances, such as cables, where currents of several amperes may be required. Analyses of the various conditions are presented in References 1 and 4.

Although cascaded transformers may occupy considerable floor space, this is offset by the versatility of having available two or three individual units and ease in handling when tests are required at lower voltages. In some applications lower-voltage units might be utilized (e.g. 100 kV each) in order to form a versatile source for site applications.

6.1.1.3 Operation of testing transformers

The simplest supply for a testing transformer consists of a variable voltage 50/60 Hz source such as a 240 V ‘variac’ transformer for small units up to 5 kVA. An alternative

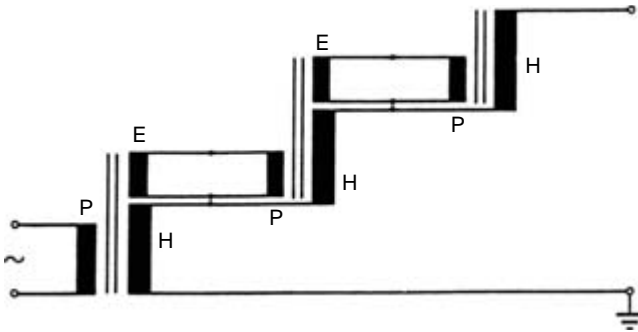


Figure 6.3 Cascade arrangement of testing transformers: P – primary windings; H – high-voltage windings; E – exciting windings

is a tapped regulating transformer with two moving contacts between which is a resistor or reactor to avoid the production of switching surges in the testing transformer during tap changing. If many tapings are built-in this method is efficient and gives little waveform distortion. Probably the commonest regulator for control of higher-kVA transformers is the induction type, in which a rotor is supplied from the source and the stator is connected in series with the transformer primary also across the source. The output of the stator can be varied over the full voltage range by rotation of the rotor [5]. The major disadvantage of these regulators is the waveform distortion but this can be minimised by appropriate design. In some cases a motor-driven synchronous generator may provide the variable voltage. No waveform problems would be expected in such a system, although interference of partial-discharge measurements has been experienced.

If a higher frequency is being applied – for example when simulating insulation structures to be used during power-transformer-induced tests at 200–300 Hz or during accelerated life tests – care must be taken that series resonance conditions do not produce unexpected voltages across the test transformer winding due to the capacitive nature of the loads. A specially designed transformer may be necessary for the higher frequencies. Such a situation can also arise at normal frequencies with 50/60 Hz units, where a runaway condition is possible. If a testing transformer is switched in at above 50 per cent of its rating the output can oscillate to above the maximum nominal voltage [1]. A reactor of appropriate value at the input (see Figure 6.4) improves the power factor of the supply, thereby reducing the current required. Quantitative determinations are necessary should there be doubt regarding the stability of the test circuits. As with all testing circuits, it is good practice to include interlocking to prevent closure of the switch to the transformer unless the regulator is set at the zero-output position.

A condition that may arise when flashover of a large non-uniform air gap with a capacitive load occurs – probably on the positive voltage peak – is for oscillations in the output circuits to develop, resulting in an increased voltage appearing across the test transformer. The effect was first mentioned by Parnell [6] and is described

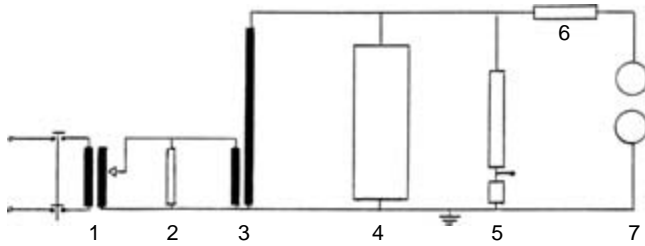


Figure 6.4 Typical power-frequency test circuit: 1. Regulating transformer; 2. Compensating reactor; 3. Test transformer; 4. Test object; 5. Peak and RMS voltmeters; 6. Damping resistor; 7. Sphere gap

in Reference 4. A series resistance in the high-voltage line will prevent the excess voltage being applied to the transformer (such resistors are not practical at the highest voltages) or it may be possible to include a thyristor configuration to short-circuit the supply at the instant of the flashover [7]. This phenomenon has been termed a ‘snapover’ [4].

The circuit in Figure 6.4 includes a capacitive divider for measurement of the high-voltage output. C_1 usually has a value of 100 pF and consists of several sections for the higher voltages with large-diameter rings at the terminal for the elimination of corona and effecting good voltage distribution along the top sections of the divider. The low-voltage arm connections may be arranged to measure both peak and rms values [1,2]. If the test transformer has a bushing with a low-voltage tap, the latter may be used for measurement, assuming a satisfactory calibration is provided. The accuracy may be established by comparison with the sphere gap flashover values for the particular loading or by a calibrated high-voltage standard divider. The use of a sphere gap is defined in Standard S6/1 (see Section 6.6 below) and Standards related to high-voltage testing techniques in IEC Publications 60060-1 to 60060-3 [S6/2].

At the lower voltages a high resistance in series with a full wave rectifier feeding a moving coil meter is sometimes used – for example, a 50 kV, 33 M Ω resistor. Such a resistor could also act as the high-voltage arm of a resistive divider with its output measured by a high-impedance voltmeter. The thermal stability and freedom from partial discharges and corona of the high-voltage components must be guaranteed. For voltages up to 100 kV a fully insulated electrostatic voltmeter was produced. Although somewhat fragile for regular industrial use, the instrument is valuable where minimum circuit loading is required and in cases where the difference between two voltages, both above earth, is to be measured.

The required accuracy of the high-voltage measuring systems and their method of calibration are specified in the Standards. A sphere gap calibration if effected correctly [S6/1] gives an accuracy of ± 3 per cent but commercial instruments including their high-voltage components would be expected to give a much improved value. These systems are calibrated against standard dividers whose ratios have been determined in a national or international standards laboratory.

It is important to note that in test circuits involving testing transformers complete reliance should never be given to a voltage reading on the low-voltage winding as a measure of the high-voltage output. The apparent turns ratio may not be correct or constant under different load conditions due to resonance effects. A high-voltage device must be included and, preferably, a second system – e.g. a sphere gap – used as a cross reference. Partial failures in the measurement system may not be immediately apparent perhaps resulting in an excessive voltage being applied to the test object or an unexpected air flashover.

6.1.1.4 Series resonant circuits

The application of tunable series resonant circuits for high-voltage testing of large-capacitive objects such as cables, power capacitors, generators and high-voltage shunt reactors is well established. The basic test circuits are shown in Figure 6.5(a) and the two possibilities for testing capacitive-type equipment in Figure 6.5(b) and (c). The natural frequencies of the circuits are given by $f_n = 1/(2\pi\sqrt{LC})$, where L is the HV inductance and C the total capacitance.

The supply circuits are only required to provide the resistive losses in the high-voltage components. A major advantage of the configurations is that they are tuned specifically to the test frequency, thereby avoiding the possibility of unwanted resonances, which can produce overvoltages and even failures in transformer systems – as well as waveform distortion. Additionally, if breakdown of the test object occurs the high-voltage collapses, thus minimizing the damage and reducing the risk of explosion.

The disadvantage of the techniques for general high-voltage testing is the lack of versatility compared with a transformer circuit. A given resonant circuit is limited by the range of load values for which it is tuneable.

Commercial series resonant test sets particularly aimed at cable testing have ratings of up to tens of MVA and voltages of hundreds of kilovolts incorporating several reactors in series. In the usual series circuit (ACRL) the reactor has a split core (Figure 6.5(b)) which may be varied mechanically to give an overall change in inductance of 10 to 20 [1]. Q values of the order of 30 or higher are possible, requiring an input of a few percent of the main circuit rating and a transformer voltage of only $1/Q$ to give the desired output. Individual units of 350 kV have been stacked in vertical assemblies to produce up to 2.1 MV (six units) [1].

In one location a tuning capacitor with a voltage rating of 1000 kV was used for testing high-voltage shunt reactors, e.g. a 33 MVAR, $500/\sqrt{3}$ kV unit.

A more recent development has been the introduction of variable-input frequency systems with fixed values of series inductance (Figure 6.5 (c)). The required test frequencies are within the 20–300 Hz range as specified and discussed in IEC 62067 [S6/3] for tests on extruded cables above 150 kV. It would be expected that the weight/power ratio for such systems would be less than the equivalent variable inductance configuration [8]. The ratios vary from 1 to 8 kg/kVA for ACRL circuits and ≥ 0.6 kg/kVA for ACFL circuits. Q factors for these systems can be >100 depending on the test frequency and the losses in the series reactor/transformer/load capacitors

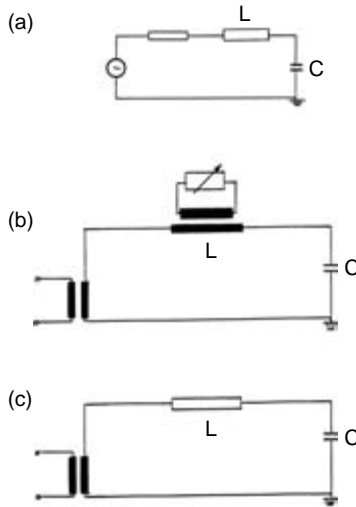


Figure 6.5 Principle of series resonant test circuits: (a) basic circuit; (b) tuneable reactor circuit (ACRL) – fixed frequency; (c) tuneable frequency circuit (ACFL) – fixed series inductance

at the particular f_n value [9]. For PD testing applications the IGBT switching pulses in the variable frequency source can be suppressed.

Parallel resonant circuits may be utilized for cable and generator testing on site in order to reduce the supply current. However, this arrangement requires a transformer of the full test voltage – but not full current – as well as a tuneable high-voltage reactor. Tuned circuits are not suitable for tests during which excessive losses can develop, as in pollution testing [4]. An appreciable voltage drop may be produced by the increase in resistive current near flashover.

6.1.2 High-frequency voltages

High-frequency voltages are sometimes used for testing low-capacitance samples, in particular overhead line insulators (see Section 7.1.1). Such voltages may be produced by a Tesla coil circuit in which a charged capacitor is discharged by an air gap through the primary of an air-cored step-up transformer. The secondary is tuned by a second capacitor to respond to the primary current oscillations. Thus a series of high-frequency, high-voltage oscillations are produced [10]. The HV winding comprises many turns of thin wire. Frequencies in the hundreds of kilohertz range and voltages up to a million are achievable with low-capacitive loads. The application of the circuit is very limited because of the oscillatory pulse waveforms and the interference created by the repetitive firing of the air gap. The system is an impressive tool for demonstration of the generation of very high voltages in the laboratory – continuous sparking can be maintained!

6.1.3 *Very-low-frequency voltages (VLF)*

Following various investigations attempting to relate the strength and PD characteristics of cable and machine insulation at 50/60 Hz to those at low frequency, a number of test supplies have been developed operating at 0.1 Hz.

VLF testing has been used in the world for many applications requiring AC testing of high-capacitance loads. Since HV DC tests can cause space charge and damage to XLPE insulation, VLF has become a widely adopted testing method for XLPE power cables. It is also an effective tool for burning down cable defects in the insulation as well as accessories.

It seems that the low-frequency PD characteristics may not always be similar to the system operating frequencies. This could be due to the large difference in rate of rise of the applied voltages, the higher stress required for inception and the longer time of application to record significant voltage reversals. VLF testing has proved to be of value for detecting electrical tree growth in XLPE insulation.

Different principles are invoked for production of VLF voltages including generation of cosine-square waves followed by polarity reversal giving a cosine function or, more recently, VLF sine wave voltages generated by electronic inverters.

6.1.4 *Direct voltages*

Direct-voltage testing circuits are necessary for checking the integrity of AC paper-insulated cables and generator insulation in addition to that for DC transmission schemes. The simplest arrangement for outputs in the 100–200 kV range and tens of milliamps is a half-wave rectifier (Figure 6.6(a)) and, commonly, a voltage doubler (Figure 6.6(b)) in which the output is twice the peak of the AC voltage. If required, a smoother output can be obtained by incorporating a centre-tapped transformer. For higher voltages, several stages are included in multiple columns comprising the capacitors, interconnected by solid-state rectifiers. A two-stage system with associated circuitry is depicted in Figure 6.6(c). The output is four times the AC peak voltage.

Cascaded systems have been built for testing and research up to the voltages required for the various DC transmission schemes. Analysis of these systems is complex and it is difficult to predict from theoretical considerations the precise output voltage and ripple content [1,4].

With large-capacitive loads a smoothing (reservoir) capacitor is probably not required, as the test object becomes the dominant component. A series-protective resistor is provided in case of external flashover or failure of the test object. The voltage output is measured by means of a high-value stable resistor connected to a meter calibrated in kilovolts. If the configuration is enclosed in an insulating cylinder of high-resistivity material, care is necessary to avoid static charging effects on the surfaces. In all direct-voltage testing the method of earthing the test object after disconnecting the supply is very critical. For large capacitances it is probably necessary to discharge the test object through a resistor of sufficient thermal capacity to avoid injury to personnel and to prevent damage due to a sudden current surge.

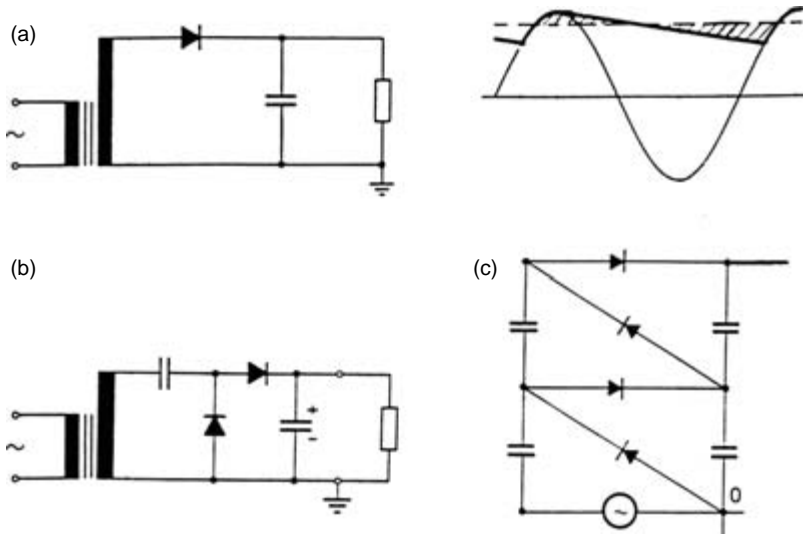


Figure 6.6 Direct voltage testing circuit: (a) half-wave rectifier and waveform; (b) voltage doubler circuit; (c) voltage quadrupler circuit

Portable DC test sets are available for low-current outputs at up to 100 kV or more with a low ripple and high stability. Such units incorporate high-frequency (e.g. 80 kHz) supplies through a small transformer.

6.1.5 Hybrid test circuits

As a possible alternative to resonant test sets and to enable a form of partial discharge measurements to be made on large capacitances, e.g. cables, hybrid circuits have been developed utilizing direct-voltage charging and fast switching to simulate power frequency wave shapes in the insulation system under test.

One method involves the slow DC charging (few seconds) of the test object through a series inductance and when at the required test level shorting the source with a high-speed switch. Due to the low loss of the reactor and cable a number of oscillations can be produced without appreciable decay at frequencies within the range 50 Hz to 1 kHz, depending on the circuit L and C values [11].

A similar system also increases the direct voltage slowly (within 10 seconds) to $2U_0$ and suddenly discharges the test object to produce the required oscillations of about 10 ms per half-period [12].

In both techniques the test voltage is applied several times to obtain significant partial-discharge results.

6.1.6 Lightning impulse voltages

The magnitudes and wave shapes of the transient voltages required for testing power-system equipment are specified in IEC 60071, as described in Chapter 1. The basic

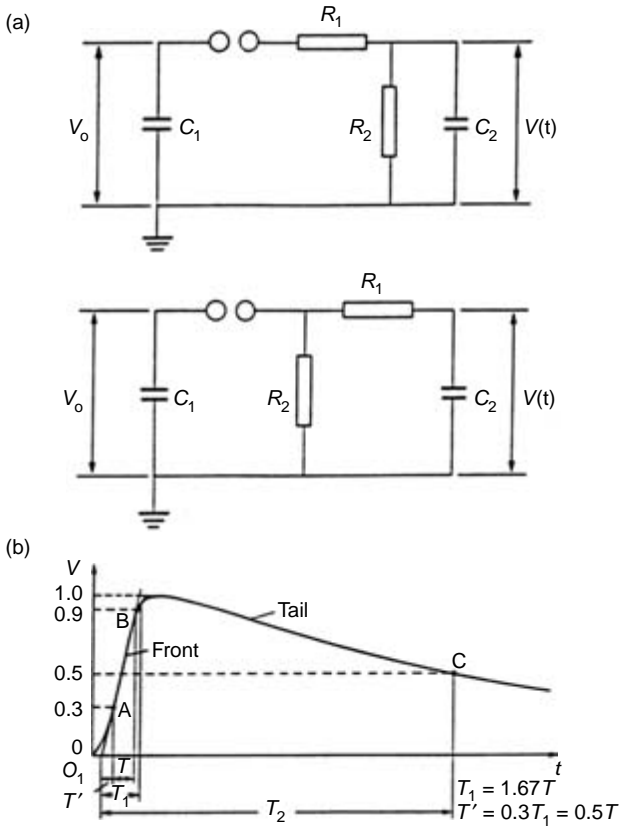


Figure 6.7 Basic impulse generator circuits: (a) equivalent circuit; (b) definition of wave shape

requirements for producing, applying and measuring such voltages are included in IEC 60060 [S6/2].

In the circuit of Figure 6.7 the capacitor C_1 is charged from a DC source to a preset value, V_0 , and then discharged through an air gap into the RC network of R_1 (front resistor), R_2 (tail resistor) and C_2 , representing the load capacitance, including a capacitive divider if connected. The position of R_2 with respect to R_1 modifies the voltage efficiency. For the lightning impulse wave $R_2 \gg R_1$ and $C_1 \gg C_2$. The output voltage V_t is given by (6.1), in which K , α and β are constants depending on the circuit parameters [1].

$$V_t = V_0 K (e^{-\alpha t} - e^{-\beta t}) \tag{6.1}$$

It will be noted that the equation represents the difference of two decaying exponentials. The standardized lightning impulse wave is included in Table 1.3 of Chapter 1.

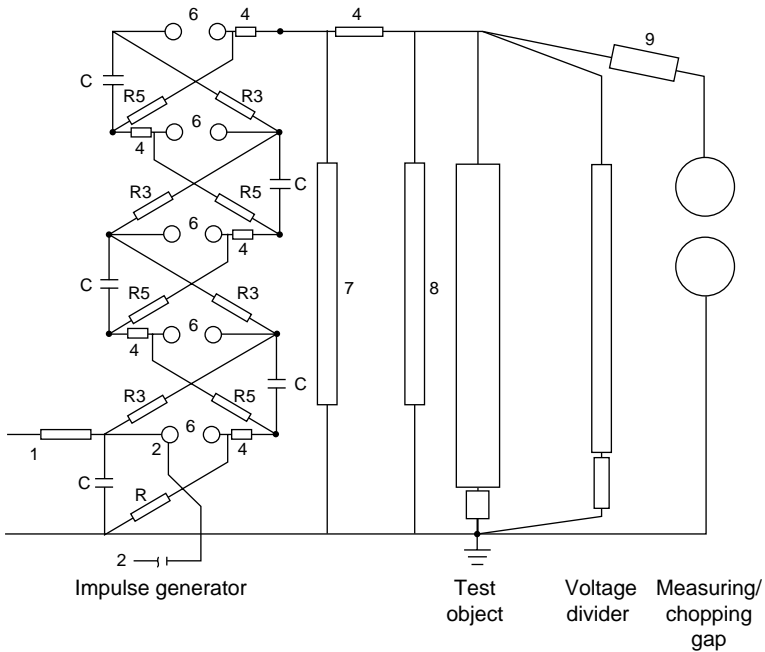


Figure 6.8 Four-stage impulse generator and associated test layout – modified Marx (Goodlet) circuit: (1) DC supply with variable input; (2) trigger electrode and input; (3) charging resistors; (4) front resistors; (5) tail resistors; (6) air gaps; (7) external tail resistor; (8) load capacitance; (9) protective resistor

In practice, multistage generators, as proposed by E. Marx in 1923, are necessary in order to achieve the very high voltages required from relatively low-voltage sources in the range ± 100 to ± 400 kV. The latter voltage tends to be the limit because of corona and clearance problems. For simplicity an impulse generator with only four stages is included in the test circuit in Figure 6.8. The four capacitors are charged in parallel and then discharged in series through the air gaps. The series connection is equivalent to C_1 in Figure 6.7. The physical configuration of the gaps and capacitors – together with the charging resistors – is such that the switching of all gaps can be effected within nanosecond times by triggering the first gap, the others being of equal dimensions but of slightly larger spacings. This occurs because gap overvoltages develop and are maintained for tens of ns by the stray capacitances to ground, between capacitors and across the gaps [1]. The operation of the gaps is facilitated if they are mounted in line of sight, allowing the lower gap discharge to irradiate those above.

In the original Marx circuit the lowest capacitor was not earthed, thus allowing one side of the first gap to be earthed. This simplified the later development of the triggering arrangements but resulted in a reversal in potential between input and output voltages. Subsequently it was suggested by B.L. Goodlet (JIEE, 1929) that one side

of the first-stage capacitor be earthed directly (not through a resistor), thus giving the same voltage polarities and, incidentally, reducing the generator height (Figure 6.8). Such a reduction may be of significant advantage in a small test area, where only three or four stages might be installed. Very high voltages of up to several million are available in a number of factories and laboratories worldwide [4]. This might be achieved, for example, by 28 stages with a charging voltage of ± 100 kV and capacitors of the order of tens of microfarads to give a maximum output of 2.4 MV at an efficiency of approximately 80 per cent. The capacitors may be in porcelain shells separated by similar spacers and stacked in columns or in metal cans mounted within the insulating framework. One scheme for distributing the front resistors and thereby reducing the voltage stresses across them is given in Figure 6.8. In addition, the tail resistors are more easily supported within the generator structure than externally. The use of distributed resistors is restrictive if frequent wave-shape changes are necessary, but this disadvantage is usually acceptable because of insulation requirements, clearance reasons and the limitation of the effects of internal oscillations. External components can be added if necessary.

In some applications the circuit is allowed to oscillate to produce higher voltages and/or a wave with specified oscillations. A series high-voltage inductor is connected in the output to create an oscillating lightning impulse (OLI) [1].

The circuit in Figure 6.8 includes the DC supply as described in Subsection 6.1.4. This must be suitable for polarity reversal by means of a built-in switching system. It is essential that an automatic earthing switch be provided at the supply terminal – direct voltages can lurk where not expected! The trigger electrode is fired by an external pulse, which also allows synchronism with the recording devices. The latter should comply with the requirements of IEC Publication 61083-1 [S6/4]. CROs and/or digital recorders monitor the output of the HV divider and other transducers if in use. The divider may be a resistive type with an HV arm of perhaps 10–20 kilohms. The lower arm must be correctly matched with the coaxial cable and input impedance of the recording instrument. Capacitance dividers of 100–1 000 pF are often used but allowance is necessary for possible distortion of the incoming signal due to the LV capacitance/coaxial cable surge impedance [1,2,4]. Many investigations have been carried out regarding the performance of dividers, especially with respect to their response to the high-frequency components of the impulse waves. No divider is a pure resistance or capacitance. Various compensating techniques including shielding and additional damping are used at the very high voltages to obtain the required accuracies. At UHV of several megavolts the tall columns and long connections may introduce additional errors in the measurements. Combined resistive and capacitive dividers are utilized under some conditions in order to obtain acceptable responses [1,4].

A sphere gap can be used for measurement or for ‘chopping’ the output wave at a predetermined time. Synchronization between the generator and main gap triggering is necessary – perhaps from less than $0.5 \mu\text{s}$ (front of wave testing) to tens of μs . Chopping times repeatable to within $0.1 \mu\text{s}$ or less may be required. For voltages above about 500 kV multiple chopping gaps are available giving more reliable firing than one large gap.

A major problem with impulse-voltage testing systems is the possibility of interference current pulses being induced, or flowing, in the earth circuits and measurement cables. The configuration indicated in Figure 6.8 assists in minimizing these effects. The latter are discussed in IEC 60060-2 [S6/2].

The objective of such test layouts is to limit the main discharge current of, perhaps, thousands of amps to a very low impedance path and to arrange the divider so its earth connections do not directly involve the high-current path. This configuration may not be successful in particular situations. Additional copper mats or thin copper foils of 10 cm width for earth connections – even with an under-floor system – may be helpful. Double screening of cables together with power isolation and good shielding of the control desk instrumentation is often essential. Experience related to the design and operation of a particular ultra-high-voltage laboratory is reviewed in Reference 4.

6.1.7 *Switching surge voltages*

For testing of the majority of purely ‘capacitive’-type equipment with standard switching surges as specified in Table 1.2 (Chapter 1), a conventional impulse generator may be used, with appropriate modification of the resistive components of the RC circuit. The slow front of 200 μs requires an increased value of the front resistor and/or an additional capacitance across the test object. Care must be taken to ensure that the energy ratings of the chosen resistors are sufficient to avoid failure by thermal overloading, which might result in flashover along their length.

An alternative method [S6/2] of producing a switching surge is to induce the required voltage in the high-voltage winding of a testing transformer, or a transformer to be tested, by application of an impulse to the low-voltage winding. For slow-impulse rise times the transferred voltage in a transformer is approximately that of the turns ratio.

A warning in the Standard is given that non-disruptive discharges can occur in the test object during switching surge applications and may result in appreciable wave-shape distortion. The effect can be very significant in pollution tests on external insulation at high voltages. If the source is of high impedance the desired disruptive discharge may not develop.

6.1.8 *High-voltage equipment for on-site testing*

On-site high-voltage tests are applied during the commissioning stage to ensure equipment is undamaged and correctly assembled when new and after locally completed repairs or invasive inspections.

Such HV tests are also required for various diagnostic procedures, in particular partial-discharge and dielectric-dissipation-factor measurements. Some of the site diagnostic requirements for individual items of equipment are discussed in Chapters 8 and 9.

All the sources considered in Sections 6.1.1–6.1.7 may be required on site. However, the normal laboratory/factory testing equipment is usually unsuitable for transportation, and special designs of portable systems are necessary. These may take



Figure 6.9 Example of high-voltage test vehicle (250 kV testing transformer and ancillary equipment) [photograph by Enerserve (Energy Australia)]

the form of custom-built vehicles containing, for example, HV testing transformers and standard capacitors (Figure 6.9), resonant test sets, generator and LV transformer for induced-voltage testing of power transformers, direct-voltage supplies for cable testing (excluding tests on extruded cables) and smaller units for separate source tests (50 Hz, VLF and hybrid supplies) for the lower-voltage systems of 11/33 kV.

It is noted that VLF techniques are used on site for withstand voltage testing of oil–paper and extruded cables and for rotating machines, thus reducing the high-value charging currents required by conventional non-resonant power sources. Voltage outputs are of the order of 50–120 kV, although systems of higher value have been described [13]. The choice of frequencies for site tests is considered in Reference 9.

Impulse generators of modular design are required for testing GIS and some transformers on site. It is possible almost to double the generator output by providing a series inductance between the generator and load and allowing damped oscillations to develop – both for lightning (OLI) and switching (OSI) surges. Frequency ranges for OLI and OSI voltages are suggested in Reference 8. In this report of CIGRE TF 33.03.04, recommendations are made as to how the Standard requirements of IEC Publications 60060-1 and 60060-2, 1994 [S6/2], might be modified to allow for on-site conditions. A number of references of developments are quoted in the article. The Standard specifying definitions and on-site testing requirements was issued in 2006 [S6/2]. The details in Table 6.1 are extracted from Reference 8 and are a guide as to the types of on-site tests that may be specified for different items of equipment. Clearly, an important factor in the design of on-site testing components is the need for greater mechanical strength than their counterparts in the laboratory and also increased awareness regarding safety aspects when setting up temporary test areas.

Table 6.1 Voltage types and sources used for site testing [8] [reproduced with permission of CIGRE]

| equipment to be tested on site | cables | | | GIS/GIL | instrument transformers | power transformers | rotating machines | substations |
|----------------------------------|-------------------|-----------------|------------------|---------|-------------------------|--------------------|-------------------|-------------|
| | oil paper cables | extruded cables | | | | | | |
| | | ll.v. | h.v. | | | | | |
| direct voltage (DC) | W | W ¹⁾ | | | | | W ¹⁾ | |
| very low frequency voltage (VLF) | W | W, DM | | | | | W | |
| alternating voltage (AC) | by ACTC | | | W, PE | W, PD | W, PE, DM | W, PD, DM | W |
| | by ACRL | W | W, PD, DM | W, PE | W, PD | W, PE, DM | W, PD, DM | W |
| | by ACRF | W | W, PD, DM | W, PE | W, PE | W, PE, DM | W, PD, DM | W |
| lightning impulse | aperiodic (IS) | | | W | | W | | |
| | oscillating (OSL) | | | W | | | | |
| switching impulse | aperiodic (IS) | | | W | | | | |
| | oscillating (OSI) | | PD ²⁾ | W | | | W | |

W – withstand voltage test
 PD – voltage test with PD measurement
 DM – voltage test with dielectric measurement (mainly tanδ)
 ACTC – transformer circuit for AC voltage generation
 ACRL – Inductance-tune resonant circuit for AC voltage generation
 ACRF – frequency tuned resonant circuit for AC voltage generation
 1) – applied in the past and no longer recommended
 2) – mainly for PD diagnostics

6.2 Non-destructive electrical measurements

The principles involved in the non-destructive electrical test methods for monitoring and proving the condition of insulating materials in sample form and in equipment are outlined below. The majority of these methods are called for in various Standard specifications. Also included in Section 6.2.4 are more recent, well-developed techniques, which are being applied to determine their viability, especially for assessing the condition of insulation on site.

6.2.1 Insulation resistance (IR) measurements

The method measures the resistance of a dielectric or insulation structure when a high-value direct voltage is applied. The commonest instrument is the Megger, which consists of a hand- or motor-driven DC generator (D) – up to 5 000 V – and a built-in moving coil instrument for measuring the ratio (‘resistance’) of the applied voltage and the current flowing. The principle is depicted in Figure 6.10, in which are shown the current coil (1) and voltage coil (2). The torques produced act in opposite senses such that the meter deflection is dependent on the ratio of voltage to current. The scale is non-uniform, being more open at the higher-resistance values where the current is small.

Although low-resistance paths in series with good insulation are not easily detectable and parallel-path effects cannot be eliminated within structures, this simple test has been developed by the industry as a valuable assessment tool for indicating insulation condition in many applications [14]. It does not correctly monitor the AC operating conditions.

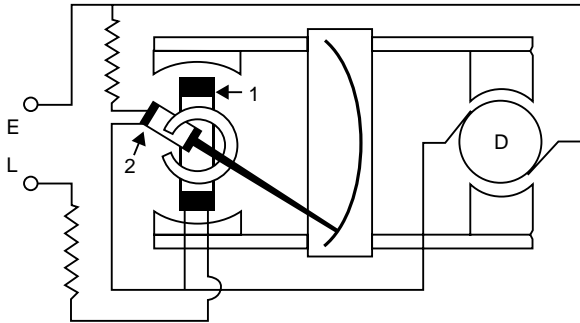


Figure 6.10 Principle of Megger circuit: *D* – generator; *1* – current coil; *2* – voltage coil

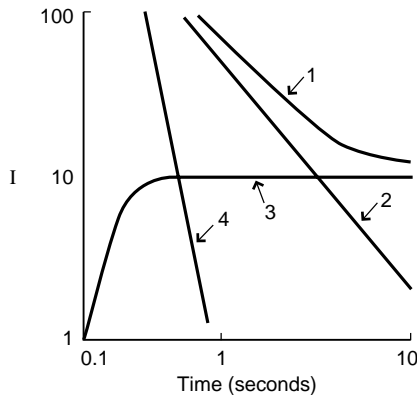


Figure 6.11 Hypothetical current - time curves during initial voltage application

A number of measurable resistance parameters based on the variation in current following application of the voltage may be interpreted as representing significant changes in the insulation condition. The total current (1) may be considered as comprising three components – the absorption current (2), the conduction ('leakage') current (3) and the capacitance-charging current (4), as shown in Figure 6.11.

The tests that might be applied can be defined as follows.

6.2.1.1 Short-time test

The short-time test is usually applied for 60 seconds and represents one point on a curve of increasing 'resistance', only giving an indication of the insulation condition (capacitance charging effect).

6.2.1.2 Time-resistance test

For good insulation free of moisture and dirt, the resistance value would be expected to increase with time until reaching a final steady (IR) value. The time-resistance test

is carried out for a period of 10 minutes or more. This also allows determination of the dielectric absorption ratio (60-second value divided by 30-second value) and the polarization index (10-minute value divided by the 1-minute value).

A satisfactory dielectric is one in which the dielectric absorption ratio is greater than 1.4 – 1.5 and Polarization Index is greater than 2.0. Corresponding values for doubtful insulating materials are of the order of 1.0 or less.

6.2.1.3 Step-voltage test

In the step-voltage test measurements are made at two voltage levels, preferably in a ratio of 1:5. If the IR value at the higher voltage is less than 75 per cent of that at the lower voltage, then the insulation is suspect. The test may be considered significant for times as short as 60 seconds, even though the absorption current may not be zero.

6.2.2 Measurements of the dielectric dissipation factor (DDF)

The measurement of the dielectric dissipation factor (formerly described as the ‘loss tangent’ or ‘dielectric loss angle’ – DLA) is well established as the primary test for diagnosing possible degradation and deterioration of equipment insulation – in the factory, laboratory and, in some cases, on site. The technique gives a measure of the bulk losses produced under AC conditions. It also enables changes in capacitance to be recorded and can be applied at operating and test voltages if an appropriate supply and standard capacitor is available.

6.2.2.1 HV Schering Bridge

Traditionally, in the majority of high-voltage laboratories and, for example, in bushing and cable factories, the Schering Bridge (devised by H. Schering in 1919) has been used for measurement of DDF. The basic circuit is given in Figure 6.12 and consists of two RC arms with a sensitive electronic detector, the latter type replacing the much earlier vibrating galvanometer tuned to the test frequency. Derivation of the balance equation [1,2] assumes that C_X (the component under test) has an equivalent series loss element and that the standard capacitor C_N is loss-free. Equivalent circuits and corrections for high-loss angles ($>3 \times 10^{-2}$) are considered by Schwab [2] and Zaengl [1]. For the low-loss case the unknown capacitance

$$C_X = C_N \cdot R_4/R_3 \quad (6.2)$$

and the DDF

$$\tan \delta = \omega C_4 R_4 \quad (6.3)$$

The DDF values for the more traditional insulating materials are in the range down to 0.001–0.003 and are measurable by a normal Schering Bridge. However, this may not be the case for the newer materials, such as XLPE and polypropylene film, which have DDF values <0.001 (see Reference 1, Chapter 2). Such sensitivities may be achievable under good conditions in the high-voltage laboratory. This assumes no corona, and probably requires double screening, including an inter-winding shield in

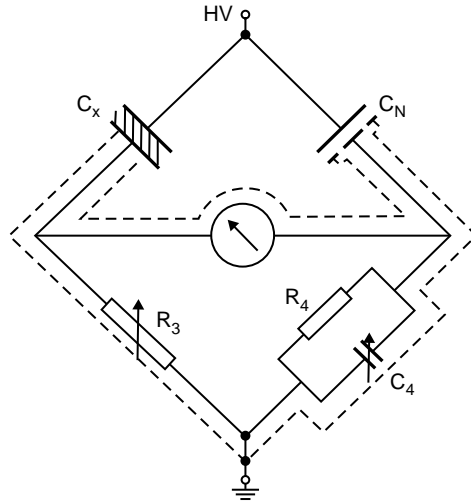


Figure 6.12 Principle of the high-voltage Schering Bridge

the testing transformer, careful screening of the low-voltage components and cables, as well as efficient earthing. For detailed discussions consult References 1 and 2.

6.2.2.2 Transformer ratio-arm bridge

For thirty years or more commercial transformer ratio-arm bridges have been available for measuring the DDF of insulation. These instruments are more sensitive, easier to screen against stray effects and more suitable for use on site than the HV Schering Bridge. Automated versions are offered for applications where many measurements are to be made, e.g. for oil testing. A circuit diagram of the principle of the bridge is given in Figure 6.13.

The main part of the bridge is a three-winding transformer or comparator. This has very low losses and leakage (high-permeability core) and is well shielded from stray magnetic fields. A major advantage is that no net mmf exists across windings W1 and W2 at balance. Also, it is unnecessary to allow for the stray capacitances of the low-voltage leads and those of the windings as no voltage appears across them – thus allowing the use of long leads [1]. As with the Schering Bridge a high-voltage standard capacitor C_N is required.

Allowance may be made for testing earthed and unearthed equipment. In the former case it must be possible to ‘float’ the lower end of the supply transformer. For the grounded condition two measurements are required – one with the test object disconnected (i.e. measurement of the stray capacitance to earth, C'_X) and the other with C'_X and arm C_X/R_X in parallel. The balance condition is achieved by varying the turns ratio of windings 1 (N_1 turns) and 2 (N_2 turns) to give zero output. At ampere-turn balance, $I_1N_1 = I_2N_2$, by adjusting R and C allowance can be made for the phase

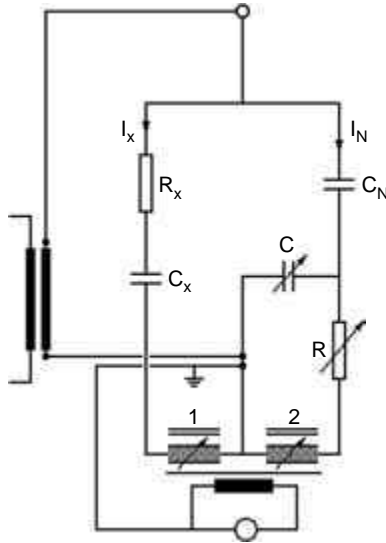


Figure 6.13 Transformer ratio-arm bridge for unearthed test object

shift in I_X due to the losses in the test object C_X . The latter is represented as a series circuit of R_X and C_X .

At balance with an ungrounded test object the values of C_X and $\tan \delta$ may be derived. The equations for determining the magnitudes of the relevant currents, neglecting the impedances of 1 and 2 and assuming an applied voltage of V , are as follows.

$$I_N = V j\omega C_N (1 + j\omega CR) / \{1 + j\omega(C + C_N)R\} \quad (\text{i})$$

By division in parallel paths:

$$I_2 = I_N / (1 + j\omega CR) = V j\omega C_N / \{1 + j\omega(C + C_N)R\} \quad (\text{ii})$$

$$I_1 = V j\omega C_X / (1 + j\omega C_X R_X) \quad (\text{iii})$$

$$\text{At balance } I_1 N_1 = I_2 N_2 \quad (\text{iv})$$

From equations (ii), (iii) and (iv) and by equating real and imaginary parts:

$$C_X = C_N N_2 / N_1 \quad (6.4)$$

$$\tan \delta = \omega R (C + C_N) \quad (6.5)$$

Because of the very low impedance of the windings it is possible to make measurements with a significant capacitance across winding 1. A value of 2000 pF is allowable in a particular test set. If this is unspecified, appropriate checks should be made, for example when measuring via the DDF tap of a bushing.

The standard capacitor, C_N , is usually a gas type (e.g. SF₆), having insignificant losses at full voltage and probably a capacitance of 100 pF. These units are very

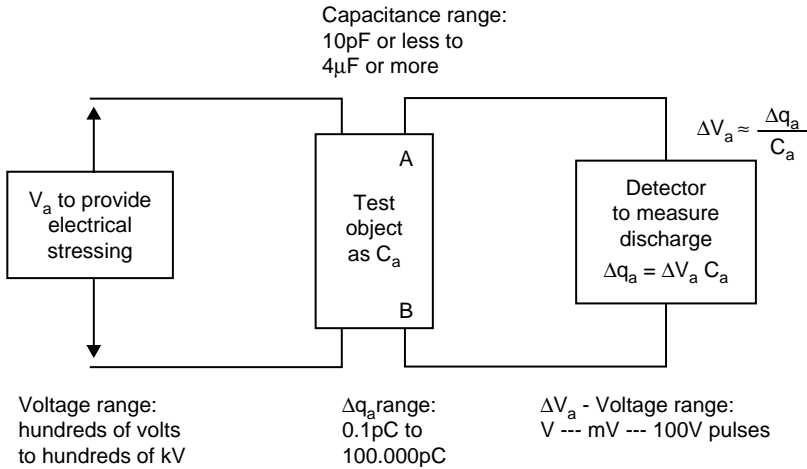


Figure 6.14 Block diagram showing PD measurement requirements

expensive. For conditions with an earthed test object, reference should be made to the manufacturer’s instruction manual.

6.2.3 Measurement of partial discharges by electrical methods

The partial-discharge measurement requirements are indicated in the block diagram shown in Figure 6.14. For simplicity, it is assumed that the apparent charge pulse magnitude is the parameter to be measured. The high voltage, V_a , is applied to the test object represented by an ideal capacitance, C_a . Partial discharges created by the stressing due to V_a will appear across the terminals AB as a small pulse voltage ΔV_a . The range of pulse voltages to be measured may be estimated approximately using the simple relationship (neglecting any parallel capacitance),

$$\Delta V_a = \Delta q_a / C_a \tag{6.6}$$

where Δq_a represents the discharge magnitude (0.1 pC up to 100 000 pC) expected in the tested equipment, the latter perhaps having capacitances in the range of 10 pF (cap and pin insulators) to tens of microfarads or larger in generators, power capacitors and cables. The pulses to be measured have rise times ranging from ns to several μ s depending on the particular insulation structure.

The values of pulse voltages (ΔV_a) for a range of magnitudes for $C_a = 100$ pF and an inception voltage of $V_a = 10$ kV (RMS) are given in Table 6.2. The equivalent energy levels are also included. It should be noted that C_a represents the total effective capacitance across A and B.

It is clear that a large-ratio voltage divider is needed at the detector input if high test voltages are to be applied. Using a simple divider would produce an unacceptable loss in sensitivity due to attenuation of the small pulses. Fortunately, the applied voltage and the pulses to be measured have widely different frequency spectra – 0/50/300 Hz

Table 6.2 Ideal PD energy levels and pulse voltages for applied inception voltage of 10 kV (RMS)

| For Δq_a | C_a | V_a (rms) | w (Joules) | ΔV_a |
|------------------|--------|-------------|----------------------|--------------|
| 1 pC | 100 pF | 10 kV | 0.7×10^{-8} | 0.01 V |
| 100 pC | 100 pF | 10 kV | 0.7×10^{-6} | 1 V |
| 10,000 pC | 100 pF | 10 kV | 0.7×10^{-4} | 100 V |

compared with hundreds of kHz up to several hundred MHz. By use of a high-voltage coupling capacitor this frequency difference enables a low-impedance path for the pulses to be retained between the terminals AB and the detector. At the same time it provides a high-ratio divider for reduction of the applied voltage by the addition of a high-pass filter at the detector input.

The form of the detector varies according to the parameter to be measured and many papers on the subject have been published. Probably the more important techniques can be grouped as follows:

- (a) measurement of individual apparent discharge magnitude using a resistance or tuned circuit input;
- (b) use of radio interference voltage (RIV) techniques with resistive input giving an 'integrated charge' value as a meter reading;
- (c) measurement of a quadratic mean, the meter response being proportional to the integral of the squares of the discharge magnitudes;
- (d) measurement of losses due to multiple-discharge sites (e.g. dielectric loss analyser).

Of these methods the first is probably the most widely used and accepted as a standard test; higher sensitivity is achieved using a tuned circuit input, because, among other advantages, the 50 Hz component can be reduced to a lower level. This technique and its application to practical cases will be described. Various commercial systems are now available but these differ only in their versatility and sensitivity of detection. The circuit developed by G. Mole of the ERA [28] will be used as the basis for the present discussion, but many of the concepts have been used by other investigators. Much of the review by Mason published in 1965 is still of relevance and includes a number of earlier references. The use of RIV measurements may be retained for some cases but it is clear that gross errors can arise and the readings may have little quantitative value as PD measurements. More advanced PD techniques developed for particular conditions are described in later chapters. These methods are not included in the revised version of IEC 60270 [S6/5]. The IEC has commenced (2006) the preparation of a new Standard covering unconventional partial-discharge measurements including UHF and acoustic techniques [S6/12].

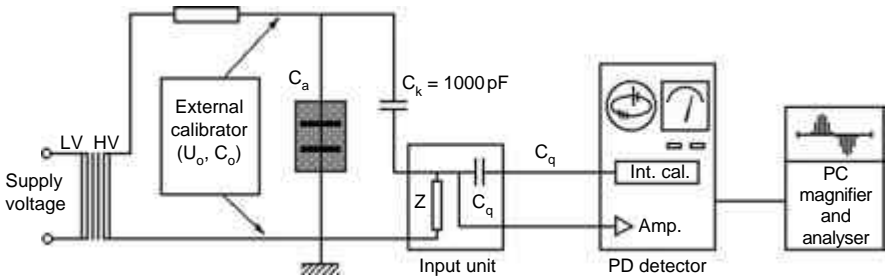


Figure 6.15 Basic partial-discharge detection circuit

6.2.3.1 Basic test circuit

The basic circuit is shown in Figure 6.15 and assumes a simple capacitive load (test object) with a coupling capacitance, C_k , for connection to the impedance-forming part of the high-pass filter and tuned circuit into the detector. In some cases the detecting impedance may be mounted at the high-voltage terminal of C_k and coupled to the detector through an optical link. The detecting impedance may be located in series with the load under some conditions but this is not desirable with low-capacitance samples as stray effects can be significant and it is impossible in some other cases because the bottom end of the equipment is permanently earthed.

The order of measurement frequencies of such general-purpose instruments is for narrow-band types possibly of $500 \text{ kHz} \pm 4 \text{ kHz}$, and for wide-band systems $15\text{--}300 \text{ kHz}$ with capabilities of measuring moderate-magnitude discharges in very large capacitances (up to $250 \mu\text{F}$). A resolution of 135 discharges per 5 ms is achievable in a particular equipment [15]. The use of oscillographic recording is essential for assistance in interpretation, even in commercial instruments used for industrial routine work. Detailed variations of the basic circuits may be ascertained from the literature, including the application of computer-based systems for monitoring and analysing the outputs of the analogue detection circuits. One of the first commercially available computerized systems was designed as an add-on to existing detectors and is depicted in Figure 6.16 [16].

6.2.3.2 Calibration procedures

In the earliest detection systems it was necessary to include a calibration method in order to attempt to quantify the parameter being measured – the apparent partial charge – for a range of different conditions. Initially the concept of an internal calibrator was introduced as indicated in Figure 6.15. In this arrangement a known step voltage pulse (in the range mV to 100 V), e_q , with a rise time $< 60 \text{ ns}$ is injected through a small capacitor C_q and its response compared with that due to a live partial discharge from the equipment under test (C_a). It may be shown that for an idealized capacitive circuit (Figure 6.17(a)) the apparent change in charge should be

$$\Delta q_a = e_q C_q (1 + C_a / C_k) = e_q C_q \text{ if } C_k \gg C_a \quad (6.7)$$

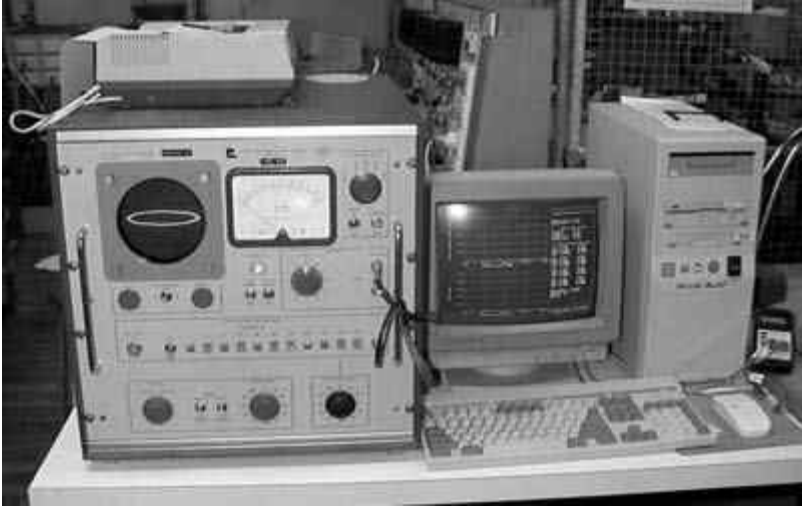


Figure 6.16 Earlier partial-discharge detector with computer-based recording and analysis system[16] [picture by University of NSW]

However during the earlier tests on large power equipment doubts arose about the possible errors produced by a variety of factors, including the influence of sample size, stray capacitance and, especially, the complex effects produced by the interaction of the frequency characteristics of the test object and the measuring system. The problem became particularly acute when testing large transformers in the 1950s. This resulted in the application of the technique of direct calibration as standardized in IEC 60270. The magnitudes of possible error are considered in References 17 and 18. For the case of the simple capacitive network and a reference pulse e_q (Figures 6.15 and 6.17(b)), a low-value capacitor, C_0 , is connected at the test object terminal and a step voltage pulse, U_0 , of rise time <60 ns injected.

For the direct calibration condition (Figure 6.17(b)) the apparent measured discharge with C_0 in circuit is

$$q_0 = U_0 C_0 = e_0 C_q (1 + (C_a + C_0)/C_k) \quad (6.8)$$

If $C_0/C_a \ll 1$ (≤ 0.1 is specified in IEC 60270)

$$q_0 \approx e_0 C_q (1 + C_a/C_k) \text{ or } q_0 \approx k e_0 \text{ or } k = q_0/e_0 \quad (6.9)$$

Thus, for the high-voltage test $\Delta q_a = k e_q$, where e_q is the detector reading and k is the scale factor. In practice k is more complex and simply represents the factor by which the instrument reading must be multiplied to determine the live apparent PD magnitude, Δq_a . The simple capacitive network indicates that for $C_k \gg C_a$ the value of k is small and therefore the sensitivity of detection increases. C_0 must be removed for the high-voltage tests if not rated for the full voltage, as is usually the case. During such calibrations, which should be carried out for each load or circuit change, it is

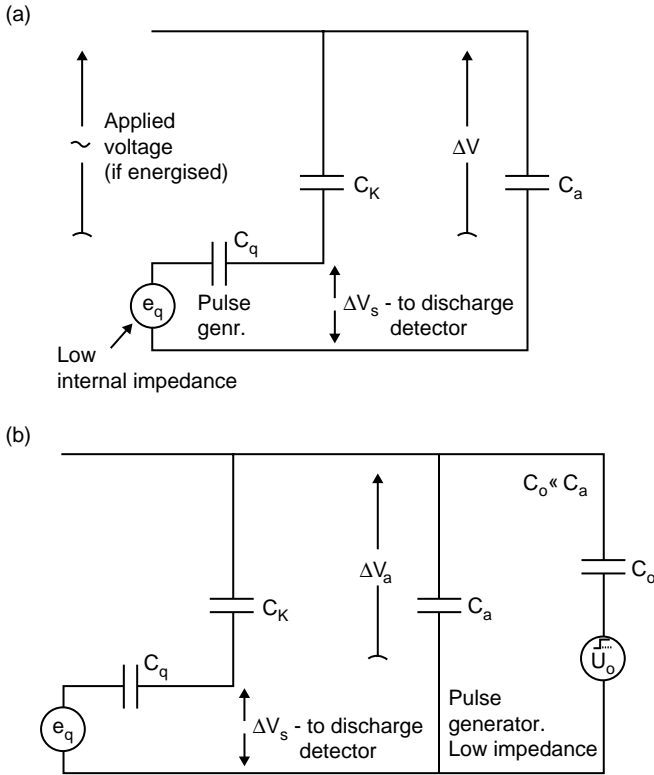


Figure 6.17 Calibration of idealized capacitive circuits: (a) indirect (reference) calibrator; (b) direct calibrator

essential that the connection between the calibrator capacitor C_0 and the test object be short and that the lead from the pulse generator to the capacitor be screened and correctly matched. This requirement may introduce difficulties when testing large (tall) components such as transformers, switchgear and bushings but is necessary in order to obtain, as far as practicable, accurate and repeatable measurements under adverse conditions. The external calibrator is usually battery-driven and should be capable of calibrating the system for the expected high-voltage test PD values. Fixed magnitudes of 5 pC, 10 pC, 100 pC and possibly 500 pC for transformer testing may be appropriate. The requirement that $C_0/C_a \leq 0.1$ must be met.

The configuration in Figure 6.16 allows immediate response to changes in PD levels during high-voltage tests by adjusting the amplifier gain and internal calibrator settings, thereby retaining the original calibration. Linearity over the expected range should be checked using an external calibrator. The alternative procedure (circuit) is to determine the amplifier output in terms of pC/mm, pC/volt or a pC meter during the calibration and maintain a fixed gain for the high-voltage test. It is possible to

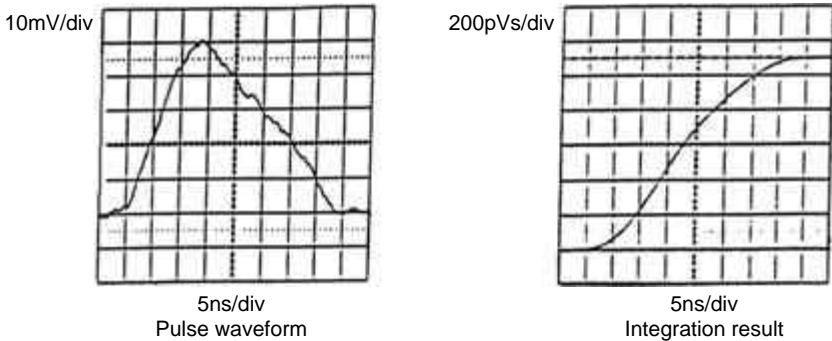


Figure 6.18 Example of calibrator check by integration method

use fixed attenuation ratios e.g. $\times 1$, $\times 10$, $\times 100$. In this system there is no direct comparison between the live discharge and the internal reference (e.g. e_q).

If a digital measuring system is in use the calibrator must be capable of producing pulses of adjustable repetition rate up to limits imposed by the resolution time of the system. Also the calibrator must be able to generate pulses at, say, 100 Hz for a specified time period in order to check that the digital instrument will record an equal number – a deviation of ± 2 per cent is allowed in IEC 60270. The latter contains an ‘informative’ Annex (E) giving guidelines for digital acquisition of the analogue partial discharge signals. A comprehensive review of the various problems and requirements is presented in Reference 19.

Calibration of the calibrator is essential in order to ensure acceptable accuracy during equipment tests. In Annex A of IEC 60270 it is specified that the charge shall be compared with a reference calibrator traceable to national standards. The comparison may be made with a PD measurement system or a digital oscilloscope with integration capabilities. A typical response is depicted in Figure 6.18 for a calibrator with $C_0 = 1$ pF, voltage 20 V and loading resistor 50Ω . In this case there is good correspondence between the pC magnitude of the pulse injected, the area of the measured pulse (approximately) and the integrated value indicated by the digital oscilloscope.

For some years development has taken place in the application of inbuilt capacitor probes for measurement of PDs in GIS equipment. The technique has been validated in an *Electra* report [20] and is included as a calibration method in IEC 60270. See Chapter 9.

A simple method for determining the apparent measurement circuit sensitivity under live conditions is to connect across the test object a very low-capacitance PD source. Various techniques are applied including the temporary connection of a thin wire ‘spike’ at the HV terminal. As suggested by Kreuger [17] consistent discrete discharges at low-voltage can be obtained with a simple configuration of a needle mounted with its tip located at the centre of an earthed hollow hemispherical electrode of 25 mm internal radius. Discharge magnitudes of 20 pC or so at 1.7 kV can be achieved, depending on the point radius. Pulses of magnitudes of 25 to 250 pC

for different point radii for a voltage of about 3 kV are quoted. This arrangement has been of value in making comparisons between different systems. PDs induced with thin wire or sharp points also allow confirmation of the position of the negative peak of the power frequency waves on the instrumentation display.

6.2.3.3 Reduction of interference

The reduction of interference occurring at the line terminal of a test object or plant item during a PD test can sometimes be minimized by use of a balanced circuit or a polarity discrimination circuit. Both configurations are included in IEC 60270 and are available commercially. The conventional ERA detector depicted in Figure 6.16 is designed to operate from a centre-tapped transformer with dual inputs suitable for connection in a balanced circuit and is capable of effecting rejection ratios of 30 to 100. Another well-established equipment developed by Kreuger and used for many years has two separate adjustable impedances allowing rejection ratios of up to 1 000 under favourable conditions [17]. The discrimination circuit developed by Black [21] recognises the polarity of the pulses at the detecting impedance. If those occurring simultaneously are of identical polarity they are rejected. These instruments have been applied in switch-yards up to 300 kV. An earlier CIGRE publication [22] may be of assistance in understanding some of the interference problems associated with PD detection. More advanced techniques and recent developments for eliminating or reducing interference are discussed in Chapter 9.

6.2.3.4 Presentation of PD measurements

In the earlier detectors – for example as developed by Mole and later by Kreuger – a visual oscillographic display was incorporated to allow observation and measurement of the amplifier output and for determining the approximate time of occurrence within the power-frequency cycle. Additionally a meter reading of the largest pulse was included.

This relatively simple concept and effective system – with some minor changes – has been the industry norm for 50 years. However, in the 1960s minicomputers made it possible to record and analyse data [23] that, previously, were recordable only by bulky PHA systems or directly from the oscilloscope screen.

The new systems became more practical following development of microcomputers until, in the 1980s, the new PCs resulted in an upsurge of portable computer-based systems in the 1990s. The latter instrumentation allows complex analyses to be carried out although the greatest value is probably the ease with which trending of changes in maximum and average charge, repetition rates and pulse-power variations can be recorded during a test and for future reference. Many attempts at relating the measurable PD characteristics to the conditions within particular insulation systems – as in the past [24] – have been made [25,26] but it is not clear that this can be achieved for all circumstances [27]. This reference also supports the view that for oil-impregnated materials the magnitude, phase relationships and repetition rates of the PDs may be more significant than the more complex parameters that can be calculated from the basic data. An example of a computer record for a discharging source is given in

Figure 2.13. CIGRE Brochure 226 [26] presents the probable response for a wide range of conditions involving partial discharges in samples and equipment. Interestingly, a number of faults in substations have been identified by excessive interference on portable telephones.

6.2.4 Dielectric response measurements

The application of polarization/depolarization measurements for assessing the quality of insulating materials is a relatively simple procedure but analysis of the data is very complex. In the following an indication is given of the time and frequency domain methods currently available. Details of the various analyses relating measurements to moisture content, ageing and possible contamination will be found in the references. A number of significant parameters can be measured at well below operating values. One of the earliest instruments was that developed by Mole [28] at the ERA in the early 1950s. The *dispersion meter* was used for many years for indicating the moisture levels in oil–paper systems, especially transformers. The advances in technology and interpretation of dielectric theory have allowed the development of improved methods.

Possibilities for time- and frequency-domain measurement have been investigated in detail during the past ten years and a number of instruments and experimental systems developed. Many tests are being carried out on equipment with oil-impregnated insulation structures, some on XLPE cables and a few on surge arresters associated with HV proving tests [29]. A review of the theory and background of dielectric response measurements is given by Zaengl [30], including 103 references. The particular case for transformers is considered in a report by CIGRE TF 15.01.09 [31].

In the following are outlined the parameters involved and the principles of measurement. The various instruments and special test procedures are not described, as the newer techniques are being trialled and assessed with respect to their value for monitoring particular apparatus.

6.2.4.1 Time-domain measurements

Low-value direct voltages are applied to the test object for a specified time t_c followed by a chosen short circuit period before isolating the sample. Depending on the test procedure it is possible to measure the voltage or currents as indicated in Figure 6.19. Many on-site tests have been carried out attempting to relate these variations to the insulation condition of oil–paper transformers, current transformers and cables (oil–paper and XLPE) using experimental methods and commercially available instruments. The techniques are not universally accepted and caution in interpretation of results is necessary, especially for transformers containing oil gaps in series with the cellulosic insulations [31].

An advantage of the procedures is that for known conditions significant data can be obtained for low electric stresses on completed equipment. The tests are applied offline and are very lengthy, and care must be taken to minimise interference, as the quantities being measured are small.

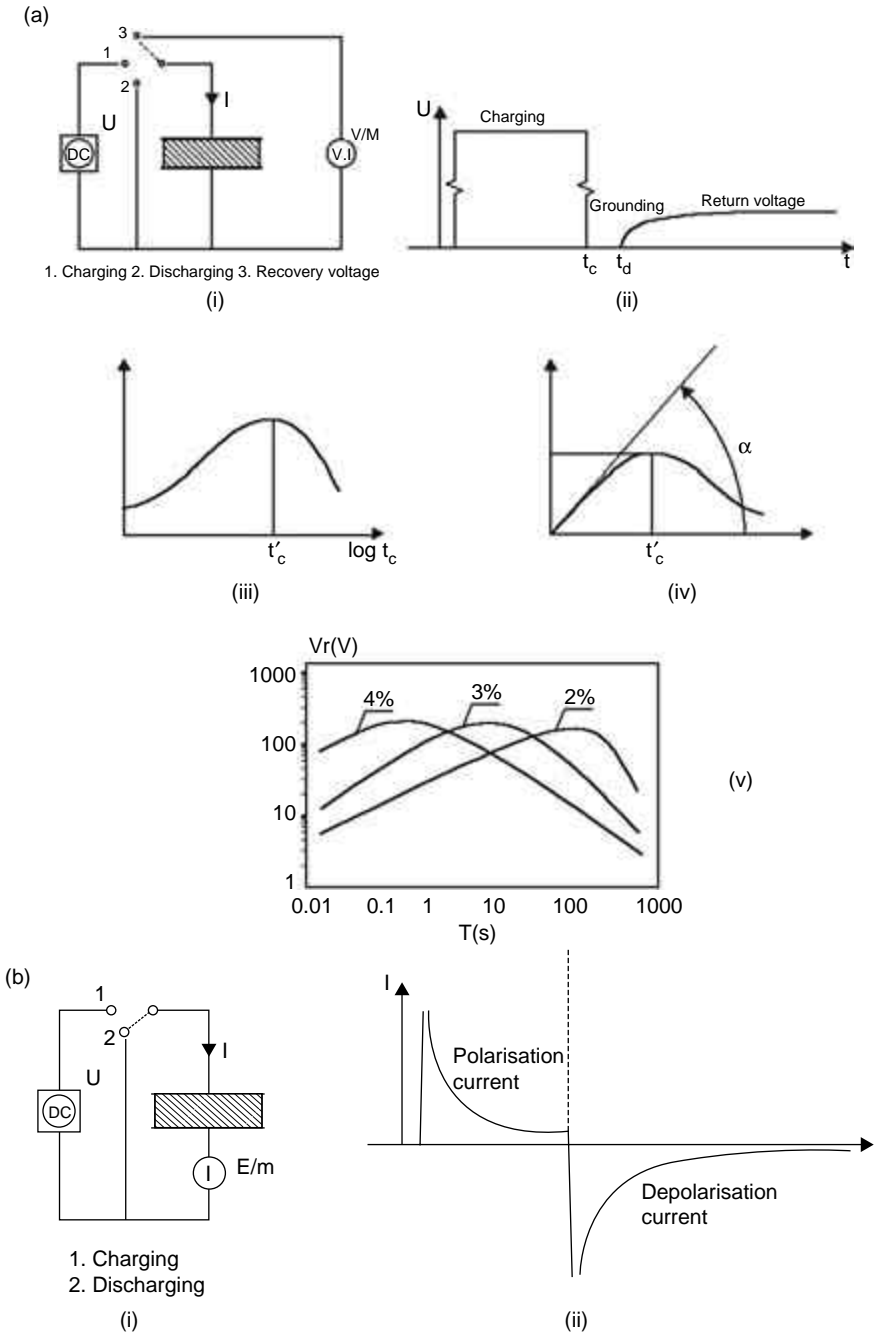


Figure 6.19 Time-domain measurements. (a) Recovery voltage measurements (RVM): (i) Circuit; (ii) Voltages; (iii) V_m values for range of charging times t_c ; (iv) Value of V_m at t'_c . Slope α of recovery voltage for t'_c ; (v) Possible variation of characteristics with apparent moisture content in oil-impregnated paper. (b) Polarization and depolarization currents and voltages (PDC): (i) Circuit; (ii) Currents

(a) Recovery (return) voltage measurement (RVM)

In the RVM mode, Figure 6.19 (a, i and ii), a DC charging voltage is applied for time t_c , then usually short-circuited for time $t_c/2$, followed by a recording of the recovery voltage for a predetermined time. The parameters that may be related to the moisture content are the maximum recovery voltage, V_m , the time of occurrence of V_m and the slope α of the initial voltage rise. In a particular instrument this procedure is repeated for many values of t_c and the critical value of t_c (t'_c) determined for the maximum recovery voltage V'_m , together with the slope α' at the value of t'_c (Figure 6.19 (a, iii–v)). The range of charging times is from 0.02 seconds to 10,000 seconds. The results are described as a ‘polarization spectra’ [32].

Experimental tests indicated that a relationship exists between the measured and deduced parameters and the moisture content in oil-impregnated paper/pressboard. However, various investigations have shown that for transformers this assumption may introduce errors in the moisture estimates because of the difference between the conductivities and dielectric constants of the oil within the ducts and those of the impregnated paper/pressboard solids. Also, the physical structure can give incorrect estimates.

In its original form the RVM technique has been applied to cables [30, Part 2]. This is especially the case for XLPE systems, where high-voltage direct voltage testing is not allowed because of possible damage to the insulation. The aim of the RVM is to detect the presence of water trees before the formation of tracking. In the case of shorter lengths of these high-resistivity cables it may be necessary to reduce the load resistance across the measurement device by use of parallel resistors of the order of tens of $G\Omega$. Another possible problem when comparing cable results is the influence of the cable length on the time constants. It has been suggested that charging at different voltages may give significant information as to the presence of water trees.

(b) Polarization and depolarization current (PDC) measurements

In this method (PDC) a step voltage of perhaps 1 000 volts is applied to the test object for possibly 10 000 seconds followed by a short-circuit within a short time interval. The polarization and depolarization currents are recorded by an electrometer as indicated in Figure 6.19(b). The procedure enables estimates to be made of the condition (moisture and ageing) of two dielectrics with different conductivities and dielectric constants. An analysis is presented in Reference 33 and more general observations in the CIGRE TF 15.01.09 report [31].

(c) Isothermal relaxation current measurements (IRC)

Another recently developed assessment method is the isothermal relaxation current measurements (IRC) mostly for polymer cables. The IRC method determines the changes of the polarization processes inside the insulation. The cable is normally charged to a DC voltage of 10 per cent or possibly higher of the operating voltage. The voltage is then removed and the cable short circuited for five seconds, followed by measurement of the depolarization current decrease with time, which may last for thirty minutes. The product of the instantaneous current and time can be an indication

of the number of voids involved and the ageing stage of the insulation, but care in interpretation is essential [30]. A form of this method is being applied commercially.

6.2.4.2 Dielectric frequency domain spectroscopy measurements (FDS)

A number of investigations have been completed in order to determine whether capacitance and loss changes over a range of frequencies (e.g. 0.0001–1 000 Hz) might indicate the presence of moisture in transformers and also in XLPE cables. It is possible this technique may be applicable to AC cables at moderately high stresses. An application of the technique is given in Reference 34, where a frequency range of 0.1 to 10 Hz was used up to 30 kVpk.

6.3 Physical and chemical diagnostic methods

There are many non-electrical techniques for determination of the condition of the insulating materials used in power equipment. The predominant application is for oil and cellulosic materials, although new techniques are being developed for assessing the state of, for example, composite insulators, the by-products of SF₆ decomposition and aged XLPE cables. A major restriction to application of the methods is the lack of access to the materials when built into equipment. Samples of oil in the case of oil-filled transformers, switchgear, cables, bushings and of gas from GI equipment may be obtained without harmful effects. However, the removal of solid insulation is normally impossible because of resulting damage to the insulation structure of the apparatus.

6.3.1 Indicators of in-service condition of oil–paper systems

In-service indicators of the condition of the oil-impregnated materials within transformers, tap changers, bushings and cables include the levels of concentration of moisture, gas, furans and particles in the oil as well as its overall quality. During refurbishment of power transformers it may be possible to remove paper/pressboard samples from non-critical locations for determination of their moisture content and degree of polymerization.

6.3.1.1 Moisture content in oil-impregnated systems

A significant factor in the operation of oil-impregnated paper systems is the need to maintain low moisture contents. The simplest technique is to monitor oil samples by means of the well-established Karl Fischer method (IEC 60814, S6/6). This publication includes tests for oil-impregnated paper and pressboard. Care must be taken when removing the required oil samples. The oil temperature at the time of removal should be noted, together with the type of oil-cooling system if operative. Preferred techniques are described in IEC publications 60475 [S6/7] and IEC 60567 [S6/8].

The oil-impregnated cellulosic material moisture levels are estimated from the oil values as indicated in Figure 6.20. These equilibrium curves were developed by Oommen in 1983. A good review of the variables and history of the derivation of

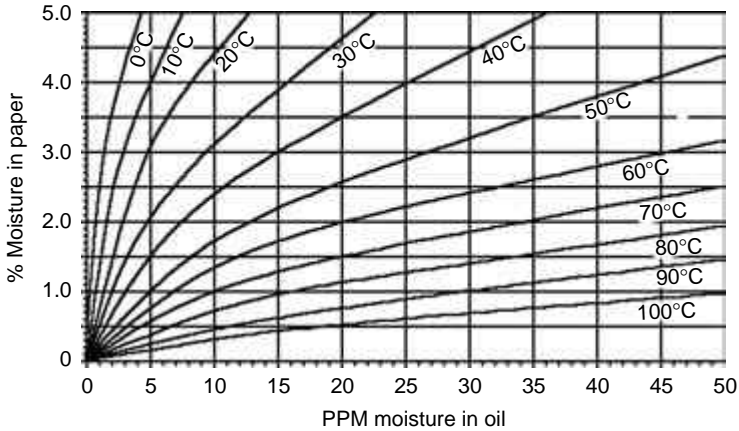


Figure 6.20 Oil–paper moisture equilibrium curves (after Oommen) [35] [reproduced by permission of the IEEE]

relationships used by the industry, including the original research by Fabre and Pichon (1960), are presented in reference [35]. Moisture contents are much less than 1 per cent at operating temperatures for new transformers through to 2–3 per cent for a well-maintained unit (with silica breather) and perhaps 4–5 per cent after thirty years of service. The last value can lead to rapid ageing and possible failure.

If the moisture in the paper and oil are not in equilibrium and not at the same temperature, errors in the estimate will arise but in practice the technique is found to be valuable.

Direct measurement (IEC 60814, S6/6) of paper/pressboard samples from failed units – e.g. current transformers – are often carried out during ‘postmortem’ investigations and refurbishments. As with oil samples, care must be taken during removal and records made of the length of time of exposure to air (and its humidity), the unit history and the precise location within the structure.

6.3.1.2 Dissolved gas in oil measurements

DGA is probably the prime online monitoring technique for detection of developing faults in power transformers and has been applied for more than thirty years. The gases considered to be of significance are hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO) and carbon dioxide (CO_2). Values vary from a few ppm to hundreds for the hydrocarbons and from several hundreds to thousands for the carbon monoxide/carbon dioxides. These levels are measured in the laboratory – or possibly within a mobile unit – using gas chromatographs manufactured for this specific function. The procedures are recommended in IEC 60567 [S6/8]. In order to obtain reliable and repeatable results, it is essential that the oil sampling be carried out according to a prescribed protocol [S6/8]

but related to the particular equipment design: power transformers, tap changers, bushings, instrument transformers or cables.

A number of online monitoring devices are available, in particular for detecting changes in the hydrogen levels in power transformers (Chapter 9).

Over the years various methods of interpretation have been proposed for identifying faults in the insulation structure – in particular the ratio system, one form of which is presented in IEC Publication 60599 [S6/9]. The coded list of faults related to particular practical situations is discussed by Duval and dePablo in Reference 36 and extended in 37. The databases and analyses are based on extensive studies by IEC TC10 and CIGRE Task Forces of SC 15. This work was continued to cover cases for which existing criteria may give an unsatisfactory interpretation. References 38 and 39 include extracts covering 179 cases where faults were identified by inspection and related to the gas levels. Also tabulated are ‘normal’ values for gases to be expected in satisfactory power and instrument transformers. It appears that the magnitudes are considerably higher than those allowed by many utilities before additional monitoring is required. Although there are some difficulties in interpretation, the technique gives a good indication of possible problems, especially if applied periodically as a trend measurement based on the experience of the particular authority. Examples from one source are presented in Chapter 9 and an advanced form of dissolved-gas analysis utilizing fuzzy-logic methods described in Chapter 10.

6.3.1.3 Furan measurements

The technique utilizing high-performance liquid chromatography for detecting furans in insulating oils is well established and is being applied by many utilities and manufacturers worldwide. The level of concentrations of different forms of furans has been shown to be indicative of the deterioration of cellulose at normal operating temperatures and may be related to anticipated life under certain conditions. The concentrations of significance are of the order of 0.05 mg/L (\approx ppm) through to 5 mg/L (\approx ppm) or higher for badly degraded insulation [38,39].

6.3.1.4 Particle counts

The concentration of different types and dimensions of particles in oil can be quantified by use of such procedures as those specified in Standard S6/10 (see under Section 6.6 below).

6.3.1.5 Oil quality

Many tests are specified for ensuring insulating oils are of the quality required. A number of Standards within the IEC describe the requirements and test methods, in particular IEC 60296 [S6/11] and associated publications. The methods covered include:

- breakdown tests
- oxidation determination
- permittivity, DDF and resistivity measurements

- sampling methods
- water determination

ISO Standards include determination of

- viscosity
- flash point
- pour point

In transformer practice the more important characteristics as indicators of oil deterioration are often considered to be acidity, DDF and interfacial tension [14].

6.3.1.6 Degree of polymerization

Oil-impregnated paper samples removed during refurbishing can be checked for their degree of polymerization. The temperature profile within a transformer may be determined from such measurements as well as determining the probable life expectancy of the insulation. DP values are in the range 1 000 for new units to 200 for those near their end of life [38,39]. Problems have arisen in obtaining comparable results between laboratories.

6.3.1.7 Other techniques

The condition of samples of deteriorated materials may be examined by many techniques including IR, X-ray, SEM, UV (for detecting waxed state) and molecular changes [40].

6.3.2 Analysis of SF₆ samples from GIS

Samples removed from a GIS are analysed by gas chromatography and mass spectrometry. The objective is to detect any SF₆ decomposition products that might have been created by, for example, low-level partial discharges.

6.3.3 Surface deterioration of composite insulators

Although the usual method of determining possible surface deterioration of composite insulators is by visual observation and perhaps leakage-current measurements, a technique has been developed [41] in Australia in which slivers of the surface material are removed for detailed quantitative analysis. By use of a special 'hot stick' the method has been successfully applied under live-line working conditions.

6.3.4 Water treeing in XLPE cable insulation

Application of the newer non-destructive techniques such as described in Section 6.2.4. has increased the possibility of detecting water trees in plastic cables. Following failures or suspected faults the only effective method of investigation is to cut out lengths of the cable and from suspected regions carefully prepared thin wafers for physical inspection. These methods are still required to confirm the presence of trees and the state of the dielectric, although new techniques are being developed.

6.3.5 *Ultrasonic methods for detection of partial discharges*

Although usually not considered quantifiable in terms of electrical charge or energy parameters, the presence and relative intensity of partial discharges in certain insulation structures can sometimes be identified by non-electrical techniques – in particular the measurement of the level and form of the sound waves emitted from various types of PD sources.

The simplest example is the application of a handheld parabolic dish in which is mounted a piezoelectric transducer (e.g. 40 kHz) connected to a battery-driven amplifier and small loudspeaker. Such devices have been commercially available for many years and are valuable for determining, for example, the location of corona discharges in substations, on overhead line hardware and in high-voltage test areas.

Techniques utilizing several transducers on the external surface of a power transformer tank for detection and location of internal partial discharges are well established for factory and site applications [42]. Extensions of these methods are described in Chapter 9.

6.3.6 *Miscellaneous techniques*

There are a number of physical inspections carried out on equipment during maintenance routines that can be categorized as assessment of the condition of the insulating materials. Such inspections include noting the oil pressure (expansion of bellows) in HVCTs, the odour of oil in an older transformer, oil leakage from tank gaskets and from valves, sludge formation on transformer windings, the surface state of outdoor insulators and the presence of ‘fretting’ (dust production) in large rotating machines.

6.4 **Summary**

The chapter gives an overview of the more important methods employed in industry and laboratories for assessing the condition of insulation in power-system equipment – as manufactured, on commissioning, during service and when undergoing maintenance or repair.

The coverage includes the techniques for generation and measurement of the required high voltages, a range of electrical non-destructive methods and a number of physical and chemical diagnostic procedures. The chapter content forms the basis for the testing and more advanced condition monitoring systems discussed in Chapters 7–10.

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6.6 Standards related to basic test methods

S6/1 IEC 60052 (Ed. 3.0, 2002): Voltage measurement by means of standard air gaps

S6/2 IEC 60060: High-voltage test techniques:

Part 1 (Ed. 2.0, 1989): General definitions and test requirements

Part 2 (Ed. 2.0, 1994): Measuring systems

Part 3 (Ed. 1.0, 2006): Definitions and requirements for on-site testing

S6/3 IEC 62067 (Ed. 1.1 2006): Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test methods and requirements

S6/4 IEC 61083-1 (Ed. 2.0, 2001): Instruments and software used for measurement in high-voltage impulse tests – Part 1: Requirements for instruments

S6/5 IEC 60270 (Ed. 3.0, 2000): High-voltage test techniques – Partial discharge measurements

S6/6 IEC 60814 (Ed. 2.0, 1997): Insulating liquids – Oil-impregnated paper and pressboard – Determination of water by automatic coulometric Karl Fischer titration

S6/7 IEC 60475 (Ed. 1.0, 1974): Method of sampling liquid dielectrics

S6/8 IEC 60567 (Ed. 3.0, 2005): Oil-filled electrical equipment – Sampling of gases and of oil for analysis of free and dissolved gases – Guidance

S6/9 IEC 60599 (Ed. 2.0, 1999): Mineral-oil-impregnated electrical equipment in service – guide to the interpretation of dissolved and free gases analysis

S6/10 ASTM D6786-02: Standard test method for particle count in mineral insulating oil using automatic optical particle counters

S6/11 IEC 60296 (Ed. 3, 2003): Fluids for electrotechnical applications – Unused transformers and switchgear

S6/12 IEC 62478 (Ed. 1.0): High-voltage test techniques: Measurement of partial discharge by electromagnetic and acoustic methods (new project, 2006)

6.7 Problems

1. Discuss the accuracy problems when applying (i) resistive and (ii) capacitive dividers for measurement of high-voltage lightning impulses.

A resistive unit has a high-voltage arm of $100\text{ k}\Omega$ and a low-voltage arm of $50\ \Omega$. It is connected to measuring instrumentation by a $75\ \Omega$ coaxial cable. How should the cable be terminated and what is the HV/LV measurement ratio for a $1.2/50\ \mu\text{s}$ impulse wave?

For a capacitive divider of 100 pF HV and $0.2\ \mu\text{F}$ LV arms, determine the ratio and appropriate cable terminations.

2. (i) Indicate why care must be taken when interpreting the readings from a Megger-type IR measurement.
(ii) Outline the advantages of a transformer ratio arm bridge compared with a Schering Bridge for measurement of insulation loss angles on power equipment.
3. Derive the relationships for the loss angle and capacitance values of the unknown capacitor C_x in the Schering Bridge circuit in Figure 6.12.

During a high-voltage test on new oil-impregnated bushing the permanent values of the Bridge components were $C_N = 100\text{ pF}$, $R_4 = 318\ \Omega$. At balance $R_3 = 700\ \Omega$ and $C_4 = 0.086\ \mu\text{F}$. The test frequency was 50 Hz .

Determine the bushing capacitance and loss angle. Comment on the $\tan\ \delta$ value if the test was carried out at $1.05 \times$ operating voltage to ground. Refer to S7/18 of Chapter 7. What further action might be taken?

4. High voltage partial discharge tests are to be applied to a range of power capacitors. Detail the test and measuring equipment required including a 100 pF coupling capacitor.

Determine the relative sensitivities for tests on the following capacitors. (i) 50 pF , (ii) 1000 pF and (iii) $10,000\text{ pF}$. If the desired sensitivity for (iii) cannot be achieved how might the test circuit be modified?

Chapter 7

Established methods for insulation testing of specific equipment

- Type tests, routine tests and special tests
- Insulators, surge arresters, switchgear, bushings, capacitors, cables, HV rotating machines and transformers
- Insulation tests for HVDC components

This chapter is concerned with existing acceptance and testing procedures for assessing the condition of the insulating materials and insulation structures in completed high-voltage power-system equipment. The techniques (see Chapter 6) chosen for proving the satisfactory state of a particular item will depend on the form and magnitude of the test voltage required, the physical size of the component, its complexity, the loading on the test supply circuits and the monitoring/fault-detection methods adopted.

Tests may be designated as *type* (design), *sample* or *routine*, depending on the form and number of items manufactured. In some instances a *prototype* is produced, which is subjected to a wide range of tests before full-scale production begins. Testing scenarios vary widely with the type of product. For example, cap-and-pin insulator samples of four or five units may be chosen for test from a batch of 2 000 while, with large plant such as generators and transformers, a series of type, routine and commissioning tests are carried out on the ‘one-off’ completed unit.

The test methods and the characteristics to be checked for each type of equipment are usually based on international and national standards formulated by experts in the particular field and subsequently approved by representatives of users, manufacturers, testing laboratories and research organizations. Many of these publications contain valuable technical information and application guides. Information on the wide range of Standards available may be obtained by contacting IEC and various national organizations such as the IEEE, ASTM, BSI, VDE and SA (see Appendix 2). In some fields new nonstandardized techniques are being trialled by the industry.

In the following are given examples of a number of the more important dielectric test procedures covered by Standards. In general terms, the descriptions are related to IEC and SAA publications and are intended only as a guide as to the requirements for particular classes of apparatus. The aim of the presentation is to indicate the complexity and types of extensive testing necessary in order to maintain a high level of operational reliability of the power system. It is essential to refer to the appropriate Standard(s) listed at the end of the chapter in order to determine the precise details for practical implementation of a particular procedure. The Standards are periodically updated.

With the exception of the induced-voltage testing from the lower-voltage winding of transformers, separate-source high-voltage supplies of sufficient VA power are necessary to prove the power-frequency withstand strengths of the insulation systems. In the majority of cases, the latter behave as predominantly capacitive loads. The capacitance also determines the required stored energy of the test equipment needed for carrying out the associated high-voltage impulse tests. Special situations include wet tests and testing of nonlinear devices. Any direct-voltage supply will be limited by the conductivity of the insulation load, including current leakage over adjacent surfaces.

The possible requirements for the various insulation tests are considered in relation to particular equipment. The sequence begins with the simpler capacitive-type systems through to the more complex involving distributed capacitances, travelling waves and capacitive/inductive devices.

7.1 Overhead line and substation insulators

The simplest capacitive-type components of the supply system are the vast numbers of overhead line and substation insulators in their different forms as described in Chapter 4. These include string (cap-and-pin – Type B; long-rod – Type A), pin, line post and station post insulators as specified in the various Standards. Composite insulators are defined in separate publications. All of these components have low capacitance values. Due to the numerous designs, the following can give only an indication of the tests that may be specified. Because of the developments in requirements and materials, the updating of Standards is a continual process.

The electrical assessment procedures are slightly different for the various classes of insulator but one or more of the following tests are specified as appropriate. The basic test procedures and waveshapes are defined in IEC 60060 [S7/1].

- dry power-frequency withstand voltage;
- dry power-frequency voltage with sporadic flashovers;
- high-frequency (100–500 kHz) flashover voltage;
- dry lightning-impulse withstand voltage;
- 50 per cent lightning flashover voltage;
- dry switching-impulse withstand voltage;
- wet power-frequency withstand voltage;

- wet lightning-impulse withstand voltage;
- wet switching-impulse withstand voltage;
- power-frequency puncture withstand voltage (and breakdown value if required);
- lightning-impulse puncture withstand voltage

High-voltage power-frequency and impulse test resources are required to meet these conditions. The usual tests are for individual components but short strings may be used to verify the characteristics of units that are to be connected in a long string.

Extensive mechanical strength tests are described in the Standards but, since these are more concerned with the physical structure – e.g. metal-to-insulation bonding and interface strength for composites – they are not considered here.

Type tests are carried out on one or more insulators in order to confirm the characteristics of the design.

Sample tests are applied to samples in a group of, for example, four and three items selected from a batch (lot) of 2 000 after completion of the routine tests. The sample tests are specified for insulators where the solid insulation puncture distance is ≤ 50 per cent of the flashover or creep path (Type B insulators). For station post insulators 1 per cent may be chosen from a lot of 100 to 500.

Routine tests are for checking each insulator on completion.

The physical arrangements for testing the different insulator configurations are outlined in the relevant Standard.

7.1.1 Porcelain and glass insulators (overhead lines)

These insulators include cap-and-pin and long-rod string types, pin type and line-post (Australia) type. Appropriate electrical insulation tests for insulator units and insulator strings/sets are included in References S7/2 and S7/3 in the Standards at the end of the chapter.

Type tests include dry impulse (1.2/50 μ s) withstand voltage and wet power-frequency withstand voltage applications. The impulse tests are carried out according to IEC 60060-1, preferably using the ‘up and down’ procedure for determination of the flashover voltage. Both polarities are applied unless it is evident that one gives a lower withstand voltage. A wet withstand-voltage test is applied and if flashover occurs a retest is allowed.

Sample tests consist of power-frequency puncture withstand voltage applications with the insulator immersed in a dielectric fluid.

Routine electrical tests are required only for Type B insulators. Power-frequency or high-frequency sources may be used. For these tests the testing transformer or high-frequency source must be stable and designed to withstand the sudden current and voltage surges produced during the many routine tests carried out.

7.1.2 Ceramic and glass insulators (post type – indoor and outdoor)

Post insulators are designated according to whether their construction includes a solid cylindrical core (puncture-proof), a cavity core with internal integral ceramic barrier or a cylindrical core and internal metal fittings with the solid insulating material of

at least half the length of the external flashover path (puncture-proof). For units with the solid length less than half of the total, and for the pedestal-post type in which the thickness of the solid is small compared with the external distance, electrical sample and routine tests are specified. References S7/4 and S7/5 are relevant.

Type tests are applied to one insulator only. The procedures are as in 7.1.1.

For indoor applications, dry lightning impulse, switching impulse and power-frequency withstand-voltage tests may be required. For outdoor applications, wet switching impulse and power-frequency tests may be required. The relative test levels for particular lightning-impulse values are detailed in Reference S7/4. Because of the variability in the basic insulation levels the dry lightning-impulse value is chosen as the reference and not the system-highest voltage. Note that switching impulses (250/2500 μ s) would usually be specified for units intended for operation in systems with highest voltages of 300 kV and above.

Sample puncture tests may be required on units where the solid insulating material distance is half or less than that of the flashover path.

Routine electrical tests are specified for the same designs as the sample tests.

7.1.3 *Composite insulators for overhead lines (string and post units)*

Extensive *design tests* are called for in the assessment of composite insulators. These involve dry power-frequency flashover tests for both the line [S7/6] and post [S7/7] insulators, in addition to steep fronted impulse (1 000 kV/ μ s) applications for the special conditions specified. Tracking tests are also required. The comprehensive sequence of mechanical, thermal and moisture tests (including leakage current measurements) may be found in references S7/6 and S7/7. *Type tests* include dry lightning impulses, wet switching impulses and wet power-frequency withstand voltages. These are applied to one insulator or insulator unit only. No electrical tests are specified for sample checks and for routine inspections.

Within the Standard, voltage levels are given for an optional radio-interference voltage test (RIV). No RIV values are quoted but the test voltage indicates the value at which corona would be expected to extinguish under dry conditions. Acceptable levels are agreed between the purchaser and manufacturer – a guide for establishing limit values is given in CISPR 18-2, Amendment 1 [1]. Detailed procedures for obtaining RI characteristics for dry high-voltage insulators are given in IEC 60437 [S7/8]. The specified reference frequency given in CISPR 18-2 is (0.5 ± 0.05) MHz but others in the range 0.5–2 MHz may be selected based on previous practice. It is expected that RI disturbances from insulators will not normally affect television reception.

7.2 **Overhead line and substation hardware**

Although the Standards recommend air clearances for the design and operation of overhead line systems and substations, it is often necessary to prove the performance of a particular configuration, especially at the higher voltage levels, where

switching-impulses or unusual pollution conditions exist. Such testing includes the determination of corona inception levels in order to ensure that unexpected flashovers do not occur and that interference does not affect local radio transmissions and receptions. This interference can invalidate some of the monitoring systems being used on site for the detection and measurement of partial discharges.

In the laboratory, levels can be quantified by PD measurements and the Radio Interference Voltage methods described in CISPR 18-2. Usually, insulators and the HV hardware will be checked simultaneously. The measurements are made utilizing a standard CISPR test set as specified in CISPR 16-1:1993 [2]. The technique has been applied for many years and is sometimes used as a partial-discharge test (see IEC 60270).

The diameters of overhead conductors for a given voltage and condition are well defined, as in Reference 3. Sometimes, however, it is necessary to determine the self-screening efficacy of multiple conductors and the satisfactory performance of a new design of spacer (or spreaders), as in quad arrangements. Proposed electrode configurations at the terminals of bushings, switchgear and arresters as well as insulators will require checking in the high-voltage laboratory at above operating voltages requiring appropriate corona-free supply sources.

7.3 Surge arresters

Surge arresters are a vital part of the power system. They must be shown to be able to withstand the steady-state voltages without deterioration, to respond correctly by reducing an excessive lightning or switching surge to a safe value and then to recover their previous power-frequency strength.

The earlier units included spark gaps and silicon carbide elements requiring tests as detailed in IEC 60099-1 [S7/9]. The tests for the later designs of metal-oxide gapless units are described in Part 4 of the Standard. The testing procedures are complex and extensive. In the following are summarized some of the type and routine tests for proving of the insulation requirements and V-I performance.

Type tests on the arrester housings include a lightning-impulse dry withstand-voltage test and a similar switching-impulse test both above the corresponding protection level. In the latter case a wet test is required for outdoor units. The power-frequency withstand test is applied for one minute with a peak value of just below the lightning-impulse protection level.

Residual-voltage-type tests on three complete sample arresters determine the highest residual voltage at the rated discharge current. From the results of other tests the switching impulse protection level for specified currents may be defined.

Type tests are carried out in order to simulate current flow from a recharged transmission line. Long-duration current-impulse withstands with virtual lengths of the wave peak within the range 500–3 000 μs are applied. A simplified circuit is described in Appendix J of IEC 600994.

Operating-duty-type tests incorporating the simultaneous application of impulse and power-frequency voltages are also included in the Standard. A major aim is to

prove that thermal runaway does not occur and that the unit can cool down during the power-frequency periods. A special multi-pulse operating-duty test representing multiple lightning strokes has been proposed [4, S7/10]. This has been shown to fail some units that would have passed the normal requirements.

Routine reference voltage tests require determination of the power-frequency voltage necessary to produce the reference current as measured at the bottom of the unit. The voltage value must be within the range specified by the manufacturer. This is a parameter that may be used for monitoring in service.

Routine lightning-impulse residual-voltage tests are carried out at, preferably, the nominal discharge current. The voltage must not exceed the appropriate specified values for a complete arrester – typically of the order of $3 \times$ the rated line voltage.

As part of the routine tests a partial-discharge contact noise measurement is made. The internal partial discharges, including disturbances due to bad contacts, should not exceed the equivalent of 10 pC. It may be practical to monitor the condition of suspect units in service by means of PD measurements.

7.4 Switchgear

In this section switchgear is deemed to include circuit breakers for on-load switching and fault protection, disconnectors (operating off-load) for isolation of the high-voltage circuits, metal-enclosed switchgear and on-load tap changers installed in transformers for changing the system voltage levels. For all of these devices a special requirement is the proving of the dielectric strength across open contacts, in addition to the usual insulation overvoltage checks to ground and between phases.

7.4.1 *Circuit breakers*

Extensive electrical, thermal and mechanical tests are specified for type and routine testing of circuit breakers [IEC 60694, Ed. 2.2 B, and 62271-100, Ed. 1.0 B, Refs S7/11 and S7/12]. The primary dielectric tests are summarized below. The power-frequency, lightning-impulse and switching-impulse withstand test voltages are tabulated in the specifications.

For ≤ 245 kV class the phase-to-phase, phase-to-earth and open-switch withstand test voltages (one-minute power frequency and $1.2/50 \mu\text{s}$ impulse) are equal, with the values for the isolating distances approximately 10–15 per cent higher.

Above 245 kV class the power-frequency test value across the open contacts is higher than the phase-to-earth levels; the switching-impulse test level between phases is greater than the value to earth; and, also, a combined switching-impulse/power-frequency test is required for checking the isolating distances. A combined lightning-impulse/power-frequency withstand-voltage test is applied across open contacts/isolating distances.

One method for applying ‘longitudinal’ test voltages without exceeding the withstand level to earth is by application of two separate out-of-phase power-frequency sources and, for impulse tests, an impulse of the withstand value to earth to one

terminal with a complementary voltage of opposite polarity to the other terminal. If a second impulse-voltage source is not available, the peak of the power frequency may be utilized. The technique is described in IEC 60060-1.

If a second voltage source is not available for open-switch or isolating distance tests, one voltage may be applied, but the value from the tested terminal to the frame of the device must not exceed the normal withstand level. The required longitudinal test voltage is achieved by increasing the frame potential to above earth and earthing the other terminal of the open contacts.

The high-voltage laboratory or factory test facility must be capable of carrying out these various procedures, the majority of which are type tests only.

7.4.1.1 Type tests

For 245 kV-rated voltage and below:

- power-frequency withstand-voltage tests for one-minute dry (indoor), wet (outdoor);
- lightning-impulse withstand-voltage tests with voltages of both polarities (1.2/50 μ s) – dry tests only.

For above 245 kV-rated voltage:

- power-frequency voltage withstand tests for one-minute dry tests only;
- switching-impulse withstand-voltage tests with voltages of both polarities (250/2 500 μ s) – dry (indoor), wet (outdoor);
- lightning impulse withstand-voltage tests with voltages of both polarities (1.2/50 μ s) – dry tests only;
- Partial-discharge tests;
(PD tests may be specified as agreed between manufacturer and customer. The tests are of importance for GIS equipment for which the standard method (see Chapter 6) or the UHF measurement systems may be used (see Chapter 9).)
- radio interference voltage test (RIV).
(RIV tests may be specified for equipment rated at 123 kV and above. The measurements are made with the contacts in both open and closed states with all other terminals earthed. The procedures for switchgear are detailed in IEC 60694. An RIV versus applied voltage characteristic curve is recorded. The acceptance level is 2 500 μ V at $1.1 \times$ phase-to-earth voltage. No guidance is given as to possible equivalent levels measured by conventional PD test methods. Such information could be of value when monitoring equipment in substations.)

7.4.1.2 Routine tests

Short-term power-frequency withstand tests are specified for new dry conditions on the complete apparatus or individual terminals. If solid-core insulators provide the major insulation, the high-voltage tests may not be necessary.

7.4.2 *Self-protected switchgear*

Switchgear containing built-in surge arresters cannot be tested at the full power-frequency withstand voltages. Methods for determining appropriate test levels as related to operating voltages are given in IEC 60694, Annex F. The impulse tests are applied with prospective voltages as listed in the normal withstand voltage tables. No disruptive discharges shall occur and records are to be provided of the waveshapes of the voltages to earth.

7.4.3 *Disconnectors (isolators)*

The dielectric withstand tests for disconnectors and earthing devices are similar to those specified for circuit breakers. Some differences in detail are included in the relevant standard [S7/13]. Problems that have arisen concerning the flashover of SF₆ units have resulted in the design of test circuits for simulating the high-frequency overvoltages produced by making and breaking operations.

7.4.4 *Metal-enclosed switchgear*

Specifications are available for the dielectric testing of switchgear assemblies in which the various components – for example a number of circuit breakers, bushings, cable terminations, instrument transformers, busbars, protective devices and associated control gear – are totally enclosed by an earthed metal enclosure. Access is provided for high-voltage and other connections. For such equipment factory and site tests may be required and, where appropriate, individual items tested before assembly. The final tests on the completed enclosure include the following.

- Type tests to check the insulation level of the complete system and partial-discharge measurements to evaluate the quality of the inbuilt insulation. IEC 62271-200 [S7/14] details the various high-voltage tests necessary to cover the many types of AC designs, to earth, between phases and across isolating distances. Impulse tests are required according to Reference S7/11.
- Routine tests at the manufacturer's works should be carried out on each assembly and on components installed at site as agreed. The power-frequency test voltage is to be less than the factory value unless a routine test was not applied previously. A PD test may also be negotiated.

In Annex B of Reference S7/14 a PD test according to IEC 60270 is specified. The difficulties in selecting a pass PD value are emphasized and, again, should be agreed. Suggested acceptance values are 10 pC at $1.1 U_r/\sqrt{3}$ where U_r is the rated line voltage. As an example of the value of PD measurements on site a fault due to the incorrect assembly of a current transformer was located in a 33 kV metal-enclosed switchgear unit. PD values were of the order 100 pC or more.

It is noted that IEC Standards have been issued for insulation-enclosed switchgear [S7/15] and for gas-insulated metal-enclosed switchgear for rated voltages above 52 kV [S7/16].

7.4.5 Transformer tap changers

An oil-immersed tap changer consists of many contacts mounted on an insulation board or cylinder, which may be near earth potential (Class I) or connected at a high-voltage position in the transformer winding (Class II). In addition a diverter switch is required for changeover between the selector contacts. The test voltages to be applied between the various electrodes are specified by the transformer designer.

The dielectric-type tests according to IEC 60214-1 [S7/17] consist of power-frequency (one minute) and lightning-impulse (three of positive and three of negative polarity) voltage withstand tests between all live parts and earth for rated voltages below 300 kV. For voltages of 300 kV and above, switching-impulse applications are also specified, consisting of three full waves as in the transformer standard (7.10).

The withstand voltage levels between parts must be suitable for the voltage differences – power frequency and impulse – appearing across the transformer tapping leads. During the appropriate tests allowance must be made for the limitations imposed by any transient voltage control devices which may be included in the tap changer.

For Class II units for operation in transformers with a $U_m \geq 121$ kV, a partial-discharge test between live parts and earth is required as a type test. The detailed procedure is specified in the standard and is similar to the power-transformer test requirements. The acceptable PD value at $1.5 \times$ rated voltage to earth is 50 pC.

No routine high-voltage tests are specified.

7.5 Bushings

The insulation systems of high-voltage bushings vary according to the materials and configuration adopted. Withstand-voltage tests are required as routine tests together with DDF and PD measurements.. Such data are used for quality control and for future reference in service. The test voltage magnitudes are determined from IEC 60071-1, depending on the particular application. Refer to IEC 60137 [S7/18] for details.

For outdoor bushings of lower voltage ratings a wet power-frequency voltage-withstand-type test is applied for one minute. Dry lightning-impulse voltage-withstand-type tests are carried out on all bushings with 15 impulses of both polarities. Dry-switching impulse-voltage-type tests are required for indoor units of the higher voltage ratings and similar wet tests for outdoor bushings of these ratings. The condition of the insulation is monitored by DDF, capacitance and PD measurements after testing and, also, by recording of impulse waveshapes during tests if considered necessary.

DDF measurements are made as routine for voltages up to $1.5 \times$ rated voltage to ground. Values at 2.5 kV and 10 kV are recorded as being useful during later service-maintenance procedures. Maximum allowable DDF values at $1.05 \times$ rated voltage are quoted according to the various materials, i.e. for oil-impregnated paper, resin-bonded paper, resin-impregnated paper, cast resin and insulating gas in capacitance-graded bushings and cast resin in non-capacitance-graded units. Allowable changes in DDF and capacitance magnitudes are specified. With composite bushings values are to be provided.

Routine dry, power-frequency, one-minute, withstand-voltage tests are applied to all bushings and partial-discharge tests at just above rated voltage. If required for a transformer installation the voltage is increased to $1.5 \times$ rated voltage. PD acceptance values are 10 pC for these conditions except for resin-bonded and cast-resin insulation systems, where levels of 100/300 pC and 100 pC respectively are usually taken as reasonable limits.

The insulation of the bushing test tap must be checked by an applied voltage of 2 kV and the DDF and capacitance values measured. These values should be 100 mR and 5000 pF or less. The lower the tap capacitance the more sensitive is the PD test as carried out according to IEC 60270 for transformers (7.10.2) and for some switchgear.

When testing for special applications it is important to use correct terminations (e.g. for re-entrant types) and to ensure that clearances within the test tank are typical of those in the equipment in which the bushing is to be installed. Air terminations may need to be screened, rod gaps removed and attention be given to the method of mounting/clamping the earthed flange to the test tank. Temporary clamps can be a source of corona. The measurement of low-value PDs requires the usual 'good housekeeping' and preferably, for routine tests, a dedicated area where the PD circuit layout can be permanent.

Guidance is given in IEC 61464 [S7/19] regarding the interpretation of DGA results for in-service oil-impregnated-paper bushings. Normal site tests include DDF and IR measurements.

7.6 High-voltage instrument transformers

The tests required for the wide range of instrument transformers applied in the power systems are detailed in IEC 60044 Parts 1–8, which includes current transformers (CTs), voltage transformers (MVTs and CVTs), combined transformers (CV/VT), and electronic types. The developments in instrument transformer design have necessitated updates of the standard.

7.6.1 *Current transformers*

The high-voltage withstand tests on CTs are applied to the paralleled primary winding terminals with the outer screens and secondary windings earthed. The major dielectric tests are summarized below. The test voltage values are based on those in IEC 60071 and tabulated in IEC 60044-1 [S7/20].

7.6.1.1 **Type tests**

Lightning-impulse voltage-withstand test: For $U_m < 300$ kV. A maximum of 15 standard impulses of each polarity is to be applied and for $U_m \geq 300$ kV only three standard impulses of each polarity are required. Waveshape changes may indicate failure.

Switching impulse-voltage withstand test: For $U_m \geq 300$ kV 15 switching impulses of positive polarity are to be applied. The test is to be under wet conditions

for outdoor units. The failure criteria are similar to those for the $U_m < 300$ kV lightning impulse tests.

Wet power-frequency withstand-voltage test: For $U_m < 300$ kV the test voltage is to be applied for 60 seconds.

Radio-interference voltage measurement: RIV tests are carried out on CTs for use in air-insulated systems with $U_m \geq 123$ kV. During the test hardware is required to simulate operating conditions. Refer to IEC 60044, Part 1, for details. By agreement a PD test may be substituted during which the measured value must not exceed 300 pC. It should be noted that the RIV and PD magnitudes are not directly related.

7.6.1.2 Routine tests

Dry power-frequency withstand voltage: The test voltage is applied for 60 seconds between the shorted primary terminals and earthed shorted secondary windings/frame. The appropriate test levels are tabulated in IEC 60044-1.

Partial-discharge measurement: Partial-discharge tests are applicable to units of ≥ 7.2 kV. The test method is specified in IEC 600270. A PD level of 5 pC should be detectable. The test may be performed with one of the two procedures: (i) during reduction of the withstand voltage; (ii) after the withstand test by pre-stressing for 60 seconds at $0.8 \times$ withstand voltage followed by reduction to the PD test voltage.

The PD test voltage is maintained for 30 seconds. The allowable levels at U_m and $1.2 U_m/\sqrt{3}$ are 10 pC and 5 pC respectively for liquid-immersed units and 50 pC and 20 pC for solid types. The system neutral is to be earthed.

7.6.1.3 Special tests

Chopped impulse tests on primary winding: Negative standard lightning impulse test voltages with chopping times between $2 \mu\text{s}$ and $5 \mu\text{s}$ are applied for $U_m < 300$ kV and $U_m \geq 300$ kV conditions. Variations in the full-wave (FW) shapes before and after the chop-wave (CW) applications may represent an internal fault.

Multiple chopped impulse test ($U_m \geq 300$ kV): Note: This test is included as an informative Annex (B) of IEC 60044-1 proposing a possible procedure for determining the response to high-frequency stresses as may be produced by, for example, isolator switching. Dissolved-gas-in-oil analyses (IEC 60599) before and after the test, with a three-day interval, are suggested for monitoring failure.

Capacitance and dielectric dissipation factor (DDF) measurements: These measurements apply only to liquid-immersed units for $U_m \geq 72.5$ kV. Values in the range 10 kV to $U_m/\sqrt{3}$ are to be recorded. The aim is to check the quality of production. Measurements are typically <0.005 , possibly 3 mR or less.

7.6.2 Inductive voltage transformers

The dielectric test requirements for inductive-type transformers are considered separately from the capacitive configuration. The relevant standard is IEC 60044-2 [S7/20]. All the specifications in relation to insulation tests are similar to those in the Current Transformer specification with the following exceptions.

7.6.2.1 Impulse withstand tests

During the impulse tests records are required of earth currents and of voltages transferred to the secondary windings. These are necessary in order to improve the sensitivity of fault detection as in the procedures for power transformer testing. Also, it may be essential to reduce the effect of core saturation between the application of switching impulses.

7.6.2.2 Power-frequency withstand tests

In order to avoid saturation of the core during the 60 seconds overvoltage-induced tests, the test frequency may require increasing to more than twice the rated value. In this case the length of the application may be reduced as for power transformers.

7.6.2.3 Partial-discharge tests

For identical test conditions the allowable PD levels are similar to the current transformer values. Phase-phase values at $1.2U_m$ are 5 pC for liquid-immersed units and 20 pC for solid designs. The various quoted values are also valid for non-rated frequencies.

7.6.3 Capacitor voltage transformers

As a CVT consists of a voltage divider and an electromagnetic unit, the assessment of the insulation condition requires separation of the components for particular tests. The appropriate procedures are described in IEC/PAS 60044-5:2002 [S7/20]. Some of the more significant tests are summarized below.

7.6.3.1 Type tests

Monitoring of the insulation state is effected by capacitance and DDF measurements and, in the case of impulse tests, by the comparison of waveshapes before and after the test sequence. The type tests include the following.

- Wet power-frequency withstand-voltage tests on outdoor units (<300 kV system).
- Lightning impulse withstand-voltage tests comprising 15 consecutive applications of each polarity for a $U_m < 300$ kV system unit and three of each polarity for a $U_m \geq 300$ kV system unit. A standard wave is to be used but if loading on the generator is too large a front rise time of up to $8 \mu\text{s}$ may be applied.
- Two chopped impulse waves of negative polarity applied to both classes of CVTs. Full waves are required before and after the chopped waves.
- Wet switching impulse tests of 15 positive polarity waves applied to outdoor units for $U_m \geq 300$ kV.
- RIV tests if specified. Conditions as for inductive current voltage transformers. A PD test may be used as an alternative.
- Ferro-resonance tests if required.

7.6.3.2 Routine tests

As an insulation monitor capacitance and DDF measurements are made before and after the high-voltage tests.

- Dry power-frequency withstand-voltage test for one minute.
- Partial-discharge test to be applied. Alternative methods are allowable, including use of balanced circuit as in IEC 60270. Permitted levels for earthed neutral are 10 pC at U_m and 5 pC at $1.2 U_m/\sqrt{3}$.
- Power-frequency withstand test is to be applied to the electromagnetic unit.

7.7 High-voltage power capacitors

The dielectric assessment of power capacitors ranges from tests on complete units of tens of microfarads for operation at approximately 7 kV (RMS) through to endurance tests (overvoltage cycling and ageing) on individual elements rated at, perhaps, 1.8 kV. Many of the capacitors are mounted outdoors in large banks for operation at the higher system voltages. They must be able to withstand adverse load-switching conditions and overvoltages and remain thermally stable under the very high internal electrical stresses. The testing of power capacitors requires dedicated supplies capable of providing several MVAR at test voltages of the order of 20 kV and for some cases to be effectively PD-free up to 10 kV. Tests for confirming the insulation performance are described in IEC 60871-1 and -2 [S7/21].

Type tests include thermal stability measurements, DDF determination at elevated temperature, an AC voltage withstand test and a lightning impulse-withstand test between terminals and container.

Routine tests are required for measurement of capacitance and DDF, for checking the AC withstand voltage and DC withstand voltage between terminals, and AC withstand voltage between terminals and container.

Special test. Endurance tests may be required on elements typical of the particular design and manufacturing process. Procedures and construction of elements for ageing and overvoltage cycling tests are specified in IEC 60871-2. Although partial-discharge measurements are not normally specified because of testing problems, facilities may be required to carry out such tests on complete capacitors. A PD-free source of up to, perhaps, 3MVAR and 15 kV (RMS) may be necessary. With the largest-rating capacitors, sensitivities of only 50 pC are achievable, which may not be considered significant by some authorities. A possible PD test sequence was described in AS 2897, 1986 [S7/21].

7.8 High-voltage rotating machines

The quality control of the insulating materials and insulation structures of large HV rotating machines during manufacture, assembly and commissioning is effected by application of a number of tests, some of which are listed below. The stator bars

are tested before assembly in the core, probably with procedures determined by the manufacturer and approved by the purchaser. The required measurements on the complete machine are specified in Standards such as IEC 60034-1 and IEC 60034-15 [S7/22]. The high-voltage tests check clearances between phases and to ground. During tests in air corona may be produced in the overhang regions of the stator windings.

7.8.1 *Stator bars*

Possible tests on individual bars might include:

- insulation resistance and polarization measurements;
- capacitance and dielectric dissipation factor measurements;
- power-frequency withstand voltage at above rated value for one minute;
- partial-discharge tests at agreed voltages – pass levels are probably of the order of 1500/2000 pC at $1.2 \times$ operating voltage.

7.8.2 *Assembled machine*

Possible tests on completed windings and machines include:

- insulation resistance and polarization measurements;
- capacitance and dielectric dissipation factor measurements over a range of voltage (see IEEE Standard 286, 2000 [S7/23]);
- power-frequency withstand voltage for one minute between phases and to ground at $1\,000\text{ V} + 2 \times$ rated voltage (line-line voltage); all stator bars are at the applied voltage during this test;
- additional, or alternative, HVDC withstand-voltage test as, for example, specified in IEEE 95, 1977 [S7/24] may be applied;
(This test is not considered suitable by some manufacturers and purchasers. The recommended DC test voltage is $1.7 \times$ power-frequency (RMS) acceptance test value applied for one minute at the full value – failure is taken as a complete breakdown. ‘Controlled’ overvoltage tests are also described during which the leakage current is monitored as an indicator of possible failure.)
- offline partial-discharge test over a range of voltages using traditional procedures (IEC 60270); the stator bars of the phase under test are ‘floated’ at the test voltage with the other phases grounded;
- online partial-discharge monitoring after commissioning at normal voltage including full load conditions.

(The various techniques are discussed in Chapter 9 and outlined in IEEE 1434, 2000 [S7/25]. The measured PD values for an assembled machine tend to be significantly higher than for individual bars – perhaps 5000 pC or more depending on the design and local conditions. Acceptable levels are based on experience with previous structures and operating machines. Such PD results form a reference for the establishment of trend characteristics as monitored during the life of the machine.)

Because of the large structures involved many units have to be reassembled on site, requiring testing of the complete machine *in situ*. Under these conditions the overvoltage power-frequency tests require a large kVA supply source perhaps consisting of a variable-tuned circuit at 50/60 Hz, or a variable frequency system (up to 300 Hz) or a low frequency test set – see Chapter 6.

In many machine designs a surge test is specified in order to check the inter-turn and ground insulation in applications where the unit may be subjected to lightning or switching impulses. The recommended tests for form-wound windings are detailed in, for example, IEC 60034-15 [S7/22]. Fault detection is by observation of the recorded voltage waves. During the overvoltage tests no puncture or flashover is acceptable.

7.9 High-voltage cables

7.9.1 Oil-impregnated cables

The insulation testing of AC high-voltage oil-impregnated cables in the factory requires the application of power-frequency and impulse-withstand voltages and the measurement of DDF over a range of voltages, the levels depending on the particular installation. Type tests include thermal stability measurements at high voltage. Details for lower-voltage mass-impregnated cables are given in IEC 60055 [S7/26]. IEC 60141 (Parts 1, 2 and 4) [S7/27] includes tests for oil-filled and gas-pressure cables up to and including 500 kV AC. For checking the terminations and joints of such oil–paper cables on site it is usual to apply direct voltage, thus avoiding the need for large VA test supplies. For example it is recommended that a 75 kV DC test voltage be applied for 15 minutes between conductors and from each to the screen for an 18/30 kV AC cable. No breakdown is allowable. The cable systems are designed to withstand the DC stresses produced.

7.9.2 Extruded cables

Following the widespread introduction of extruded cables three IEC Standards have been prepared covering the operating voltage ranges 6–30 kV [S7/28], 30–150 kV [S7/29] and 150–500 kV [S7/30]. The need for detailed insulation recommendations within the standards is partly due to the known susceptibility of XLPE to partial discharges and, also, guidance as to the values of low losses to be expected in such materials. An indication of the more important dielectric tests required as manufactured are summarized below. For precise details, refer to the relevant Standard.

7.9.2.1 Type tests for extruded cables

- PD measurements are specified after the bending and heat cycling tests. The allowable PD magnitudes at $1.5 \times$ operating voltage are ≤ 5 pC, the latter being the required background noise.

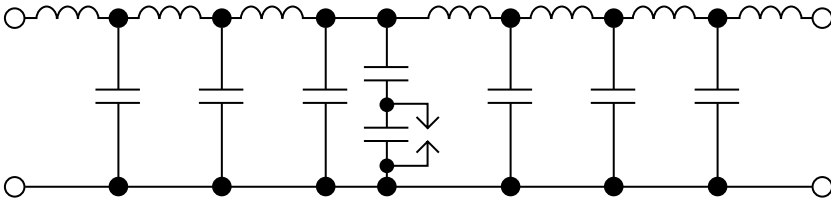


Figure 7.1 *Equivalent circuit of PD defect in a power cable [5] [reproduced by permission of CIGRE]*

- DDF measurements at operating and ambient temperatures are specified. For XLPE the expected values are $\leq 10 \times 10^{-4}$ and in the tens of mRs for EPR at operating voltages.
- Power-frequency withstand-voltage tests are required for long and short periods depending on the thermal conditions.
- Lightning-impulse withstand-voltage applications at temperatures of 95–100°C are followed by a 15-minute power-frequency withstand voltage. Switching impulses are specified for the heated system at voltages ≥ 300 kV.

7.9.2.2 Routine tests for extruded cables

- Power-frequency withstand test requirements range from five minutes at approximately $3.3 \times$ operating voltage to earth for the lower voltage systems to twice for 60 minutes at the highest voltages [S7/30].
- PD tests are specified at $1.5 \times$ operating voltage to earth. The method of calibrating when testing a ‘long’ cable using the conventional detection system (IEC 60270) is described in Reference S7/31.

The well-known circuit representation of a cable as a transmission line containing a PD defect is depicted in Figure 7.1 [5]. This reference presents a good analysis of the various developments in cable PD measurements. Figure 7.2 indicates how reflections are produced by a single discharge in a long cable. The example is for a partial discharge at 450 metres of an open-ended 480-metre-long cable [5]. The first pulse at the measurement end is followed by a reflection from the far end and a series of pulses set up as shown. The double pulses are due to the small 30-metre reflection distance at the far end. The intervals between the pulse pairs represent the transit times for the forward and reflected waves. Analysis of such data – probably in the presence of noise – enables the estimation of location of discharges and possible attenuation effects [5].

7.9.2.3 Installation tests for extruded cables

The commissioning of AC polymeric cables using HVDC for testing was not recommended by SC21(B1) of CIGRE (1990), since it is seen as being ineffective and possibly causing damage to the insulation, including the accessories assembled on site. AC tests of a 60-minute duration for voltage levels in the range of $2U_0$ at the

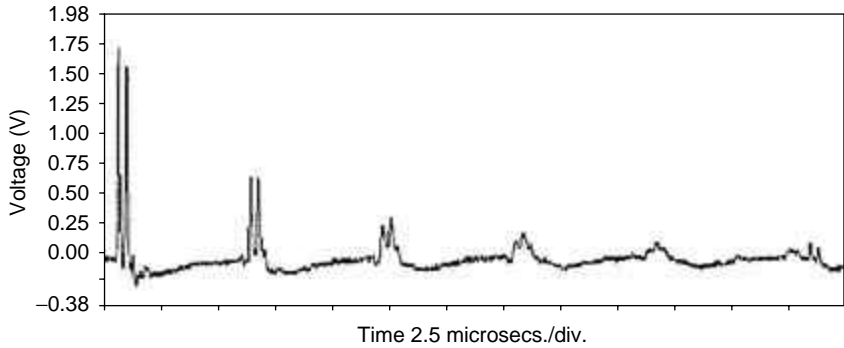


Figure 7.2 Attenuation of a multiple reflected PD pulse in a power cable [5] [reproduced by permission of CIGRE]

lower voltages down to $1.1U_0$ for 500 kV systems [S7/30] were subsequently proposed [CIGRE Brochure 173, Reference 6]. Twenty-four-hour tests at a voltage of U_0 may be employed if agreed, or higher if the supply is less than the power frequency. A test-frequency range of 20 Hz to 300 Hz is quoted in S7/30. Such power supply sources are now available, as reviewed in Chapter 6.

The special case of long extruded AC submarine cables (36–170 kV) is reported in *Electra* [7]. IEC revisions of the particular standards are related to the various proposals. A later CIGRE report [8] gives collation of practical test results obtained on installations using the levels recommended. The results confirm the conclusions of the earlier work.

7.10 Distribution and power transformers

The dielectric tests on distribution and, especially, power transformers are complex as the turn-to-turn, inter-winding and winding-to-earth insulations are required to be proved for two or more windings under steady-state and surge conditions [S7/32]. These requirements often necessitate the application of special arrangements – in design and when testing – in order to achieve the specified test levels.

7.10.1 Power-frequency overvoltage withstand tests

In three-phase units, particularly with three-limb cores, the single-phase induced power-frequency test can result in large voltage differences between phases but these may be reduced as indicated in Figure 7.3. A number of other configurations are possible [IEC 60076-3]. The recommended inter-phase air clearances are also given in IEC 60076-3.

For windings with one end nominally earthed (non-uniform insulation) it is usually impossible to induce the specified turn-to-turn voltage of twice normal and the correct HV terminal-to-earth voltage simultaneously, unless the neutral terminal is supplied

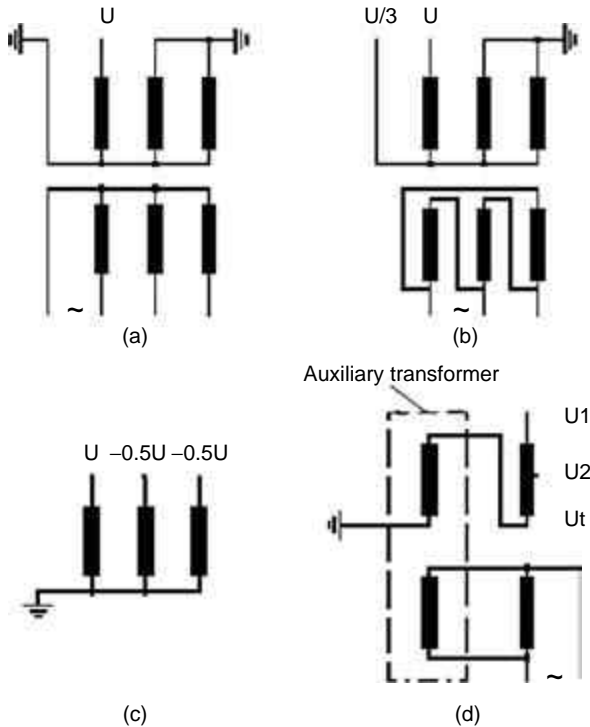


Figure 7.3 Single-phase induced-voltage tests to ground on three-phase and 1-phase transformers with non-uniform insulation [S7/32] [reproduced by permission of SAI GLOBAL]: (a) five-limb core (withstand overvoltage test and PD test); (b) three-limb core (withstand overvoltage test). Extra insulation at neutral; (c) three-limb core (withstand overvoltage test and PD test). $1.5U$ between phases; (d) 1-phase auto-transformer (withstand overvoltage test). Auxiliary testing transformer maintains correct voltage ratio between HV and Common terminals

from an independent source – for example, for an auto-transformer as in Figure 7.3(d). For such conditions the neutral end bushing and the transformer insulation levels may need to be of a higher value than required for normal tests.

Previously, the detection of failure during power-frequency short-term tests of 60 seconds – or less at higher frequencies to prevent saturation of the core during induced tests – was simply taken as collapse of the test voltage. If agreed, the Standard now includes a specification for partial-discharge measurements as a monitor of possible failure during the short-duration (ACSD) test sequence. The HV withstand-voltage test duration for frequencies greater than twice normal is given by the relationship $120 \times (\text{rated frequency}/\text{test frequency})$ seconds with a minimum of 15 seconds. In some cases the terminal voltage magnitude and waveform may be monitored via the bushing tap or an HV capacitor divider used for measuring the output voltage.

7.10.2 *Partial-discharge tests*

If a partial-discharge test is specified, the conventional technique applied is that described in Chapter 6 utilizing the HV bushing (and tap) as the coupling capacitor for the higher-voltage units. For lower-voltage units, e.g. dry-type distribution transformers, separate coupling capacitors are required [S7/32]. The PD test is usually carried out as a single-phase test. The test sequences for both the short-term duration (ACSD) and the long-term duration (ACLD) tests are similar. The duration of each and the voltage magnitudes are given in the Standard. The ACLD test is considered to be a quality-control test and not for proving the design.

In both types of test a five-minute 'conditioning' period at $1.5U_m/\sqrt{3}$ kV to ground is induced before increasing the value to the withstand test voltage for the ACSD test and to $1.7U_m/\sqrt{3}$ for the ACLD test. After lowering the voltage to $1.5U_m/\sqrt{3}$ kV, partial discharges are measured continuously for assessment during a five-minute period for the ACSD condition and during a sixty-minute period ($U_m > 300$ kV)/30-minute period ($U_m < 300$ kV) for the ACLD test. Also, values in the final five-minute periods at $1.1 U_m/\sqrt{3}$ are included in the assessment. Other PDs measured throughout the sequences are not considered significant in judging the success of the tests.

Single-phase tests on three-phase transformers are preferably made with connections as in Figure 7.3 (c). The maximum voltage is applied for the one-minute equivalent as determined from the test frequency. The other times are independent of frequency. Allowance must be made for synchronizing the discharge detector with the test frequency to assist with interpretation of the PDs.

7.10.2.1 Interpretation of PD measurements

The introduction of PD measurements during the short-duration over-potential test (ACSD) may enable the detection of the inception and extinction voltages and the discharge magnitudes to be determined if a disturbance is present during the application. Due to the rapid rise of voltage it may be difficult to estimate the precise time and values. An automated detection system would be of assistance. Because of the variabilities this part of the test is not used for PD assessment purposes. However, the data obtained might be of assistance to designers and the manufacturer if a fault is suspected.

In both types of test a continuous PD value of >300 pC after the high-voltage application is not acceptable. The value at the conclusion is to be <100 pC with the voltage 10 per cent above operating voltage. This is based on a background interference of 100 pC that might be considered to be a high value. In some specifications the allowable value is 50 pC at $1.2 \times$ maximum phase operating voltage to ground. It is also noted that bursts of apparent discharges higher than 300 pC may be ignored. Research has shown that such unsustainable discharges can be produced by some types of fault and, perhaps, should be recorded for future reference. The acceptance or otherwise of PD values near the limit can be difficult as the error in measurement may be as much as 20 per cent, depending on the conditions and calibration.

7.10.2.2 Calibration and fault location

The execution of partial-discharge tests in the factory environment can be difficult due to physical conditions and the size of the larger oil-impregnated high-voltage units. Apart from the good 'housekeeping' required, a particular problem is the need to include satisfactory procedures for injecting calibration pulses at the bushing terminals, possibly at 7 metres above ground level – see IEC 60270 and S7/32. If several bushing taps are available – for example at the HV and common terminals of an autotransformer and at the terminal of a tertiary winding – a profile of the expected PD outputs for injections at the three terminals can be set up. By comparing this distribution with that measured during the high-voltage PD test it may be possible to determine the electrical location of a particular disturbance, especially if real-time comparisons by means of simultaneous recording are included in the detection system. This concept is discussed in IEC 60076. In case large discharges are detected, most manufacturers (and many utilities) have available ultrasonic PD detectors for physical location of the disturbances. More advanced transformer PD detection and location techniques are discussed in Chapter 9.

Within the testing scenario the decision as to the correct procedure to follow after the detection of an apparently significant discharge can be very complex. The simplest but expensive action is to drain the unit and refill with dry oil under vacuum – even this process might take several days before retesting is possible. Removing the core and coils from the tank is a major decision even if the PD location is well defined by the electrical/ultrasonic measurements. Damage due to a large-magnitude discharge possibly caused by the short-time overvoltage test and developed during the ACS D test may not be visible. The inspection would be aimed at looking for manufacturing faults or design problems in the area indicated.

Monitoring of the insulation condition may also be effected by measurement of DGA levels of oil-immersed units. IEC 61181 [S7/33] covers the application of such techniques for factory testing. More detailed guidance for service conditions is given in IEC 60599.

For three-phase dry-type transformers the routine partial-discharge test consists of a pre-stress interphase voltage of $1.8 \times$ rated voltage U_r followed by PD measurements at $1.3U_r$. The allowable PD value in this case is only 10 pC, which is comparable with the values for other types of equipment with similar insulation systems.

7.10.2.3 Lightning- and switching-impulse voltage tests

The detection of internal failure during lightning-impulse tests is difficult and has resulted in the development of sensitive procedures enabling small changes such as turn-to-turn disturbances to be observed by means of oscillographic and/or digital records.

Except for major failures perhaps involving a line-to-earth breakdown or shorting of a significant fraction of the winding, the applied voltage records give minimal indication of a problem, particularly during lightning-impulse testing. More sensitive detection is effected by recording the waveforms of the neutral current and, for example, the current and voltage transferred to an adjacent winding. If the transformer tank

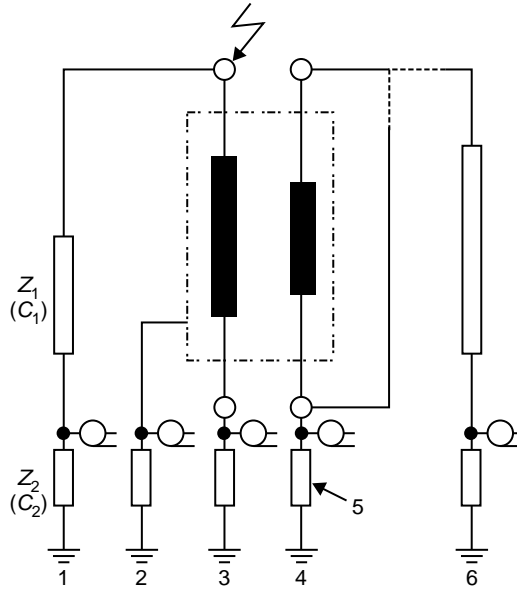


Figure 7.4 Voltage measurement and fault detection during lightning-impulse tests on transformers [S7/32] [reproduced by permission of SAI GLOBAL] 1. Voltage measuring circuit; 2. Tank current; 3. Neutral or winding current; 4. Capacitively transferred current; 5. Current shunts; 6. Voltage measurement and transferred voltage $Z_1(C_1)$, $Z_2(C_2)$ impedances (capacitances) in the voltage divider

can be insulated from earth it may be advantageous to record the tank-to-earth current. Possible locations of the measurement impedances are shown in Figure 7.4. These tests are carried out under single-phase conditions with the other phases earthed.

The expected waveforms at the various measurement positions are determined in the factory by injection of low-voltage electronic pulses from a recurrent-surge generator (RSG), or its equivalent, at the HV terminals to be tested. This allows correct choice of the current shunts and determination of transferred voltages. The latter must not be allowed to exceed the designed insulation levels. Conversely the simple shorting and/or earthing of other windings can produce unacceptable internal stresses during the impulse test. Of special interest are voltage stresses in the tapping windings. Although not strictly accurate, because of the omission of the oil, the winding impulse design calculations can be checked and simulation of faults may be possible on the transformer in its untanked state using RSG techniques.

An indication of the types of waveforms to be recorded and interpreted is presented in Figures 7.5 and 7.6 [S7/32]. The examples were selected from many in the Standard and show the difference between a large failure in a tapping winding and a small breakdown between turns after a CW. There is no simple method of determining precise acceptance criteria. The requirement of no change (excluding

proportionate magnitude levels) in the recorded waveform at reduced voltage and at full test voltage sometimes necessitates careful consideration and, perhaps, agreement in interpretation between the purchaser and manufacturer. This may be particularly relevant for chopped-wave tests where sudden changes occur at the time of chopping (effected after a few μs) tending to mask any high-frequency changes due to a fault. Depending on the number of recording channels available, and the particular case, time bases chosen are in the range 0–10/25 μs for the earlier part of the wave and 0–100 μs for the later times.

The detection of failure during switching-impulse tests is simpler than for lightning-impulse tests, as the voltage distribution within the windings and phases is effectively linear and similar to power-frequency conditions. Records are made of the line voltage and, probably, of the neutral current waveshapes. The required waveform must have a virtual rise time of at least 100 μs with a time greater than 90 per cent of the test value for 200 μs and a time from virtual zero to the first zero crossing of $\geq 500 \mu\text{s}$. The recording time bases required are from 100/500 μs to 1 000/5 000 μs . Typical examples are given in IEC 60076-4. The front must be such as to give an approximately uniform distribution within the winding.

A major factor when applying switching surges is the possibility of core saturation, resulting in waveform distortion. In order to allow comparison between records at different levels it may be necessary to apply lower-level impulses of opposite polarity, or even direct voltage, to establish acceptable core conditions. The withstand voltage may be applied directly to the winding under test or induced from a lower-voltage winding. The voltages are approximately in the ratio of the turns.

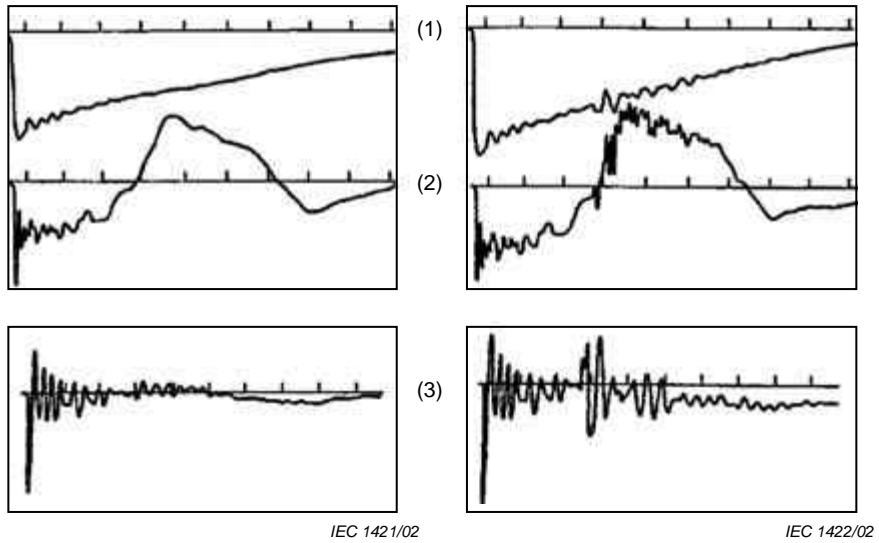
During switching surge tests on three-phase transformers it is important to ensure the clearances between phases are adequate [IEC 60076-3]. Tests are usually carried out with negative impulses, as air flashover voltages are greater than for positive waves. The non-restoring internal insulation is assumed to have the same strength for both polarities. Superimposed oscillations due to inter-phase capacitive coupling may produce higher than expected voltages [IEC 60076-4], which must be controlled, possibly by resistive damping.

The test is successful if no sudden change occurs in the shape of the line voltage. Corresponding changes in the neutral current, if recorded, may also indicate a problem.

7.10.3 *Summary of transformer HV test requirements*

The appropriate high-voltage tests for voltage (kV) classes $U_m \leq 72.5$, $72.5 < U_m \leq 170$, $170 < U_m < 300$ and $U_m \geq 300$ are tabulated in IEC 60076-3 [S7/32]. The tests relate to uniform and non-uniform insulated transformers. The appropriate withstand-voltage magnitudes ('one-minute' test) and impulse levels for each operating system are given in the Standard Tables.

- **Switching-impulse withstand voltage (SI):** If the ACSD test is not applied the SI test is specified for those units subjected to the ACLD test.
- **Lightning-impulse withstand voltage (LI):** When specified this test covers chopped waves (see Figure 7.6) as a special test.



Reduced full wave (62.5%) without fault

Reduced full wave (75%) with fault

(Amplitudes not equalized)

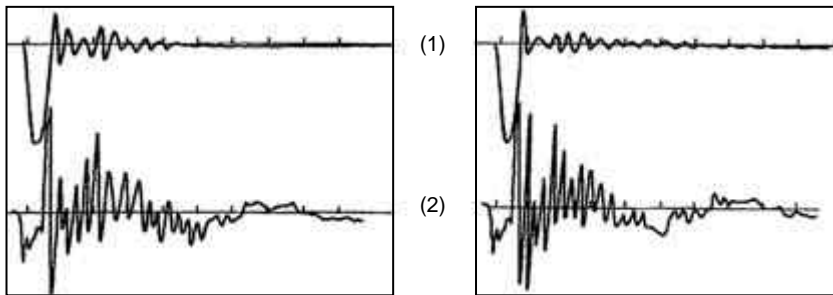
1 Applied impulse, 100 μ s sweep

2 Capacitively transferred current from the shorted adjacent winding to earth, 100 μ s sweep

3 Neutral current, 100 μ s sweep

Note: Failure indicated after 30 μ s in voltage, capacitively transferred current and neutral current oscillograms

Figure 7.5 Lightning-impulse full wave failure – interlayer breakdown in coarse-step tapping winding of a 400/220kV transformer [reproduced by permission of SAI GLOBAL]



Reduced chopped wave (70%) without fault

Chopped wave (115%) with fault

1 Applied impulse, chopped wave, 50 μ s sweep

2 Capacitively transferred current from the shorted adjacent winding to earth, 50 μ s sweep

Note: Failure indicated immediately after chopping in both the voltage and capacitively transferred current oscillograms

Figure 7.6 Lightning-impulse chopped-wave failure – between turns breakdown in fine-step tapping winding of a 400/220kV transformer [reproduced by permission of SAI GLOBAL]

- **Separate-source AC withstand voltage:** The test checks the insulation from the neutral to ground for non-uniform windings and the whole of the insulation to ground for uniform windings.
- **Short-duration induced AC withstand voltage (ACSD):** A PD test may be applied if agreed between manufacturer and user.
- **Long-duration induced AC voltage (ACLD):** The test includes PD measurements for 30/60 minutes at overvoltages to confirm the absence of damaging PDs during service.

In cases where lightning-impulse chopped waves are specified a possible sequence might be 1FW (50–75 per cent), 1FW (100 per cent), several CW for reference (50–75 per cent), 2CW (100 per cent), 2FW (100 per cent), 1FW (50–75 per cent). The chopping time should be in the range 2–6 μs . Failure is determined by careful comparison of records taken during the reduced chopped waves and those at the full level (Figure 7.6). It is assumed that the chopping times at reduced and full voltage are approximately equal. A slight difference in chopping times (perhaps $<0.1 \mu\text{s}$) might result in changes similar to those caused by a fault during application of a CW.

7.10.4 *Additional tests*

In addition to the well-established tests reviewed above, a number of newer tests are being trialled especially for in-service monitoring. These include more advanced PD systems, DC charging and relaxation measurements and frequency response analysis (FRA). Details of some of the various techniques are considered in Chapters 6, 8 and 9.

7.11 **Dielectric testing of HVDC equipment**

The choice of lightning and switching impulses for HVDC equipment depends on the insulation coordination levels of the system. The relevant direct voltage tests as related to the continuous DC operating voltages are, in general, agreed between manufacturer and user. A discussion of voltage stresses and test requirements for converter stations and HVDC cables is presented in References 9 and 10. Guidance on coordination procedures is considered in IEC 60071-5 [S7/34] for converter stations.

An important aspect of the protective methods is the correct application of surge arresters, especially related to the thyristor valves. The testing of such valves is specified in IEC 60700-1 [S7/35], including methods for determining the test levels based on given test safety factors. For example these are, respectively, 1.6 and 1.3 during the one-minute and three-hour DC tests of external insulation to earth. The three-hour value is reduced to 0.8 for a valve test. Partial-discharge tests are required during these applications, the PD values and repetition rates being recorded during the last hour. The number of pulses greater than 300 pC must be $\leq 15/\text{minute}$ – a spread of allowable values of up to 2000 pC (1/minute) is allowed. The measurements are according to IEC 60270 and must incorporate methods for counting and recording

the pulses. AC partial-discharge tests are also required, the limit being 200 pC during a 30-minute test at a voltage based on the equivalent peak-to-peak, steady-state operating level and a safety factor of 1.15. The standardized lightning and switching surge (three of each polarity) test levels are $1.15 \times$ surge protective level of the valve arrester and 1.2 for steep surges. The various complexities in testing the dielectric strength of thyristor valves when subjected to the combined effects of DC, AC and surge conditions are detailed in the standard.

Recommendations for tests on paper-insulated cables for DC transmission voltages up to 800 kV are included in a CIGRE report [11]. It is recommended that the factory high-voltage acceptance test be a negative DC voltage of $1.8 \times U_0$ applied for 15 minutes. The allowable power factors of the manufactured cable lengths are specified – for example, for an oil-filled cable rated at 400 kV DC, the value should not exceed 46×10^{-4} at a maximum RMS stress of 20 kV/mm. Type tests include combined polarity reversal/load cycles with a voltage of $1.4 \times U_0$. Impulse- (lightning- and switching-) superposed tests with the cable at a negative DC voltage of U_0 are described for each case. Positive and negative impulses are to be applied with recommended minimum values of $1.15 \times$ lightning impulse protective level and $1.15 \times$ switching surge level of the particular installation. Details of the procedures are given in the report. The suggested site test is a negative DC voltage of $1.4 U_0$ applied for 15 minutes.

Extruded insulation for DC transmission cables has been limited to commercial applications up to voltages of 80 kV and 150 kV as in the HVDC Light VSC projects in Australia (2000/2002) including extruded cable lengths up to 180 km. A few failures have occurred in other schemes, possibly due to space-charge problems following polarity reversals. Material developments and the introduction of the new converter technology (voltage source converter, VSC), which does not reverse the polarity, may give impetus to the wider use of extruded HVDC power cables [12]. This is reflected in the proposals for establishing test procedures for such cables in the range 80–250 kV included in the report by CIGRE WG 21.01 [13]. A number of the proposals are similar to those in Reference 11, although allowance is made, for example, for the longer time constants. The type load tests at $1.85 \times U_0$ include 24 + 24 hours load cycles and differences in impulse tests for a VSC system. AC tests are recommended where practical for monitoring insulation quality. The factory-acceptance and post-installation tests are to be HVDC.

Bushings for the converter transformers and reactors must be tested separately under HVDC conditions, as the designs are not similar to AC units, the voltage stresses being governed by the resistivities and temperatures of the insulating materials. Long-term PD tests would probably be required.

The testing of the converter transformers requires application of HVDC voltages to the valve windings in addition to appropriate AC and impulse tests to all windings. The procedures aim to cover the condition of superimposed AC and DC voltages. These include PD tests under DC conditions requiring long-term testing to allow the correct voltage distributions to be established. After 50 years of testing experience in the industry, IEC has published a standard [IEC 61378-2, S7/36]. A Trial Use Test Code was published by the IEEE in 1999 [C57.129]. The series reactors are subjected

only to DC and impulse high-voltage tests, the latter checking the dielectric strength across the winding as well as to ground.

Other components requiring HVDC tests include the surge arresters and insulators. A standard for ceramic and glass string insulators was issued in 1995 [IEC 61325, S7/37].

7.12 Miscellaneous items

As part of the monitoring and maintenance procedures on site, it is essential to have available safe and reliable equipment for use by personnel, especially when carrying out high-voltage tests and live-line working. There are many rules and regulations issued by responsible authorities covering the form and application of items such as earthing sticks, live-line working tools, 'cherry-picker buckets' and associated vehicles (see Figure 1.7), insulated gloves and insulation mats. All these devices must be subjected to routine high-voltage tests and, usually, insulation resistance measurements at regular intervals – possibly every six months in some cases. IEC Standards include 60855, 60900 and 60903 [S7/38–40].

7.13 Summary

In this chapter are presented the forms of standardized tests that have been developed by the industry over many years in order to produce reliable and economical equipment for application in the power-supply systems. Although new tests are being continually introduced to allow for changes in insulating materials – polymers, cast resins, XLPE, SF₆ – and in some design concepts, the basic methods are usually retained.

It is interesting to note the differences in choice of test sequences as determined by the type of equipment. For example impulse tests on cables, insulators, bushings and switchgear require ten or more applications while for transformers only two FW shots are usually specified. Surge arresters are a special case involving simultaneous application of power-frequency and impulse voltages.

7.14 References

1. CISPR 18-2: Admnt. 1, 1993, 'Radio interference characteristics of overhead lines and high-voltage equipment; Part 2: Methods of measurement and procedure for determining limits'
2. CISPR 16-1: 1993, 'Specification for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity measuring apparatus'
3. 'Guidelines for design and maintenance of overhead distribution and transmission lines', HB C(b)1-1999 Australian Standards
4. Darveniza, M. *et al.* 'A multiple pulse lightning impulse generator', *Proceedings of the 6th International Conference on High Voltage Engineering*, Paper

- 47.07, Aug/Sep 1989, New Orleans (see also *IEEE Trans. Power Delivery*, April 1994;9:764–71, Ref. In AS 1307.2)
5. CIGRE WG D1.33 TF 02.05, ‘Practical aspects of the detection and location of partial discharges in power cables’, 2006, Brochure 297
 6. CIGRE WG 21.16, ‘Partial discharge detection in installed extruded cable systems’ July 2000, Brochure 173
 7. CIGRE WG 21.02, ‘Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30(36) to 150(170) kV’, *Electra*, April 2000;(189):29–37
 8. CIGRE TF 21.05, ‘Experiences with AC tests after installation on the main insulation of polymeric (E)HV cable systems’, *Electra*, December 2002;(205): 27–35
 9. Lips, H.P., ‘Voltage stresses and test requirements on equipment of HVDC converter stations and transmission cables’, 2000, Paper P2-06 CIGRE
 10. CIGRE WG 14.32, ‘HVDC converter stations for DC voltages above +/ – 600 kV’, *Electra*, December 2002;(205):51, Brochure 215
 11. CIGRE WG 21.02, ‘Recommendations for tests of power transmission DC cables for a rated voltage up to 800 kV (*Electra* 72, 1980 Revision)’, *Electra*, April 2000:39–55 (see also *Electra*, February 2005; (218))
 12. CIGRE WG B4.37, ‘VSC Transmission’, *Electra*, April 2005;(219):29–39, Brochure 269
 13. CIGRE WG 21.01, ‘Testing DC extruded cable systems for power transmission up to 250kV’, *Electra*, February 2003;(206):47–53, Brochure 219

7.15 Standards related to Chapter 7

The reference of the nearest equivalent Australian Standard is included where appropriate.

S7/1 IEC 60060: High-voltage test techniques (AS 1931.1, 1996)

S7/2 IEC 60383: Insulators for overhead lines:

Part 1: Ceramic or glass insulator units for AC systems.

Part 2: Insulator strings and insulator sets for AC systems (AS 2947, Parts 1, 2, 4)

S7/3 IEC 60433: Insulators for overhead lines – Ceramic insulators for AC systems – Characteristics of insulator units of the long rod type

S7/4 IEC 60273: Characteristics of indoor and outdoor post insulators for systems with nominal voltages greater than 1 000 V (and for indoor organic units) (AS 4398, 2005, Parts 1, 2)

S7/5 IEC 60168: Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1 000 V (AS 4398, 2005, Part 2)

S7/6 IEC 61109: Composite insulators for AC overhead lines – Definitions, test methods and acceptance criteria

S7/7 IEC 61952: Insulators for overhead lines – Composite line post insulators for AC with a nominal voltage greater than 1 000 V (AS 4435.4, 2005)

S7/8 IEC 60437: Radio interference test on high-voltage insulators (AS IEC 60437–2005)

S7/9 IEC 60099: Surge arresters:

Part 1: Non-linear resistor type gapped arresters for AC systems (AS 1307.1)

Part 4: Metal-oxide surge arresters without gaps for AC systems

S7/10 AS 1307.2: Surge arresters – Part 2 Metal-oxide arresters without gaps for AC systems

S7/11 IEC 60694 (Ed. 2.2, 2002): Common specifications for high-voltage switchgear and controlgear standards

S7/12 IEC 62271-100 (Ed. 1.1, 2003): High-voltage switchgear and controlgear – Part 100: High-voltage alternating-current circuit-breakers (AS 62271.100, 2005)

S7/13 IEC 62271-102 (Ed.1.0, 2003): High-voltage switchgear and controlgear – Alternating current disconnectors and earthing switches (AS 62271.102, 2005)

S7/14 IEC 62271-200 (Ed.1.0, 2003): High-voltage switchgear and controlgear – Part 200: AC metal enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV (AS 62271 200, 2005)

S7/15 IEC 62271-201 (Ed.1.0, 2006): High-voltage switchgear and controlgear – Part 201: AC insulation-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV

S7/16 IEC 62271-203 (Ed. 1.0, 2003): High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV (AS 62271.203, 2005)

S7/17 IEC 60214-1 (Ed.1.0): Tap-changers –Part 1: Performance requirements and test methods (AS 60214.1, 2005)

S7/18 IEC 60137 (Ed. 5.0, 2003): Insulated bushings for alternating voltages above 1 000 V (AS 1265, 1990)

S7/19 IEC 61464 TR2 (Ed. 1.0, 2003): Insulated bushings – Guide for the interpretation of DGA in bushings where oil is the impregnating medium of the main insulation (generally paper) (AS TR 61464, 2006)

S7/20 IEC 60044: Instrument transformers (AS 60044 Parts 1, 2, 5)

60044-1 (Ed. 1.2, 2003) – Part 1: Current transformers

60044-2 (Ed. 1.2, 2003) – Part 2: Inductive voltage transformers

60044-5 (Ed. 1.0, 2004) – Part 5: Capacitor voltage transformers

S7/21 IEC 60871: Shunt capacitors for AC power systems having a rated voltage above 1 000 V (AS 2897, 1986, withdrawn)

60871-1 (Ed. 3.0, 2005) – Part 1: General

60871-2 Ed. (2.0, 1999) – Part 2: Endurance testing

S7/22 IEC 60034: Rotating electrical machines

60034-1 (Ed. 11.0, 2004) – Part 1: Rating and performance (AS 1359.101, 1997)

60034-15 (Ed. 2.0, 1995) – Part 15: Impulse voltage withstand levels of rotating AC machines with form-wound stator coils

S7/23 IEEE Std. 286, 2000, IEEE: Recommended practice for the measurement of power factor tip-up of electric machinery stator coil insulation

S7/24 IEEE Std. 95, 2002, IEEE: Recommended practice for insulation testing of AC electric machinery (2 300 V and above) with high direct voltage

S7/25 IEEE Std. 1434, 2000, IEEE: Guide to measurement of partial discharges in rotating machinery

S7/26 IEC 60055-1 (Ed. 5.1, 2005): Paper-insulated metal-sheathed cables for rated voltages up to 18/30 kV (with copper or aluminium conductors and excluding gas-pressure and oil-filled cables) – Part 1: Tests on cables and their accessories (AS 1026, 2004)

S7/27 IEC 60141: Tests on oil-filled and gas-pressure cables and their accessories 60141-1 (Ed. 3.0, 1993) – Part 1: Oil-filled, paper or polypropylene paper laminate insulated, metal-sheathed cables and accessories for alternating voltages up to and including 500 kV

60141-2 (Ed. 1.0, 1963/67) – Part 2: Internal gas-pressure cables and accessories for alternating voltages up to 275 kV

60141-4 (Ed.1.0, 1980/90) – Part 4: Oil-impregnated paper-insulated high pressure oil-filled pipe-type cables and accessories for alternating voltages up to and including 400 kV

S7/28 IEC 60502: Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1.2$ kV) up to 30 kV ($U_m = 36$ kV) (AS 1429.1, 2006)

60502-2 (Ed. 2.0, 2005) – Part 2: Cables for rated voltages from 6 kV ($U_m = 7.2$ kV) up to 30 kV ($U_m = 36$ kV)

60502-4 (Ed. 2.0, 2005) – Part 4: Test requirements on accessories for cables with rated voltages from 6 kV ($U_m = 7.2$) up to 30 kV ($U_m = 36$ kV)

S7/29 IEC 60840 (Ed. 3.0, 2004): Power cables with extruded insulation and their accessories for rated voltages above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) – Test methods and requirements (AS 1429.2, 1998)

S7/30 IEC 62067 (Ed. 1.1, 2006): Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test methods and requirements

S7/31 IEC 60885-3 (Ed. 1.0, 1988): Electrical test methods for electric cables – Part 3: Test methods for partial-discharge measurements on lengths of extruded power cables (AS 1660.3, 1998)

S7/32 IEC 60076-1 (Ed. 2.1, 2000): Power transformers – Part 1: General (AS 60076 Parts 1, 3, 4, 11)

60076-3 (Ed. 2.0, 2000): Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air

60076-4 (Ed. 1.0, 2002): Power transformers – Part 4: Guide to lightning impulse and switching impulse testing – Power transformers and reactors

60076-11 (Ed. 1.0, 2004): Power transformers – Part 11: Dry-type transformers

S7/33 IEC 61181 (Ed. 1.0, 1993): Impregnated insulating materials – Application of dissolved-gas analysis (DGA) to factory tests on electrical equipment

S7/34 IEC/TS 60071-5 (Ed. 1.0, 2002): Insulation coordination – Part 5: Procedures for high-voltage direct-current (HVDC) converter stations

S7/35 IEC 60700-1 (Ed. 1.1, 2003): Thyristor valves for high-voltage direct-current (HVDC) power transmission – Part 1: Electrical testing

S7/36 IEC 61378-2 (Ed. 1.0 (2001): Converter transformers – Part 2: Transformers for HVDC applications

S7/37 IEC 61325 (Ed. 1.0, 1995): Insulators for overhead lines with a nominal voltage above 1 000 V – Ceramic or glass insulator units for DC systems – Definitions, test methods and acceptance criteria

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7.16 Problems

1. Analyse and discuss the function and influence of Standards on the application of insulation in the high-voltage power industry. Highlight their importance economically and technically and the need to standardize assessment/condition monitoring methods for equipment and materials whenever appropriate.
2. Determine the PD pulse separation at the measurement end of the cable in Section 7.9.2 for a source located at 100 metres from the far end. Why is the apparent pulse velocity less than the value based on a cable-relative permittivity of 2.2?

Chapter 8

Sensors for insulation condition monitoring

- Ultra-high-frequency sensors
- Fibre-optic sensors
- Directional sensors

Sensors play an important role in insulation condition monitoring. For different insulation structures and materials used in various equipment, it is necessary to select the most suitable sensors. The environmental noise also affects the selection of the sensor. This chapter presents some advanced sensors recently developed for condition monitoring of electrical insulation.

As discussed in previous chapters, insulation of HV equipment can be examined from the measurement of some important parameters such as insulation resistance, dielectric dissipation factor, partial discharge and dissolved gases in oil. A rapid change of these parameters can be seen as the symptom of incipient faults and should be closely monitored. Other parameters such as temperature, dew point and water in oil are also important because they have significant impacts on the service life and electrical and/or mechanical strength of an insulation system. Accurately monitoring these parameters is a basic requirement for condition monitoring. The conventional PD sensors such as wide-band and radio-interference sensors (refer to Chapter 6) are useful, but may not be satisfactory in some cases, which has resulted in the development of new sensors as an important area for world researchers.

8.1 Ultra-high-frequency sensors

PD electrical detectors have different frequency bands. As discussed in previous chapters, conventional detectors are categorized as narrow-band (e.g. radio-frequency detector with 10–20 kHz bandwidth and centre frequency up to 50 MHz) or wide-band (e.g. the ERA impedance sensor from 10 kHz up to 1 MHz bandwidth). Since a PD pulse at the discharge site covers a very wide frequency spectrum, the frequency band

of a detector can significantly affect the recorded signal, which may be displayed on the screen or transferred to an A/D converter for digitising. Both waveshape and magnitude will be changed after passing through the detector of a certain bandwidth.

During the last decade, ultra-high-frequency (UHF) sensors have been widely used for PD detection on transformers, generators, GIS and cables. The frequency band ranges from 100 MHz to 2 GHz. With such a wide frequency bandwidth, much energy of a PD is received in the detector, giving a higher signal–noise ratio. Therefore, the overall sensitivity is improved. The resulting signal waveshapes of various detectors are given in Figure 8.1 for comparison.

Wide-band detection, as shown in Figure 8.1(b), is commonly used in commercial PD detectors for offline PD detections on HV equipment. With these types of detector, apparent discharges can be measured fairly accurately, which is important for insulation-condition assessment.

The UHF sensors are widely used in GIS and cable terminations because of the high sensitivity [3]. Due to the significant attenuation of high-frequency pulses travelling along cables, stator windings and busbars, only localized PDs are detectable. The typical installation and structure of a UHF sensor installed on a 230 kV GIS are shown in Figure 8.2 (a). The sensor is basically a capacitive coupler with a detection frequency between 500 MHz and 2 GHz. For generators, an antenna-type UHF sensor is inserted in the stator bar slots (under the wedge) to detect PDs in the conductor [4]. UHF detection is also applied to power transformers by locating antennae in valve or preformed openings in the tank, as illustrated in Figure 8.2(b) and (d) [5,6,7]. Details of PD measurements using these sensors will be discussed in Chapter 9.

Figure 8.3 shows a portable PD detector with exchangeable capacitive and inductive sensors, which detect the electromagnetic transients of PD events. In the mode for differential measurement, it may pinpoint the location of a PD source if it is not completely screened electromagnetically. The sensors are of wide frequency bands. Using two capacitive sensors connected to the inverting and non-inverting inputs respectively, the PD may be located by a PD pulse polarity method.

8.2 Optical-fibre sensors

Insulation condition monitoring relies on sensors to detect electrical or non-electrical parameters of an insulation system. Current methods for online monitoring of HV equipment often have problems in accessing high field areas and in reliably detecting electrical signals in noisy environments. Optical-fibre sensors offer a radically different approach to these problems and are gaining much attention in the power industry. The technological base stems from an intensive effort in optical-fibre communications. Their ruggedness and flexibility make it possible for them to reach previously inaccessible areas. The effects of external variables on the fibre can be sensed via a number of very precise changes on the light beams travelling along it. There is therefore a great potential for optical fibres to replace the role of conventional

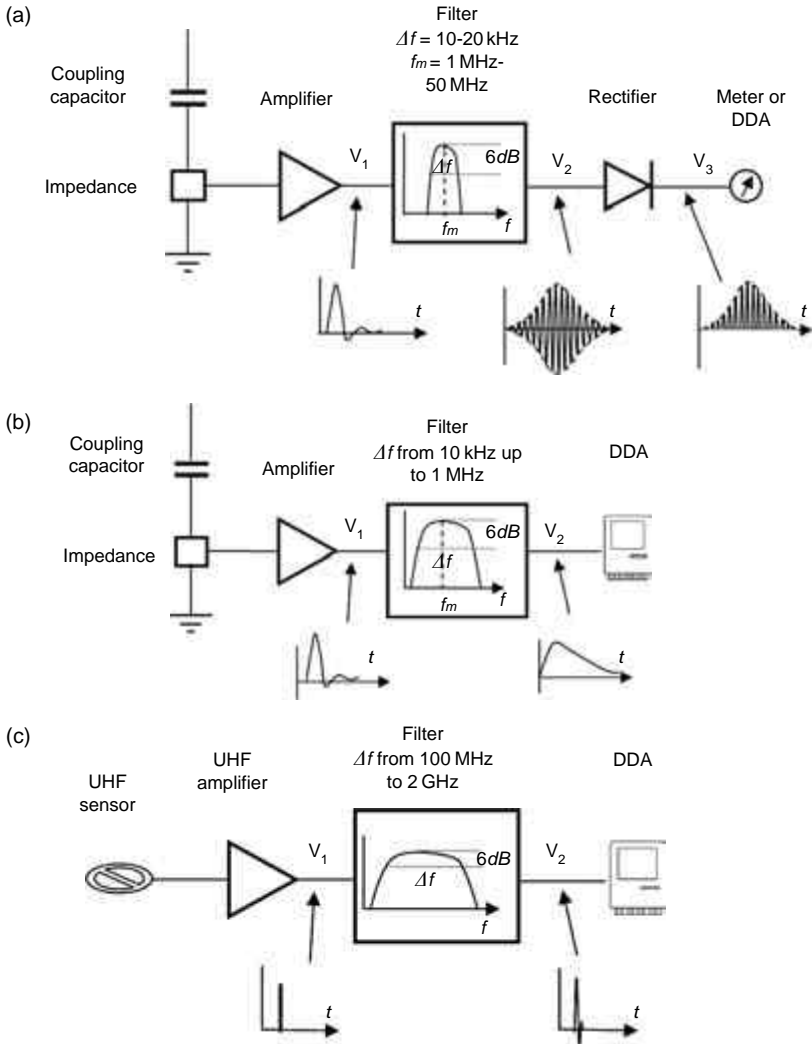


Figure 8.1 The PD waveshapes detected by different detectors with frequency pass bands of: (a) narrow band of 10–20 kHz, (b) wide band of 100 kHz–1 MHz and (c) ultra-wide band of 100 MHz–2 GHz, where DDA – digital data acquisition system, Δf – frequency bandwidth and f_m – centre frequency [1,2]

electrical devices in a number of sensing applications. However, it will be necessary to develop calibration methods in different applications.

Optical-fibre sensors are particularly well suited for condition monitoring applications because they are lightweight, durable, sensitive/insensitive to several

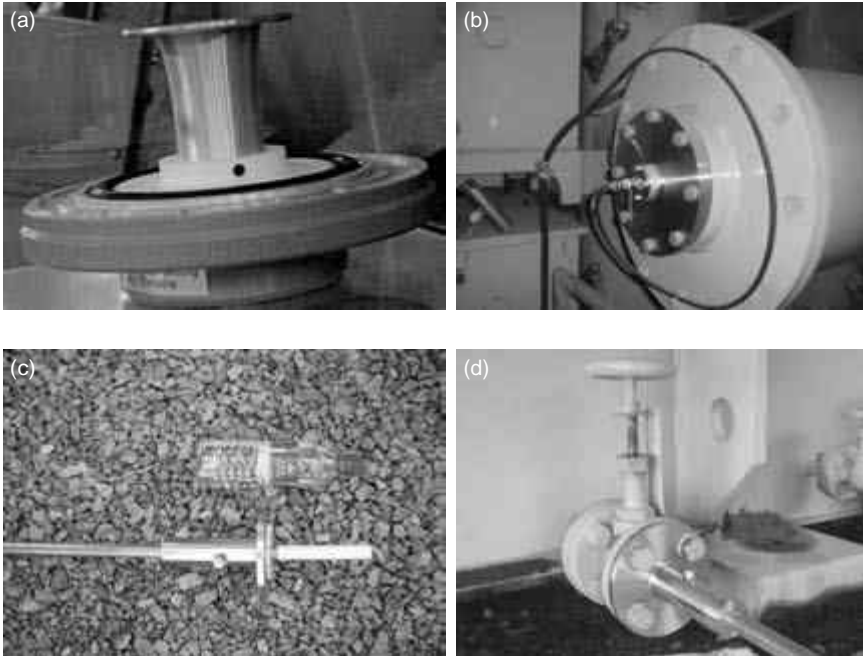


Figure 8.2 UHF sensor used for PD detection on various HV equipment. (a) UHF sensor for GIS; (b) UHF sensor installed on a 400 kV GIS; (c) UHF sensor for transformers; (d) The UHF sensor installed on a 66 kV/10 MVA transformer through the oil outlet valve [5,6]



Figure 8.3 A portable PD detector with exchangeable capacitive and inductive sensors [courtesy of Lemke Diagnostics AG, URL: <http://www.ldic.ch>, <http://www.hvdiagnostics.de>]

parameters, and can be incorporated within the equipment itself without being intrusive. The parameters that can be monitored range from chemical species (degradation by-products, contaminants and wear debris), internal/external strain fields, pressure, fracturing and fatigue to vibrations, acoustic emission and temperature.

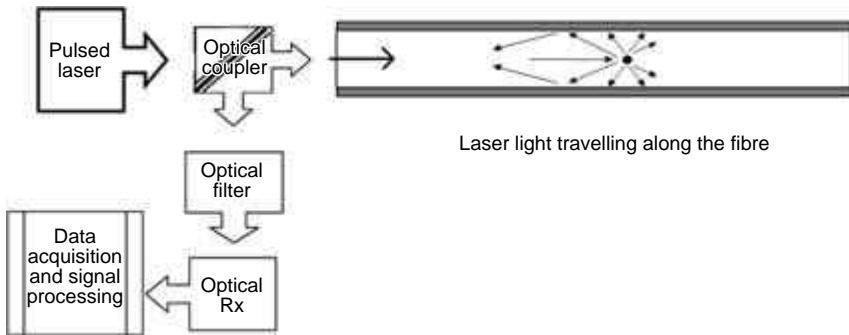
The high expectations of optical fibres as information carriers in communication systems has been justified by their performance over the past three decades. Due to the high bandwidth and low attenuation properties, each fibre is capable of replacing 1 000 copper wires. As a sensor, an optical fibre can carry much more information. Light that is launched into and confined to the fibre core propagates along the fibre unperturbed unless experiencing an external influence. Any disturbance to the fibre alters the characteristics of the guided light, which can then be monitored and related to the magnitude and location of the disturbing influence. The characteristics of the light that may be monitored in sensing applications include amplitude, phase, wavelength, polarization, modal distribution and time-of-flight.

8.2.1 Basic physics of optical-fibre sensing

There are many different types of optical-fibre sensor. According to the method by which the light is modulated in the fibre, they fall into four main groups [8], as follows.

- **Intensimetric:** Intensimetric optical-fibre sensors are based on the modulation of light intensity in the fibre and are generally configured as a distributed sensor. The light intensity may change in the form of fracture loss, time-of-flight, refractive index, amplitude and wavelength.
- **Interferometric:** Optical-fibre interferometers are generally intrinsic sensors. With the light from a source equally divided and directed through two (or more) fibre-guided paths, the beams are then recombined to mix coherently. Fingerprint types can be established in relation to the optical phase difference experienced by the two light beams. Single-mode fibres are used and very high sensitivity can be achieved.
- **Polarimetric:** The principle of polarization sensing is based on the birefringence within the fibre. When launching a polarized light beam along the principal axis of a single-mode fibre at 45° , the two orthogonal polarization eigenmodes are equally excited and degenerated. The degeneracy is increased if the fibre is subjected to an external force and a phase difference is induced in the two eigenmodes. The state of polarization in the fibre can then be related to the magnitude of the external force. These types of sensor are not as sensitive as interferometers, but have longer sensing lengths.
- **Modalmetric:** Optical fibres are microphonic and the detection sensitivity is based on the modulation in the distribution of modal energy in the fibre. This type of sensor is sensitive, but the modulation of the modal pattern is normally nonlinear in relation to all disturbances, resulting in fading and drifting in the output signal. Usually, these sensors are used in conjunction with other techniques such as microbending and polarimetry.

(a)



(b)

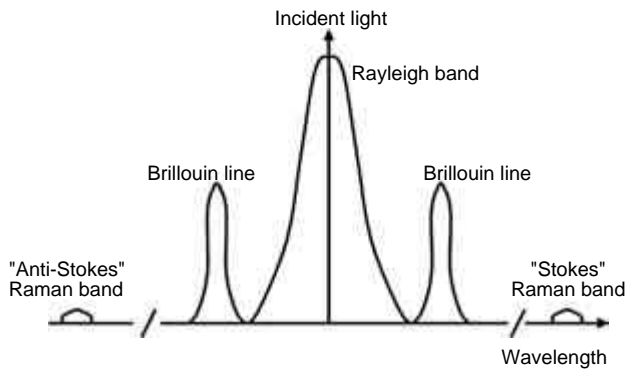


Figure 8.4 *The block diagram of an interferometer optical-fibre sensor and the back-scatter spectrum [8,10]*

The block diagram of an interferometer optical-fibre sensor is shown in Figure 8.4.

Optical-fibre sensors are rapidly proving to be a vital new tool for insulation researchers. The devices have already found uses in temperature, pressure and vibration measurements. Speciality fibre technology is opening up more opportunities in insulation condition monitoring such as PD measurements and transformer oil moisture detection. A few typical applications are listed below, although further investigations are necessary before they can be fully utilized in the industry.

8.2.2 *Optical-fibre PD sensors*

8.2.2.1 **Partial discharge measurements on generators and GIS**

The acoustic emissions from partial discharges can be detected by optical-fibre sensors. Researchers have investigated different types of such sensors and have found that achieving sufficient sensitivity is the most difficult problem. In a GIS chamber, the typical acoustic vibration generated by PDs is 1×10^{-5} g to 1×10^{-2} g, where $g = 9.81 \text{ m/s}^2$. Most of the acoustic energy from PDs is at ultrasonic frequencies,

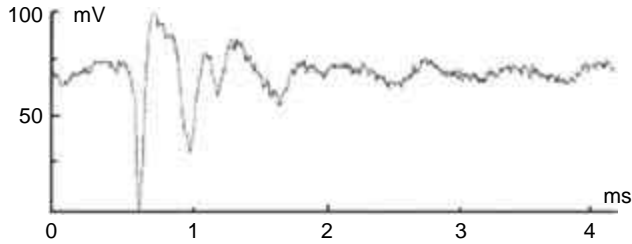


Figure 8.5 The typical responses of an optical-fibre sensor to PDs in a generator stator bar tested in the laboratory. The discharge magnitude was approximately 500 pC [8]

i.e. around 10 kHz. At this frequency, the acoustic vibration acceleration can be translated into displacements in the order of 10^{-14} m to 10^{-12} m. For generators, the magnitude of PDs is much higher than in GIS, but even so more sensitivity is required before a reliable sensor can be used. The PD energy detected depends on the length of the sensing fibre, the acoustic power and the numerical aperture of the fibre.

Monash University and FFT Ltd have jointly developed the Foptic μ Strain sensor and associated instrument [8]. The technique is based on a well-known fibre-optic interferometric principle that can achieve a wide-frequency bandwidth of 1 MHz. The sensor is less complex and of lower cost than other optical-fibre sensing systems. Only a short sensing length of 6 mm is necessary, which makes the installation easier. The sensor has been tested on a generator stator bar in the laboratory and the typical response of this sensor to PDs in the generator stator bar is shown in Figure 8.5.

8.2.2.2 Partial discharge measurements on transformers

PD measurements on transformers using electrical methods are very difficult because of the low level of discharge to be measured and the large interference at site. In a 330 kV substation, corona discharges from the overhead transmission lines can reach 3 000 pC or more, while the PD level to be measured could be less than 100 pC. In such a noisy environment to detect PDs smaller than 5 per cent of noise would be impossible by conventional methods. Optical-fibre sensors are immune from electrical interference and can be installed around the winding, which is excellent for PD monitoring on transformers. However, the sensitivity of optical-fibre sensors is not sufficiently high for such an application.

A novel optical sensor was developed [9] that uses an optical-fibre head instead of a piezo-electric sensor for the detection of acoustic emission from the PD source, as shown in Figure 8.6. The acoustic pressure changes the shape of the optical fibre, which carries laser light injected from terminal 1. As a consequence, the phase of the light will change according to the pressure. When reflected from the mirror at the fibre head 3, the change will be detected and converted to an electrical signal. The magnitude of the signal will vary according to the acoustic wave pressure from the PD source.

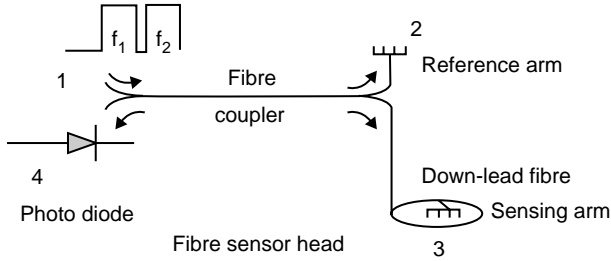


Figure 8.6 The principle of an optical-fibre system for acoustic detection of PDs in a transformer [9]

8.2.3 Optical-fibre temperature sensors

Since the maximum operating temperature is critical for HV equipment such as transformers and power cables, it is important to know their internal temperature distribution and thermal environment. The continuous, cyclic and short-time overload capacities of a piece of HV equipment are very dependent on its hotspot temperature, excessive values of which cause increases in insulation deterioration.

8.2.3.1 Hot-spot detection in power transformers

Transformer loading is mainly determined by the winding temperature and it is of vital interest to the designers and users to assess correctly the hot-spot temperatures, excessive values of which cause increases in insulation deterioration. Because of the complicated and compact structure, a transformer can have very different temperature distributions inside the tank. The conventional temperature sensors can measure only the tank surface and oil temperatures, which to a large extent are only average temperature indications. Optical-fibre sensors make it possible to detect the temperature of hot spots deep inside the windings. Electrical isolation between the windings and the temperature measurement is system inherent in the use of an optical-fibre connecting cable of good dielectric characteristics. The small size of the sensors makes it possible to reach many locations in the windings. An optical fibre can also be wound with the transformer winding, so enabling the temperature distribution to be readily measured and hotspots identified using a distributed temperature-sensing (DTS) technique. In such a sensing system, the optical fibre acts as both the sensing and the data-transmitting medium. The temperature-distribution profile of a transformer winding detected by a DTS system is depicted in Figure 8.7.

8.2.3.2 Hot-spot detection in power cables

Figure 8.8 shows the temperature profile of part of a 10 km, 230 kV cable measured using a DTS detector. There are a number of spikes and dips along the cable with the maximum difference of 20°C. The temperature variation is associated with the local thermal environment around the cable. Weather conditions and the thermal conductivity of the medium in direct contact with the cable surface (soil, air in duct, etc.)

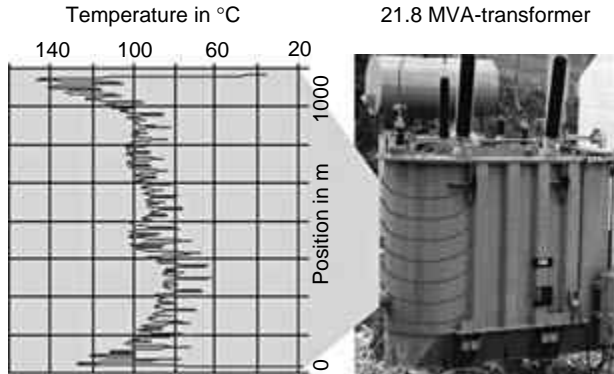


Figure 8.7 The temperature distribution along a transformer winding detected by an optical-fibre sensing system [10] [courtesy of Sensa Ltd, <http://www.sensa.org>]

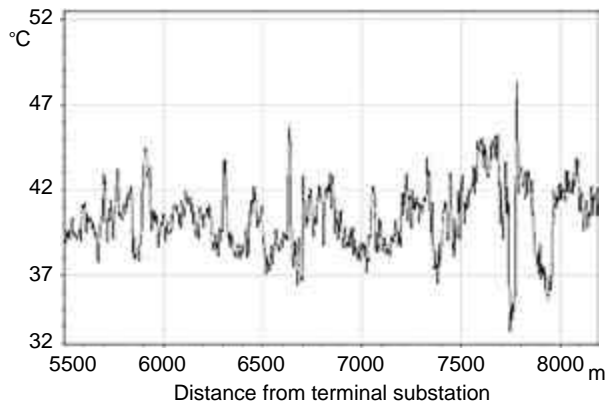


Figure 8.8 Temperature profile of a 230 kV underground cable within a section of about 3 km length

have a significant effect on heat dissipation from the cable. The thermal capacity of the cable itself also needs to be investigated, especially when considering the dynamic temperature change. Lack of understanding of the external thermal environment may present further risk to the performance of underground cables.

With the recent development of optical-fibre-based DTS, remote continuous monitoring is now implemented in a number of cables around the world. The advantages of DTS are as follows.

- Hot spots along a cable circuit can be accurately located [11].
- The cable capacity can be more effectively utilized.

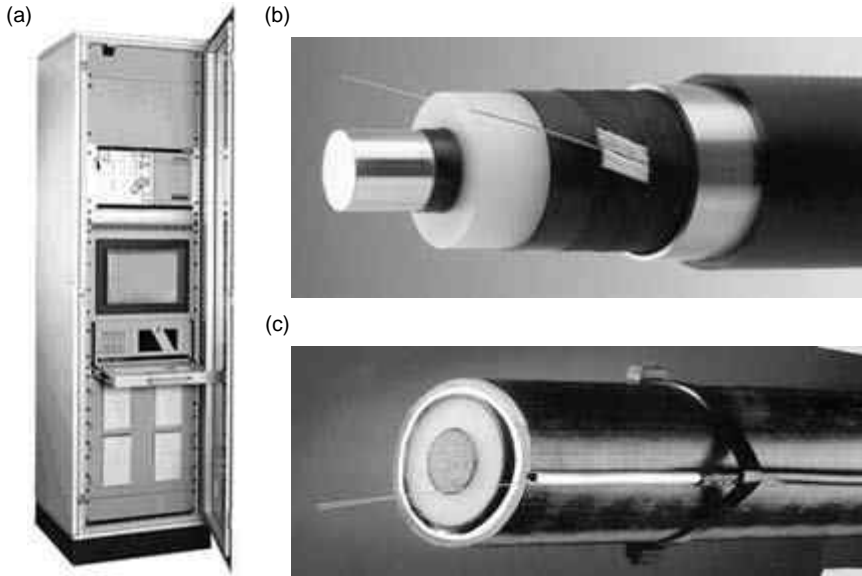


Figure 8.9 The DTS system made by Sensa Ltd and the cables with fibre sensors integrated (b) or laid on the surface (c) [10] [courtesy of Sensa Ltd, <http://www.sensa.org>]

- The temperature record provides important information about the thermal history of a cable that can then be used to analyse insulation ageing for life prediction and maintenance planning.
- It assists in system operation by generating an alarm when the temperature exceeds the limit.
- The real-time temperature measured is important for cable emergency load management [12].

Figure 8.9 shows the DTS system widely used in underground HV power cables [12]. The optical fibre can be integrated inside the cable (under the sheath), attached to the surface or in the duct next to the cable.

There are various optical-fibre techniques for temperature sensing. Figure 8.10 shows the sensing system using optical time domain reflectometry. The laser light is injected through the optical coupler to the optical-fibre sensor and reflected back at the mirrored end. While travelling along the fibre, the light is distorted by the temperature in a certain pattern. The reflected light is then received after coupling back to the detector and compared with the injected light in its phase and magnitude, which can then determine the temperature at different locations along the fibre:

- emission-to-sampling time defines the measurement position;
- the light intensity at a particular location gives the temperature.

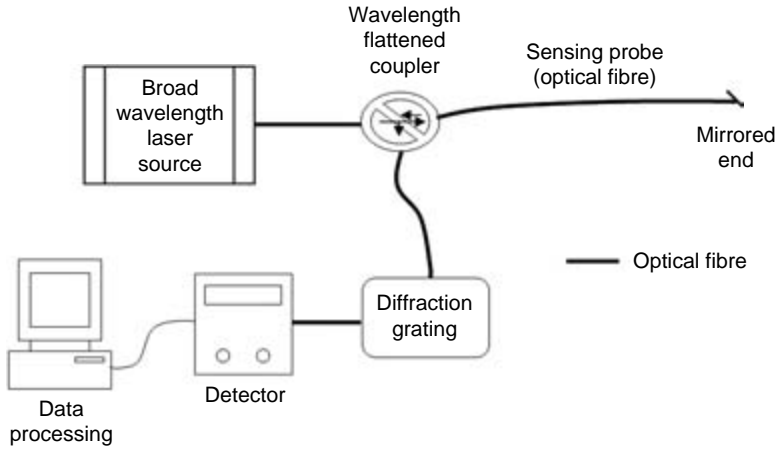


Figure 8.10 The block diagram of a distributed optical fibre sensing system [8]

An important characteristic of DTS is the temperature sensitivity, which can be increased by the use of Raman scattered light.

Point sensors are also available to detect temperature at important parts of a cable, e.g. cable joints and terminations. The data can be collected locally and transmitted to the control centre or laboratory for continuous monitoring and analysis.

8.2.4 Advantages and disadvantages of optical-fibre sensors

The principal advantages of optical fibres over conventional sensors are:

- small size, low weight and robustness;
- low unit cost for sensor;
- corrosion resistance, high-tensile strength and high fatigue life of optical fibre;
- non-conductivity and immunity to electromagnetic interference;
- very wide-frequency bandwidth and fast response times;
- ability to measure very wide temperature range;
- high spatial resolution and high sensitivity for some events;
- simultaneous sensing of more than one parameter.

The major disadvantages of optical-fibre sensors are that:

- the optical fibre may be sensitive to different influences, which could require the isolation of unwanted parameters;
- the detection and signal-processing instruments can be complicated and costly;
- the long-term stability of an optical-fibre sensor in particular power equipment environments needs examination;
- it has a low sensitivity to partial discharge at this stage of development.

8.3 Directional sensors for PD measurements

For HV equipment with earthed metal sheaths or enclosures such as transformers, power cables and HV motors, electrical noise sources are mainly external – for example, corona on the conductor connected to the HV terminal. On such a conductor, PD pulses travel from the equipment terminal outwards and electrical noise travels inwards, as shown in Figure 8.11 for a shielded power cable. The propagation direction of the pulses is therefore a useful indicator for identifying the noise. The conventional method for determining the direction of a travelling wave on a conductor is to connect two HV capacitors to the conductor at a certain distance apart. External noise will arrive at the outer sensor first and at the other after a short time delay. The distance has to be >3 m to make the delay sufficiently long for the electronic circuit to make the comparison. The use of HV capacitors for this purpose is expensive and can cause additional risks to the HV network.

8.3.1 Directional coupler sensor

EHV underground power cables are critical for the reliability of electrical transmission systems. It has been found that cable accessories such as joints and terminals are the weakest parts in terms of the insulation strength. For the voltage above 220 kV, it is required that the PD level should be very low or undetectable under the operating voltage. The directional coupler system (LDS-5, Lemke Diagnostics AG) shown in Figure 8.12 provides an effective means to discriminate external interference and corona noise from the testing voltage supply.

The directional couplers are installed between the cable sheath and the semiconductive layer. There are four outputs from the couplers, which are marked A, B, C and D in Figure 8.12. The noise travelling from left to right will be picked up by A and C outputs and from right to left picked up by B and D. However, PDs from the

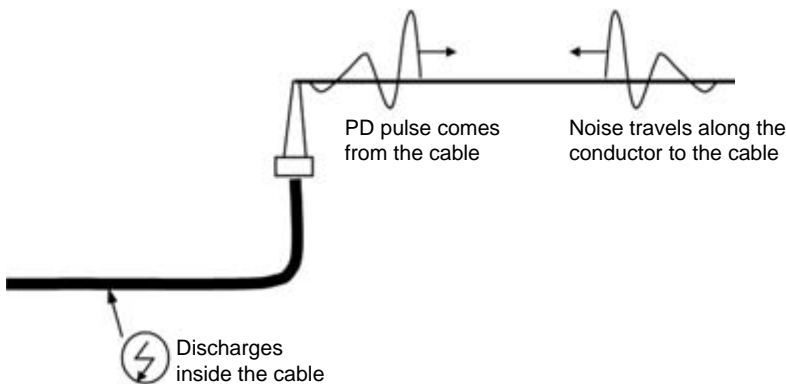


Figure 8.11 The PD pulse from a cable and the external noise travelling in opposite directions

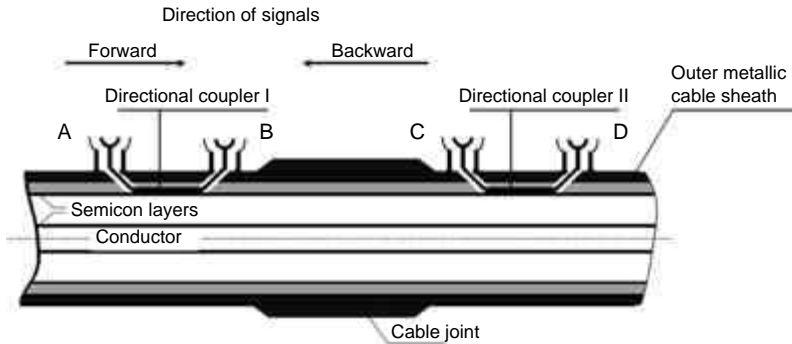


Figure 8.12 The directional couplers installed on both sides of a cable joint for PD detection at the high measurement sensitivity [courtesy of Lemke Diagnostics AG, URL: <http://www.ldic.ch>, <http://www.hvdiagnostics.de>]

cable joint will be picked up only by B and C, which are distinguished from the noise originated on both sides.

8.3.2 Directional field sensor

The new directional sensor developed jointly by Monash University and Insultest Australia Ltd does not require a connection to the HV conductor [13]. It consists of a 1.2-metre-long rectangular detector that picks up the electrical and magnetic fields associated with the PDs. The fields reflect the voltage and current of a partial discharge. With the correct configuration, the voltage and current signals produced by the PDs from the HV equipment will have the same polarity, but those due to external noise will be of opposite polarities. By comparing the polarities of the two signals, the direction of travelling pulses can be detected. The principle of the system is shown in Figure 8.13.

Because of its high sensitivity the sensor can be installed at ground level, with a distance of 200–300 mm from the HV conductor (busbar), as shown in Figure 8.14. There is no need to connect the sensor to the HV conductor. The sensors have been installed at two power stations giving some encouraging results. A ring-type directional sensor was also developed, which can easily be installed around the cable terminal or transformer bushing with a clearance of 100–300 mm. Investigations are being carried out to improve further the measurement sensitivity for the detection of PDs in transformers and XLPE cables [14,15].

Outputs of the directional sensor of Figure 8.14(b) for PDs travelling along the busbar in different directions are given in Figure 8.15. It can be seen that for a PD travelling from left to right, the first peaks of the electric and magnetic probe outputs have the same polarity, whereas, for PDs travelling from right to left, the polarities are opposite.

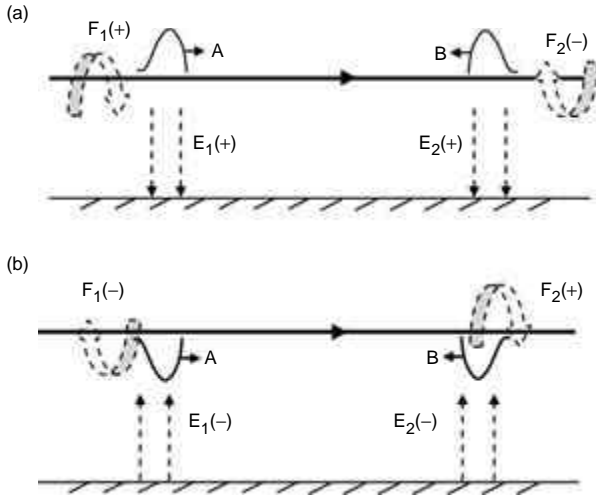


Figure 8.13 Electric and magnetic fields generated by PD pulses A and B travelling in opposite direction along a conductor. (a) Positive impulse. (b) Negative impulse, where E – electric field; F – magnetic field. The positive direction is from left to right [14]

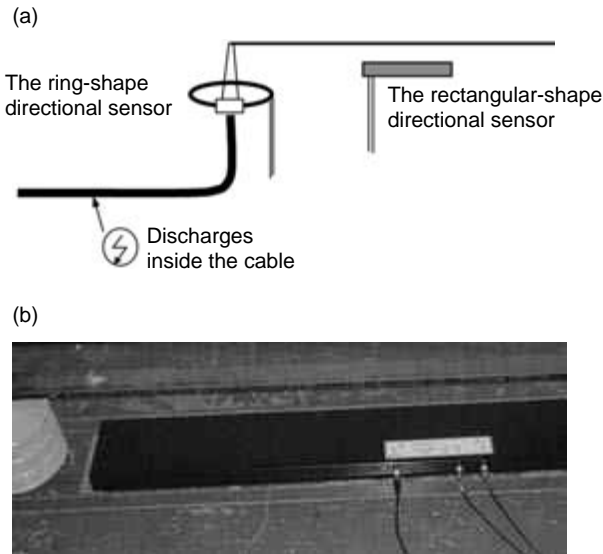


Figure 8.14 The new directional sensor jointly developed by Insultest Australia and Monash University HVICM Group: (a) the schematic diagram; (b) the directional sensor tested in an HV laboratory under a 15 kV busbar [13]

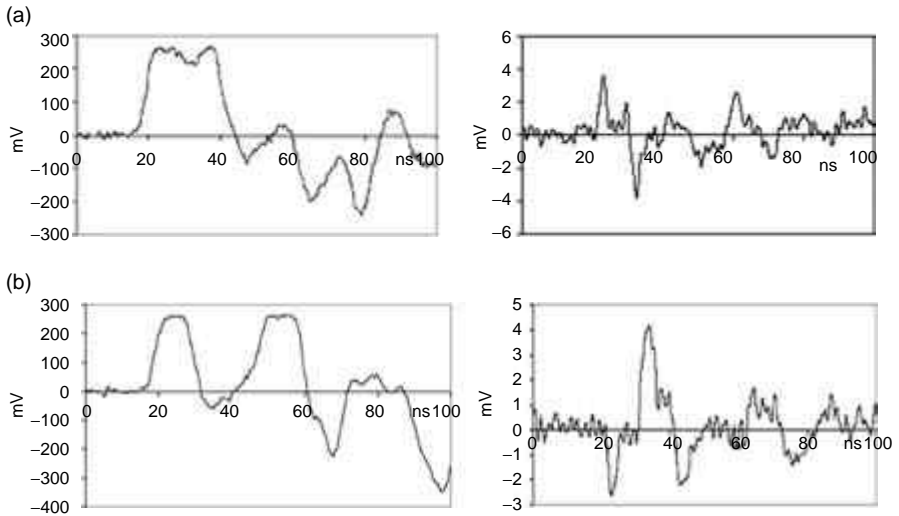


Figure 8.15 The outputs of electric (left traces) and magnetic (right traces) field probes for a partial-discharge pulse travelling along an HV busbar: (a) from left to right; (b) from right to left [13]

8.4 Summary

There is a pressing need to monitor accurately the insulation condition of HV equipment in the industry. Condition monitoring of in-service equipment is complex due to the noise problems and access difficulties. New sensors for online condition monitoring are promising and are the core of any new techniques. However, much experience is still required and further improvements necessary before the new sensors can be widely accepted by utilities.

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8.6 Problems

1. What are the advantages of optical sensors for PD measurement on HV equipment? Why are they not widely used in industry?
2. The bandwidth of a detector can significantly affect PD measurement sensitivity and the effectiveness of noise immunity. Give three examples for each case of applications of narrow, wide and UHF band detectors in PD measurements respectively.
3. Why does the directional field sensor discussed in this chapter detect the direction of travelling PD signals along a conductor? What are the principles of electric and magnetic field measurements?
4. The direction of a travelling PD pulse along a conductor can also be determined by placing two capacitive coupling sensors at a certain distance apart along the conductor. What is the principle of this directional sensor? What are the limitations of this type of directional sensor (in frequency band, distance between sensors etc.)?

Chapter 9

Online insulation condition monitoring techniques

- Noise-mitigation techniques
- Non-electrical online condition monitoring techniques
- Electrical online condition monitoring techniques

Offline condition assessment of the insulation in HV equipment is applied extensively in order to minimize the possibility of failure in service. However, the required testing and measurement procedures are sometimes impractical, costly and not indicative of operating conditions. This chapter considers the alternative of online monitoring by means of which more continuous assessment is possible under operating conditions. Some of the developments during the past decade are discussed, including a number of new techniques aimed at overcoming many difficulties in implementing in-service measurements. The cost, reliability and convenience of the new systems need to be balanced against the savings effected by reduction in outages and the extension of life of the insulating materials.

9.1 The main problems with offline condition monitoring

Although offline insulation tests, either destructive or non-destructive, are valuable for the assessment of HV equipment condition, there exist several disadvantages.

1. The equipment has to be taken out of service, which may cause an unnecessary outage or reduction in electricity supply. For example, a large steam turbine generator has to run continuously during the maintenance interval of 3–4 years. A power transformer at the critical location in a power system may need 3–6 months' preparation for loads to be transferred before it can be taken out of service.
2. The equipment cannot be continuously monitored during operation. A fault may occur between planned offline tests. Such periodic measurements cannot guarantee to detect all developing defects of significance.

3. The equipment's electrical, mechanical and chemical stresses may be impossible to duplicate when testing offline. Some insulation defects cannot be activated and detected under offline conditions. For example, during insulation tests on a stand-still generator, mechanical vibration does not exist and the voltage and temperature distributions can be very different from those present during operation.
4. The cost involved in offline tests can be expensive and time-consuming. Since the equipment has to be taken out of service and all necessary safety issues need to be addressed before the testing voltage source and instruments can be connected, long preparation and measurement times are common.

The above factors indicate that it is preferable to monitor insulation condition online. However, there are additional difficulties when testing online, such as the noise problem during PD measurements. Also, online condition monitoring results may be less accurate, although providing a meaningful continuous record, and the instruments more expensive. Nevertheless there is an increase in the development of online condition monitoring techniques and this is expected to lead to the wide application of centralized (integrated) online condition-monitoring systems.

9.2 Noise-mitigation techniques

Noise or interference is one of the difficult problems encountered during online condition monitoring, especially during electrical sensing such as in online PD measurements. Many techniques are available for noise suppression, but each may be effective only for particular equipment types and under certain conditions. Selection of noise-mitigation techniques should be made according to the specific sample/equipment, circuit connection and noise environment.

Since 1970, PD measurements on HV equipment have gained considerable importance. Extensive research has been carried out around the world for improving measurement accuracy and suppressing noise. Noise-discrimination methods mainly fall into two categories: software and hardware.

Hardware: Hardware development in PD measurements has been continuous for over half a century. Various sensors and test circuits have been developed to discriminate against noise. Although some techniques need further improvement, they are effective and may be used to establish a reliable measurement system for PD online detection. The main techniques in hardware development include:

1. new sensors such as optical-fibre sensors, directional sensors and VHF/UHF sensors, which were discussed in Chapter 8;
2. noise-gating techniques;
3. differential discrimination circuits;
4. multiple terminal measurements and comparison.

Software: Advanced digital signal-processing techniques have been used in insulation condition monitoring areas for about three decades [1–5]. The development of fast digital A/D converters also makes it possible to process noise-contaminated signals more rapidly and accurately. Although many new and advanced digital processing

techniques have been used in communication, robotics and other areas, the main techniques adopted in PD measurements are probably the following:

1. digital band-pass filters and adaptive filters;
2. digital signal averaging;
3. statistical analysis, fingerprint analysis and pattern recognition;
4. cepstrum analysis;
5. linear prediction;
6. wavelet analysis;
7. neural network analysis;
8. expert systems;
9. fuzzy-logic analysis.

Some reasonably new and effective techniques are described in this section.

9.2.1 Noise gating

Noise gating has been successfully used in PD measurements with pulse-type interference. The block diagram of a gating circuit is shown in Figure 9.1. The measurement circuit of the PD detector includes fast analogue or digital switching circuits/gates. The gate is controlled by a triggering circuit that is activated whenever noise is detected. The switch is then kept open for a certain period, e.g. 1–50 μs , depending on the behaviour of the noise and its oscillating nature. The PD measurement circuit is thus temporarily blocked and no noise can enter the measurement system. After the noise pulse finishes, the switch is closed and ready to measure the subsequent PDs. The noise from corona discharges usually lasts for 1–5 μs for high-frequency band measurements (up to 10 MHz) and 10–20 μs for lower-frequency band measurements (up to 500 kHz). In order to block noise from thyristor exciters of a generator, the blocking window should be 20–100 μs long. After the high noise is blocked, the amplifier in the detector circuit can be adjusted manually or automatically to increase the signal magnitude before sending it to the A/D converter. This can normally improve the measurement accuracy and sensitivity.

The noise-blocking process can also be illustrated in Figure 9.2, in which the noise pulses are blocked in several window sections, leaving only PDs detectable by the system.

For the detection of airborne noise and that entering the HV terminals, an RF antenna, Rogowski coil or other types of coupling sensors may be used to detect the

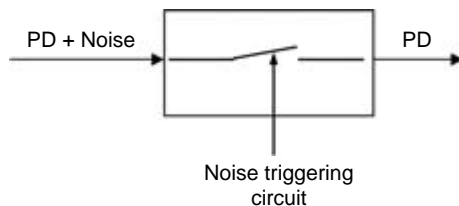


Figure 9.1 Block diagram of a noise-gating system

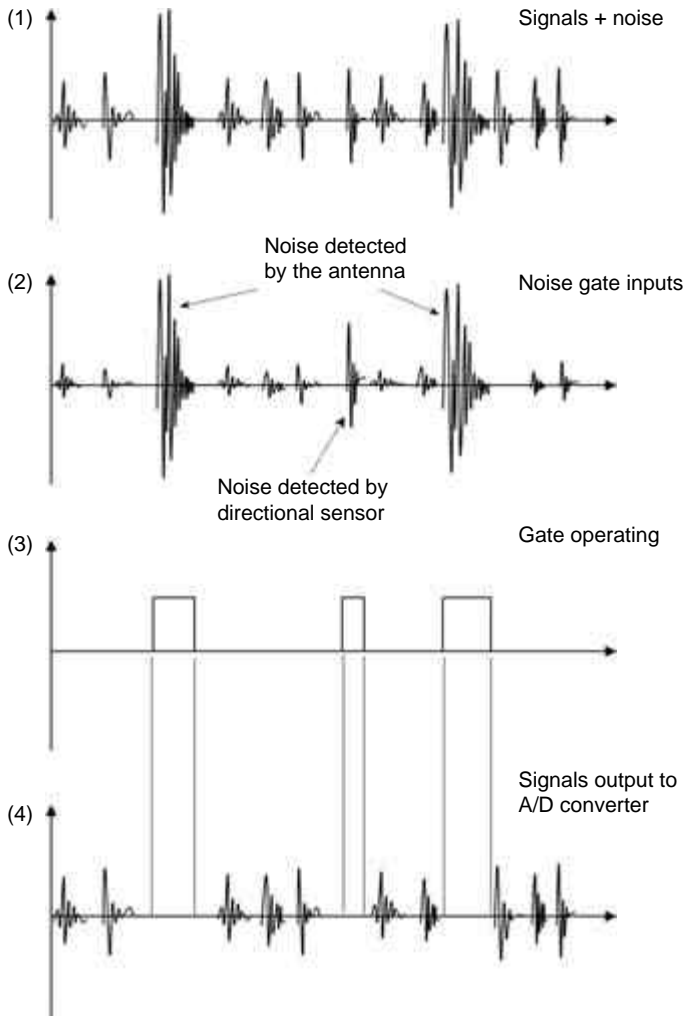


Figure 9.2 Noise gating process: (1) signal + noise; (2) noise detected by various sensors; (3) gating windows generated by noise; (4) noise removed by gate leaving PD signals to be measured

noise. Noise entering the HV terminals may also be detected by a directional sensor, as discussed in Chapter 8.

Noise may also be removed in the software of the measurement system. The detected noise can be registered in the computer program by a triggering channel and subsequently removed. For example, in the peak detection and A/D converter circuit, if the noise input channel shows a positive sign or the noise exceeds the trigger level, an additional bit will be attached to the digital signal from the A/D converter and later

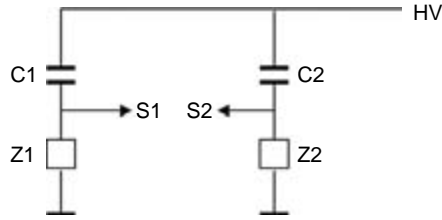


Figure 9.3 PD detection using the balanced circuit

removed in the analysis program. Software noise gating is very fast and can easily be implemented in the system, but may reduce the speed of the measurement system.

9.2.2 Differential methods

A differential circuit is designed to compare outputs of two parallel circuits. If certain criteria are met, the outputs are identified as noise and cancel each other. Otherwise the outputs are considered as PDs in the equipment and measured accordingly.

9.2.2.1 Balanced circuits

With a balanced circuit connection, PDs inside one item of equipment and noise entering from the terminal will give different responses S_1 and S_2 at the sensors, as shown in Figure 9.3. Discharges inside C_1 or C_2 produce different amplitudes and opposite polarities at the sensors, whereas noise from outside the equipment generates pulses of the same polarity, similar waveshape and almost equal amplitudes under favourable conditions. C_1 and C_2 could be two single-phase transformers, two bushings of a circuit breaker, two HV current transformers or a voltage transformer and a discharge-free capacitor. Although this is a well-known technique, the following points may be ignored, resulting in unsuccessful results.

- The measurement system must have enough resolution, which is usually achievable with wideband detectors. A poor resolution can cause overlapping of subsequent pulses, making it difficult to identify signal pairs from the same source.
- S_1 and S_2 caused by terminal noise may have different amplitudes if C_1 , C_2 and associated circuits are not identical in all frequency ranges. Terminal connections may also contribute to the difference. The problem can be alleviated if the two measurement channels can be calibrated by injecting at the common terminal and compensated by adjusting Z_1 and Z_2 .
- Although the time delay between S_1 and S_2 may cause inaccuracies, it can give additional information for discrimination of noise. This delay may be detectable for cables and certain types of transformer or generator windings.
- If C_1 and C_2 are items of equipment with HV terminals connected to long busbars, possible signal coupling between the busbars should be considered. The coupling coefficient varies in different conditions and careful calibration would be necessary.

9.2.2.2 Noise discrimination using additional discharge-free capacitor

Dave Allan of PowerLink, Australia [6], has developed a system to detect online PDs in transformer bushings using an additional discharge-free capacitor, as shown in Figure 9.4. The capacitor can be raised to touch the conductor connected to the terminal of the bushing. Signals are detected from the bushing capacitor tapping and from the PD-free capacitor for comparison. Noise from outside the transformer can then be identified. The technique has been used successfully in several substations up to 275 kV, especially for CTs in which PDs <100 pC were measured.

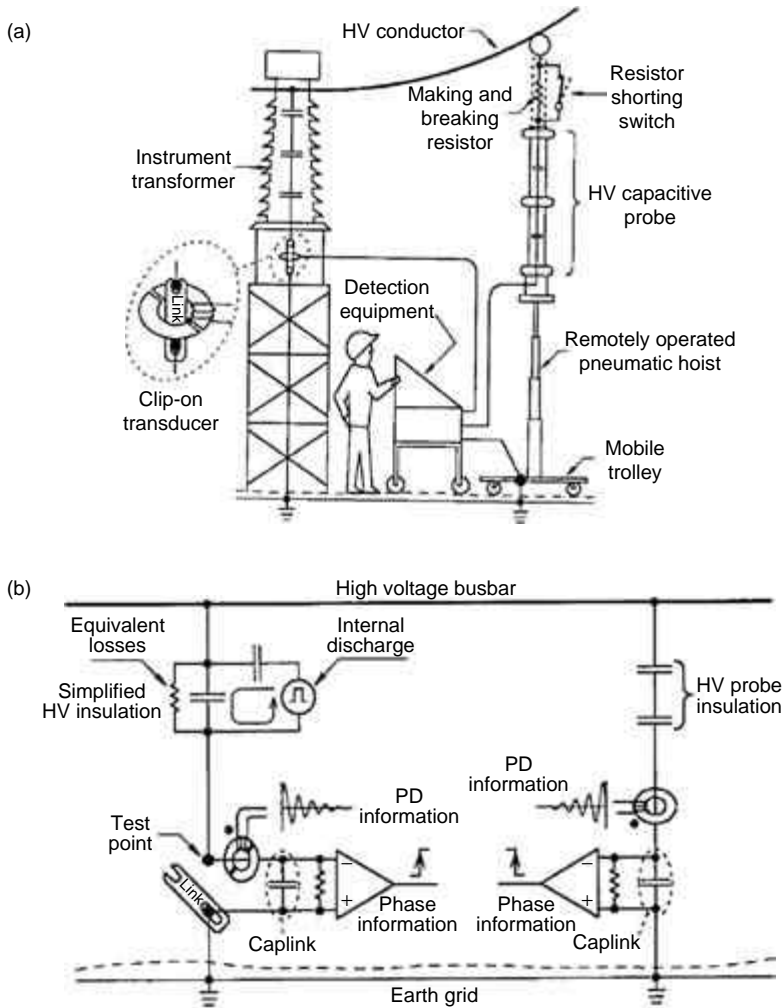


Figure 9.4 Online detection of PDs in a transformer bushing using an additional discharge-free capacitor [6]: (a) pictorial representation of the detection system; (b) principle of the technique [courtesy of Dave Allan]

9.2.2.3 Parallel circuits in HV equipment

By using two HV devices of different phases where high-frequency coupling exists, it is possible to discriminate noise by comparing the polarities of the first peaks of PDs occurring at the same time on each phase, e.g. between transformer bushings and between capacitive instrument transformers. However, in some cases a parallel circuit may be found in one piece of HV equipment for differential PD measurements. A circuit suggested by Malewski [7] is shown in Figure 9.5, where discharge pulses are detected by two high-frequency current transformers clamped around the neutral lead and the tank grounding lead of a transformer. The pulses detected at the neutral lead are reversed and added to the pulse from the tank grounding lead following certain attenuation. The sum (i.e. difference between the two CT outputs) is filtered and measured. The noise from outside the transformer produces pulses of the same polarity and are cancelled in the system, whereas internal PD signals of opposite polarity are enhanced.

Another possible differential circuit consists of two shields preinstalled in a reactor for PD detection. The two brass shields are semicylindrical in shape and located symmetrically inside the tank with leads connecting to the detection terminals. The shields act as capacitive couplers to sense PDs in the winding. Noise entering the reactor at the terminal will show the same polarity of voltages at the detection terminals, whereas

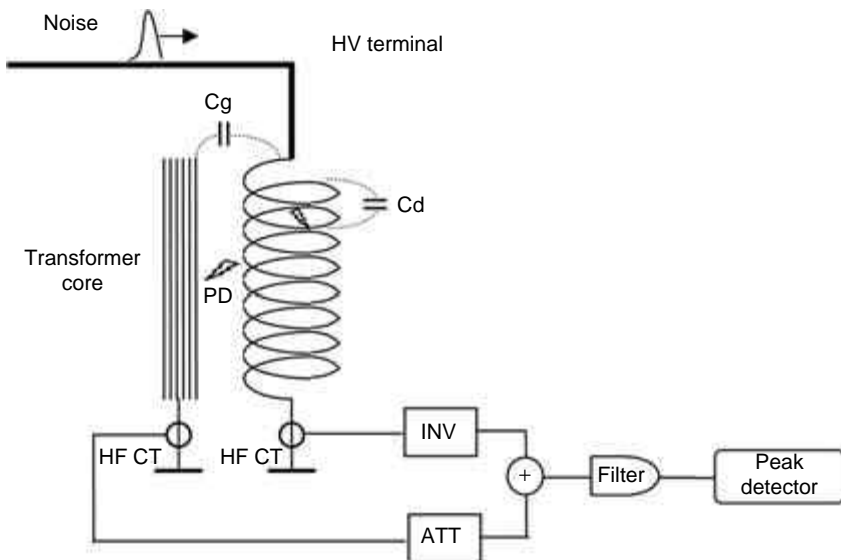


Figure 9.5 A differential circuit for noise discrimination for PD measurements on power transformers [7], where C_d – capacitance between winding turns and disks, and C_g – capacitance between HV terminal shield, winding and transformer core. Two HF CTs are clamped around the earthing leads of the core and the winding respectively

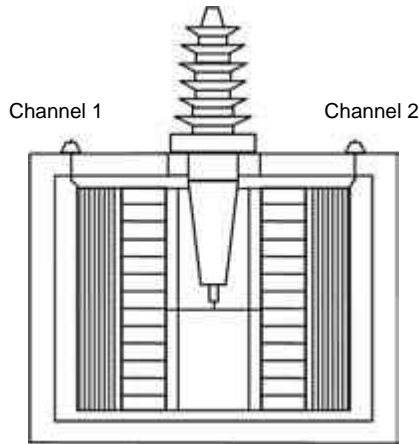


Figure 9.6 The symmetrical shields installed in an HV reactor for noise discrimination in PD measurements

PDs inside the winding generate voltages of different polarities at the terminals. The internal configuration of the reactor is shown in Figure 9.6.

9.2.3 Noise identification by signal waveform analysis

Noise may have spectra different from those of PDs, depending on its origin, frequency characteristics and location in relation to the detector. The following characteristics are helpful in identifying noise from particular sources.

- (a) Airborne pulsating noise normally has a spectrum of very high frequency and appears in the detector as high-frequency oscillations that last for relatively short times, e.g. pulses from car/truck ignitions and sparking at loose electric contacts.
- (b) Pulses from a generator exciter have much lower frequency spectra but large energy. They normally oscillate at 20 kHz–200 kHz and last for 10–500 μ s in a wideband measurement system. The low-frequency components could be filtered out by a high-pass filter.
- (c) Interferences from broadcast radio and TV stations normally appear as bursts at a certain frequency. The oscillation starts at a low magnitude, increases to a particular higher value before slowly attenuating to zero. Multiple bursts could link or overlap, thereby making a more complicated envelope of oscillation. The magnitude may change significantly, or jump up and down, if magnitude-modulated broadcast is involved in the interference.
- (d) Because of the skin effect, a conductor increases attenuation of the high-frequency components of a pulse travelling along it. This is apparent for cables and transformer and generator windings. After travelling a certain distance along a cable or winding, the waveform can be significantly smoothed at the wavefront. This distortion can be useful for the identification of noise or PDs from far distance.

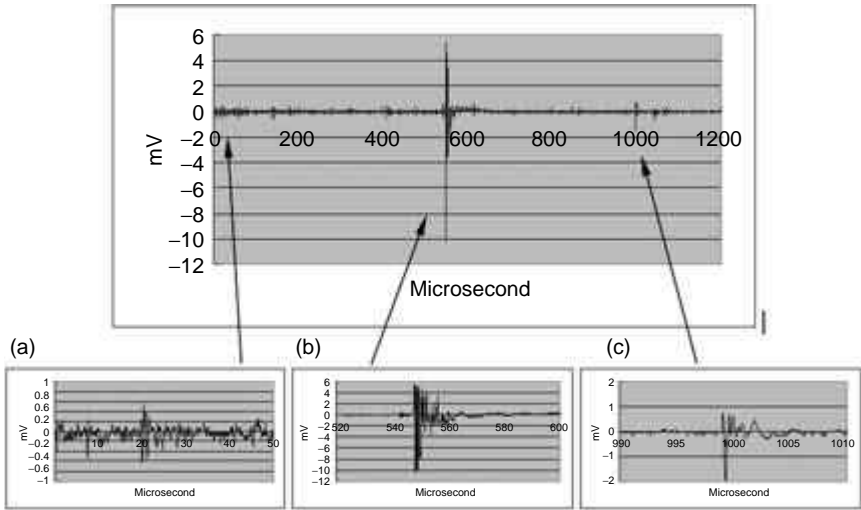


Figure 9.7 PDs and noise detected on an in-service generator using an HF CT clamped around the neutral are identified from their waveform: (a) airborne noise from motor sparking; (b) noise from the exciter; (c) PDs from the generator

Figure 9.7 shows a series of pulses detected from a generator. The very fast and short oscillations were from sparking of pump motors induced through the air. The long oscillating pulses at lower frequency were from the exciter thyristor.

Figure 9.8 shows a new technique developed by Professor G.C. Montanari and TechImp [9]. The technique is based on time-frequency transformation and fuzzy-logic classification. The equivalent time length T and bandwidth W are extracted from each pulse detected during partial-discharge measurements. Since T and W are dependent on the source and location of pulses, PDs and noise can crowd in a few regions in the W - T plane, as shown in Figure 9.8 (b). The pulses from different origins can then be separated and analysed in phase-resolved distribution (d). The features of PDs or noise from individual sources can then be analysed in some detail with fuzzy logic and other methods, leading to their identifications (e).

9.2.4 Multiple terminal PD measurements

In some equipment, it is possible to discriminate internal PDs from those occurred at the terminals or outside noise. For example, using a multiple-terminal measurement technique, PDs inside the equipment could be identified or even located. This method is especially useful for equipment having winding structures or distributed parameter circuits such as transformers, generators and cables. The principle can also be used on other types of equipment.

This technique has been applied by the authors for PD detection on transformers, especially those with interleaved windings [11]. There usually exists a frequency

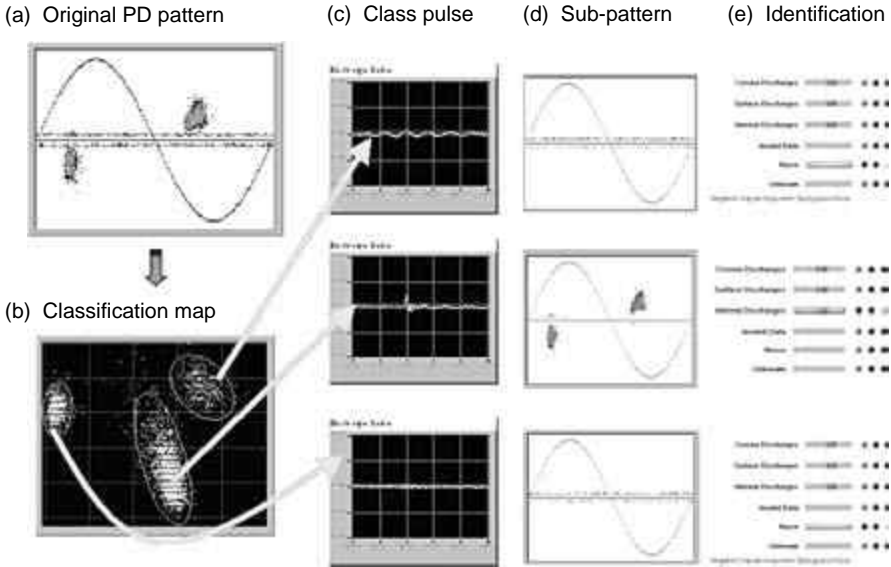


Figure 9.8 PD separation and noise-identification technique developed by TechImp [9]: (a) original PDs and noise in the phase resolved distribution; (b) PDs and noise separated to three regions in the equivalent time-length/equivalent bandwidth plane; (c) typical PD pulses and noise in the three regions; (d) the phase-resolved distributions of PDs and noise separated in (b); (e) the type of PD or noise identified by a fuzzy classification method [courtesy of Prof. G.C. Montanari]

range in which an interleaved winding can be approximated by a capacitive ladder network [10]. In ideal situations, the position of a charge may be uniquely determined by the ratio of the capacitively transmitted pulses at both terminals of the winding. As shown in Figure 9.9, after filtering with a pass-band of 300–400 kHz, which falls within the capacitive range of the model transformer winding, the ratio is monotonous with the injecting position. This suggests a method for locating discharges and discriminating noise from outside of the equipment.

Figure 9.10(a) shows the measurement results on a 66 kV transformer winding presented in three-dimensional form [10,11]. There were two discharge sources in the winding and a corona discharge at the terminal. The ratio of each pair of terminal pulses was used to determine the discharge position and displayed on the x-axis, the discharge magnitude on the y-axis and the number of discharges on the z-axis. It can be seen that the two discharge sources can be easily identified in the 3D graphs and the corona noise identified and removed from the analysis. The PDS and corona are separated according to the ratio of terminal pulse pair and analysed in the format of number-versus-magnitude (pC) and number-versus-phase distributions, as shown in Figure 9.10(b). The type of PD, or otherwise a corona, may be identified from the

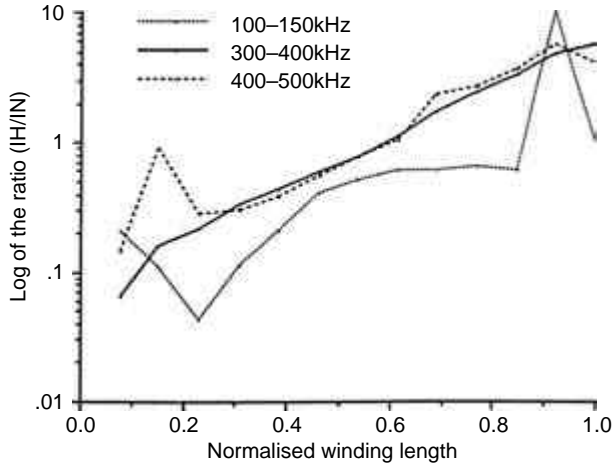


Figure 9.9 Plot of the ratio of terminal voltages versus the position of simulated discharges injected at various positions along a model transformer interleaved winding after digital filtering with various pass-bands

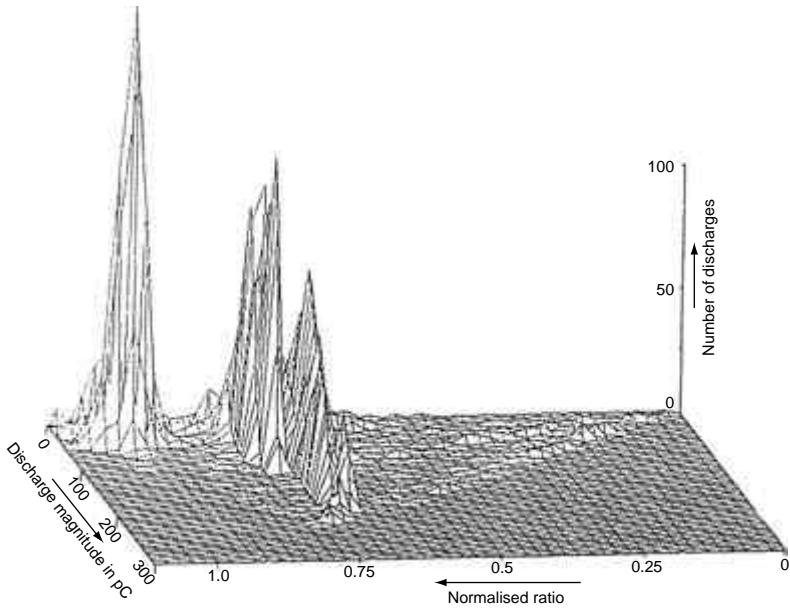


Figure 9.10 (a) A 3D pattern of PD activities of two discharge sources in a 66 kV interleaved winding and corona at the terminal [11]. x-axis: the ratio of terminal discharge pairs; y-axis: the magnitude in pC; z-axis: the number of discharges.

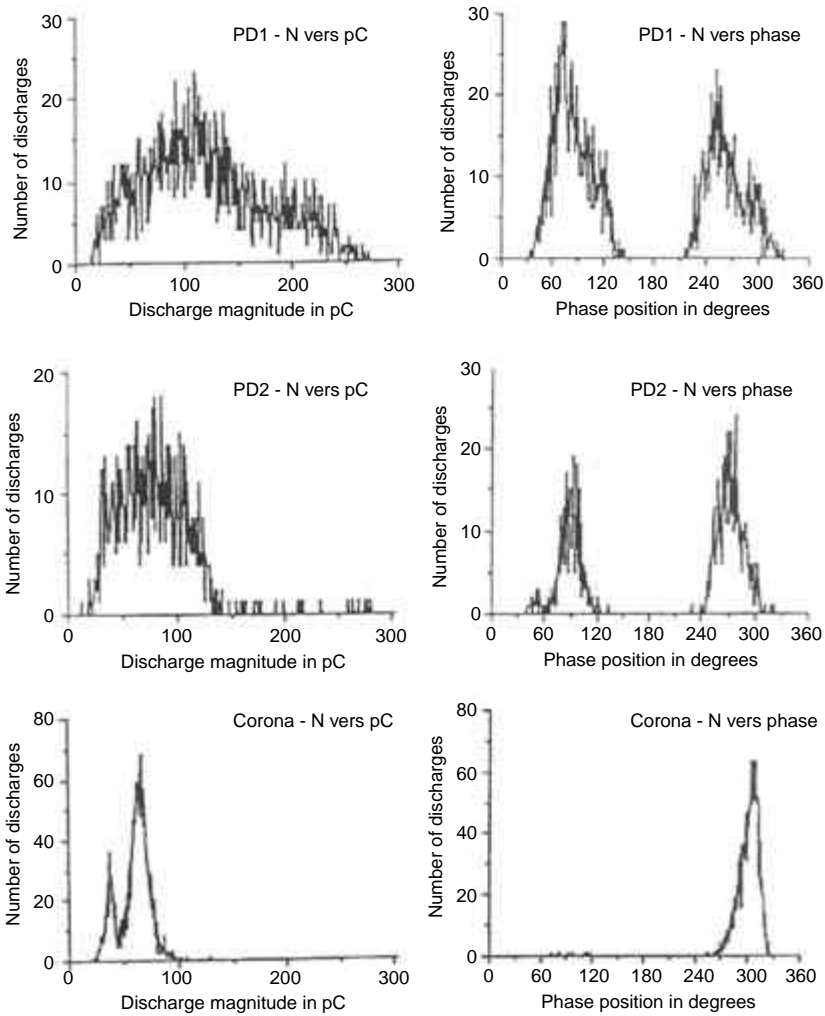


Figure 9.10 (b) Based on their ratios of terminal pulse pair, the two PDs and corona are separated and analysed in number-versus-magnitude (pC) and number-versus-phase distributions. The number-versus-phase distribution of corona shows its distinguishing characteristic that the majority of discharges occur in the AC negative half cycle.

characteristics, for example, the majority of corona discharges are in the AC negative half cycle. If the terminal disturbance includes internal PDs at the line end of the winding, software methods such as waveform analysis can be applied for separating the two types of pulse. These techniques can also be used to separate discharges from the different locations, thus allowing independent analyses. The method is excellent for assisting in the assessment of local insulation problems.

9.3 Non-electrical online condition monitoring

Online condition monitoring is preferable for continuous assessment of equipment integrity and prevention of incipient faults. The more widely accepted online insulation monitoring techniques for HV equipment rely on non-electrical characteristics such as temperature changes, acoustic emission from partial discharges, decomposition of the oil, including increase in gas content, and deterioration of the gas in GIS.

9.3.1 Temperature monitoring of the insulations

Abnormal temperature on equipment surface may indicate a deterioration of insulation losses, an increase of leakage current or a loose contact. The application of optical-fibre sensing techniques for measuring the localized changes of insulation temperatures within transformers and cables (DTS) is discussed in Section 8.2.3. Other temperature-detection methods include thermal scanning and irreversible temperature labels, which are portable or of lower cost.

9.3.1.1 Thermal scanning

Various infrared cameras are available on the market for remote thermal scanning. Because there is no need to install a sensor and the measurement is at a safe distance, the thermal scanners are widely used in the industry. A typical infrared imager is shown in Figure 9.11(a).

9.3.1.2 Irreversible temperature labels

Irreversible temperature recording labels can accurately and economically sense and record surface temperatures. Each label contains one or more sealed temperature-sensitive chemical indicators that change permanently and irreversibly from silver to black at its calibrated temperature. The response time is less than one second and, depending on the temperature rating, an accuracy of ± 1 or 2 per cent is achievable. The labels are of miniature size, weight and thickness (nominal 0.01"), which allows installation in areas and on parts that are not practical for other instruments. The label can be useful for temperature monitoring of small transformers, isolators, VT, CT and switches. A photo of a label is shown in Figure 9.12.

9.3.2 Online DGA

Dissolved-gas analysis in oil (DGA) has been widely used for the diagnosis of HV equipment with paper/oil insulation such as transformers, reactors and cable joints for many years and in many cases is the primary method of monitoring. Although periodic sampling and tests in the laboratory (offline test) have been successful in diagnosing incipient faults, there are a number of problems associated with offline DGA testing: for example:

- (a) the sampling frequency has to be conservatively selected to be effective; even so, offline periodic tests may fail to predict some failures;

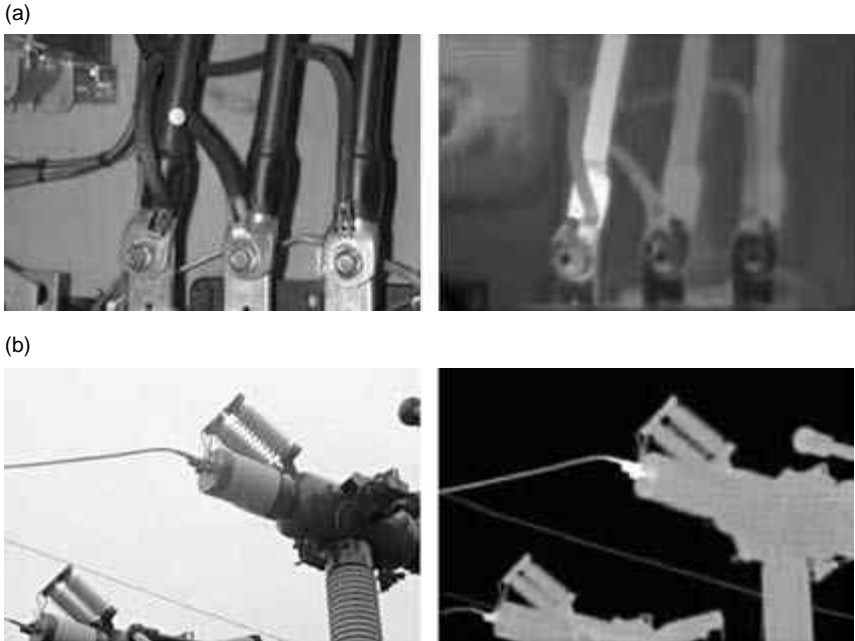


Figure 9.11 Remote thermal scanning; (a) the infrared image of LV connectors – Phase A shows a higher temperature indicating a problem of loose contact; (b) an HV air blast circuit breaker with the image showing a loose contact at the terminal [courtesy of Thermascan Ltd, <http://www.thermascan.co.uk/home.html>]

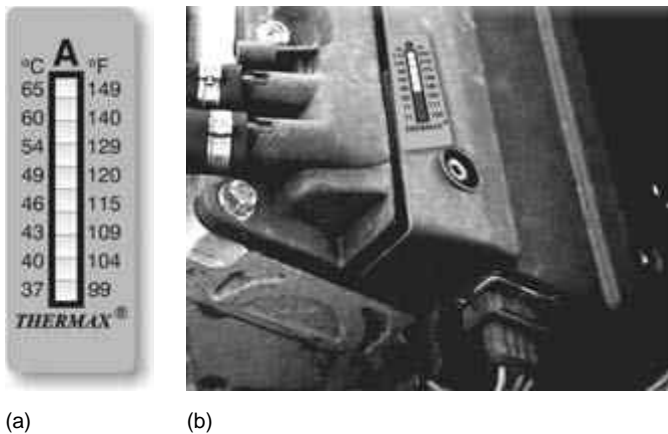


Figure 9.12 The TMC 8 level temperature label (a) and its application to the monitoring of a machine (b) [courtesy of Thermographic Measurements Co. Ltd, <http://www.t-m-c.com>]

- (b) excessive numbers of tests may incur unacceptable costs;
- (c) care is necessary in oil sampling to prevent contamination.

The main gases produced by different faults are shown in Figure 9.13. In summary, the criteria for key gas concentrations are given in Table 9.1 [12].

For some important HV transformers, online continuous monitoring of key gases is preferable. This makes it possible to monitor fast-developing faults and to evaluate their progress so that the necessary resources can be marshalled for the refurbishment or replacement of the transformer.

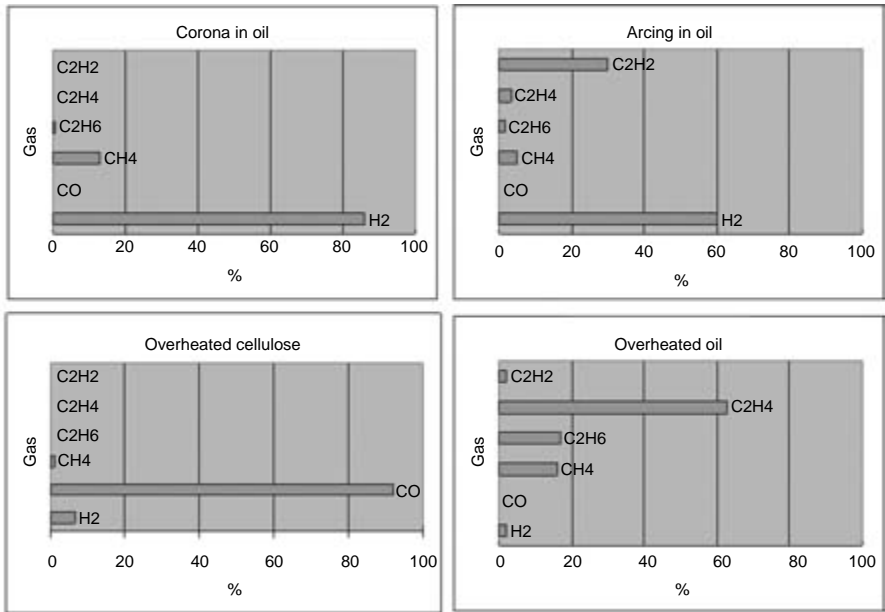


Figure 9.13 The profile gases for different faults [12]

Table 9.1 Criteria for key gas concentrations [12]

| Gas | Concentration (ppm) | Type of fault |
|---|-------------------------|----------------------|
| Hydrogen | >50 | Partial discharges |
| CO and CO ₂ | >300 and 3 000 | Degradation of paper |
| Ethylene C ₂ H ₄ | > 100 | Overheating of oil |
| Acetylene C ₂ H ₂ | >2 | Arcing in oil |
| Furan | >5 ppm (and DP >200) | Ageing of paper |



Figure 9.14 Online hydrogen monitoring on a transformer [13] [courtesy of GE Oil & Gas, http://www.gepower.com/prod_serv/products/substation_md/en/monitoring_instr_sys/hydran.htm]

A particular instrument for continuous monitoring is shown in Figure 9.14. Normally, one or a few gases are monitored by the instrument. The Hydran, made in Canada, is specifically designed to detect hydrogen and carbon monoxide in the oil. Other instruments may detect additional gases, but are more costly.

9.3.3 Acoustic-based techniques for PD detection

9.3.3.1 Transformer windings

The ultrasonic impulses transmitted through the mechanical structure of a winding associated with PDs may be used for location. If it is impossible to utilize electrical pulses from the PD and the physical conditions are favourable a discharge source may be located using a number of appropriately placed acoustic transducers. Reasonable accuracy is obtained if reflections are not significant and only direct path signals are present [14,15]. Triangulation location systems may also be used to pinpoint a location in space, provided it does not lie deep within the transformer or below a certain magnitude. An advantage of these methods is their independence of electrical noise. In some cases the detecting sensitivity has not been satisfactory, especially when the discharge sources are deep inside the coils. Enhancement of the signals may be realized by digital signal processing and averaging. However, if there is more than one discharge source and large interference is present, averaging of the acoustic signals from different sources is likely to result in confusing results. Further work is still being carried out, in particular with respect to improving sensitivity and accuracy, location of inner winding faults and interpretation of characteristic oscillations with both external and internal acoustic transducers.

9.3.3.2 Cable terminations

Acoustic PD measurements have also been developed for cable terminals and proved successful. A particular detector consists of a fibreglass stick or pipe, a sensor and

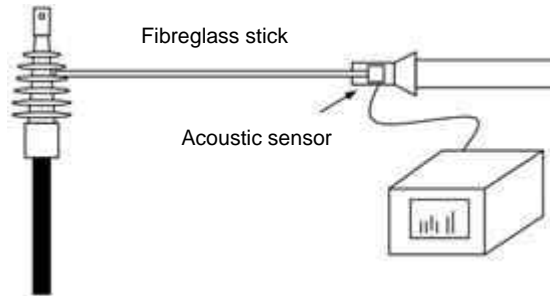


Figure 9.15 Acoustic PD detector with long fibreglass stick used for voltages up to 33 kV [17]

a monitor, as shown in Figure 9.15. Since the insulated stick/pipe can be directly applied to the cable terminal and works as a sound-wave guide, the sensitivity of measurement is higher than for other acoustic sensors placed at a distance from the discharge source.

9.3.3.3 Portable acoustic PD detector

Acoustic guns are also used for the detection of discharges around equipment surfaces such as the HV terminals (for corona discharges). As shown in Figure 9.16, the battery-powered portable PD detector can be used for PD detection on HV equipment. With the directional feature, the detector can help to locate PD sources and alleviate the noise problem in site measurements. However, for internal discharges in the insulation, the



Figure 9.16 A battery-powered detector used in PD detection and location of HV equipment [courtesy of May Elektronik GMBH, <http://www.may-elektronik.de/>]

sensitivity may be reduced. Nevertheless, they are used widely in the laboratory and at site to detect corona discharges due to insulation design problems, cracking on porcelain insulators and bad contact, etc.

9.4 Online acoustic/electric PD location methods for transformers

Examples are given of the application of acoustic transducers used in conjunction with (i) the associated electrical pulse measured at the terminal (9.4.1) and (ii) the radiated electrical pulse detected by a sensor within the transformer tank (9.4.2). The viability of the methods depends on knowledge of the velocity of sound through the oil (approximately 1.4m/ms) and the fact that the electrical pulses are detected almost instantaneously.

9.4.1 Acoustic transducers and winding terminal measurements

The usual combined tests are carried out with a number of acoustic transducers external to the tank and records obtained at the terminal (bushing tap) of the electrical pulses as well as those from the transducers. By triggering on the acoustic pulses and determining the prior time-delay range expected for the electrical signal – estimated from the tank dimensions and the structural layout – it is possible to obtain an indication of the probable location of a PD source.

An improvement on the above procedure is to measure electrical PDs at both the HV terminal and the neutral and apply the signal separation methods detailed in Section 9.2.4 in order to achieve signal enhancement. This also enables an estimation of the PD magnitude at the source if within the winding. A new technique has been developed using a combined electric/acoustic method [15]. The measurement circuit for a 330 kV single-phase transformer is shown in Figure 9.17. After digital filtering of the discharge signals measured at the HV terminal and neutral, the ratio of each pair of signals was used to separate them according to their different source locations and distinguish each from external interference. The electrical signals that were likely to be occurring at the same discharge source were averaged, as were their associated acoustic signals, resulting in a significant improvement in the detection sensitivity and location estimate as shown in Figure 9.18. By suitable calibration techniques and knowledge of the probable location within the winding, an estimate of the PD magnitude at its site may be possible.

9.4.2 Application of internal combined acoustic and VHF/UHF transducers

A particular system for location of PDs in transformers has been developed by the University of Technology, Sydney, and Siemens Ltd [16]. The technique utilizes specially designed composite acoustic transducers, which are matched to the acoustic impedance of the oil and have a short ring-down time. Around each transducer is located a capacitive ring for detection of the radiated RF pulse. The capacitive sensor

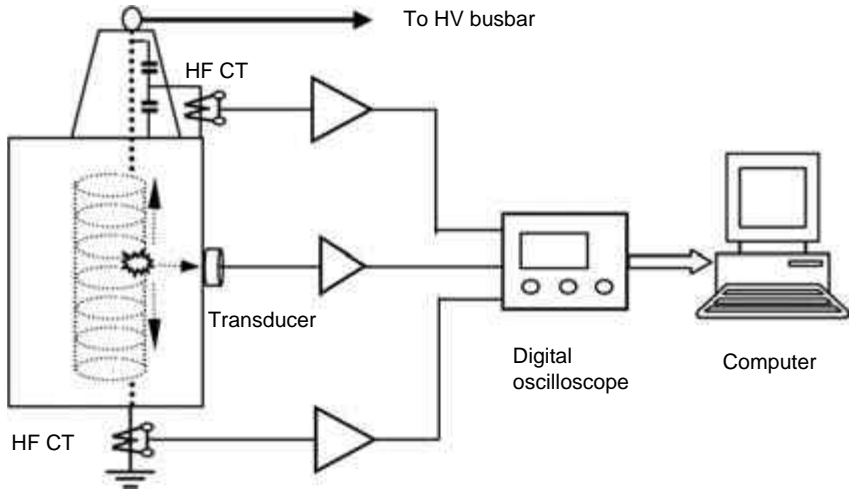


Figure 9.17 Circuit connection of PD measurement on a 330kV single-phase transformer using a combined electric/acoustic PD detection method

operates in a tuned circuit within 10–100 MHz. The combined unit is inserted through the transformer tank side/lid mounted on an inspection plate as shown in Figure 9.19. A modified arrangement allows insertion through an oil drain valve. The face of the combined transducer is kept flush with the inner surface of the tank thus minimizing the possibility of forming a hazard during the transformer operation.

Due to the internal mounting, interference effects are reduced and sensitivity increased compared with externally located transducers. Acoustic matching of the sensor is good. However, the versatility in positioning is reduced. Also, the VHF sensor is not calibrated in terms of pCs. The system can incorporate continuous remote monitoring of any changes in the output of a number of acoustic transducers, which may identify a PD based on correlation of the sound and RF signals. The signal processing includes estimates of the locations in relation to the sensors.

9.5 Electrical online condition monitoring

Although offline insulation tests, either destructive or non-destructive, are very useful for the assessment of HV equipment condition, as indicated in Section 9.1, it is preferable to use online tests. With electrical online tests, the insulation defects can be directly assessed from the values and changes of the electrical properties. However, since all HV equipment is under high electrical stress, the electrical interferences such as corona and harmonic voltages always make online electrical monitoring more difficult. Advanced techniques in hardware design and software analysis have to be utilized in achieving the desired results.

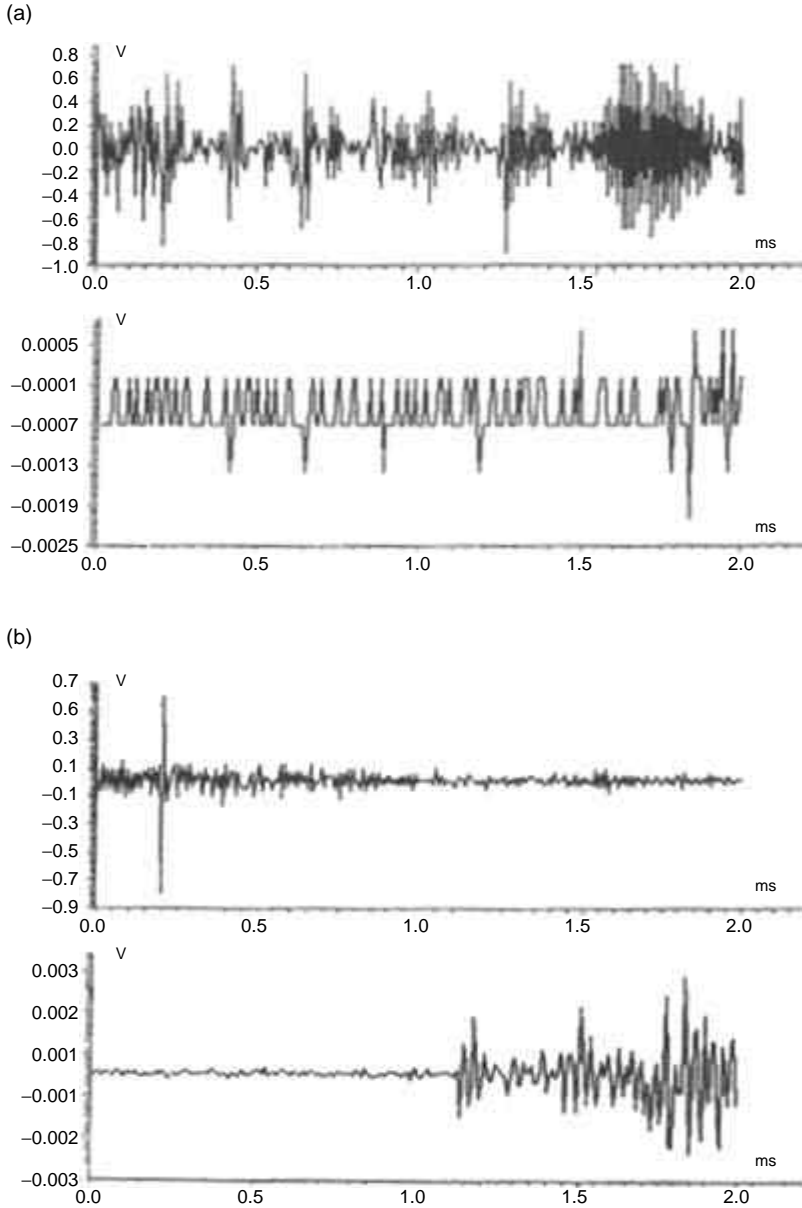


Figure 9.18 The electrical and acoustic PD signals simultaneously measured on a 330 kV transformer [15]: (a) a single record; (b) after averaging 30 times the discharges from the same source (X – millisecond, Y – volt)

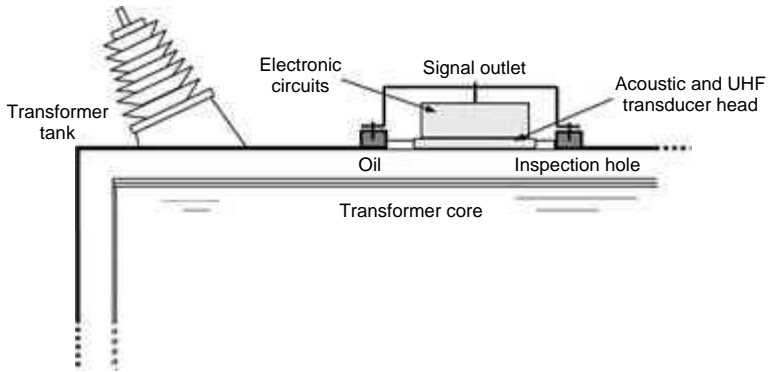


Figure 9.19 Combined acoustic and RF transducers for installation in inspection hole [16]

9.5.1 Online dielectric dissipation factor and capacitance measurements

As discussed in Chapter 2, dielectric dissipation factor (DDF) or dielectric loss angle (DLA), and capacitance are important indicators of insulation deterioration. During laboratory tests, various instruments can be used to accurately measure DLA and capacitance of HV equipment (see Chapter 6). However, accurate measurement of DLA and capacitance is more difficult for equipment in service.

9.5.1.1 Principle of DLA and capacitance measurement

For a lossless capacitor, the current leads the voltage 90° . Practically, the loss always exists and changes the phase difference to slightly smaller than 90° , as shown in Figure 9.20. The voltage of an HV device can be measured through a voltage transformer (VT) and the current flowing through the device by a current transformer in the earth lead. For most CTs and transformer/reactor bushings, the DLA and capacitance can be determined by the voltage and current measured but not to the accuracy as described in Chapter 6. It should be noted that, because the phase shift is very small, it is difficult to measure accurately the DLA and capacitance using this method. Also, as it changes with temperature and other environmental parameters, the DLA of a piece of HV equipment may change significantly with time, which makes the detection of equipment insulation deterioration less sensitive. Although this has been the main disadvantage, from sophisticated calibration and temperature compensation reasonable reliability can be achieved for the detection of insulation defects through trend analysis.

9.5.1.2 Relative measurement method

The difference in DLA or phase of the current (after a shift of 120° or 240°) between different phases of equipment can be used to detect more accurately an insulation

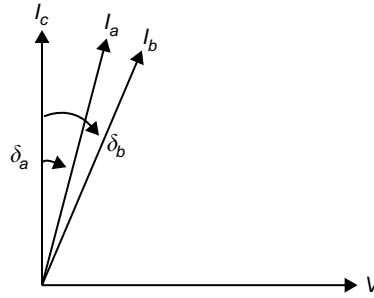


Figure 9.20 Phase difference between voltage and current for a lossless capacitor, and for phases a and b with different losses

Table 9.2 Identification of the faulty phase from comparison – examples

| | $\Delta\delta_{ab}$ | $\Delta\delta_{bc}$ | $\Delta\delta_{ca}$ | Remarks |
|---------------------------|---------------------|---------------------|---------------------|--|
| Comparison between phases | Larger | Larger | Small | Phase b may have an insulation problem |
| Change with time | Small | Larger | Larger | Phase c may have an insulation problem |

problem in one phase. By monitoring the difference between phases and its changes with time, the faulty phase can be identified and repaired accordingly, as shown in Table 9.2.

9.5.1.3 Practical online measurement system

A few integrated DLA and capacitance-monitoring systems have been developed in the world for online continuous condition monitoring of CTs, capacitive VTs and transformer bushings. The one developed by Dave Allan of PowerLink, Australia, is shown in Figure 9.21 [6]. The system comprises current (voltage) sensors to measure the current waveform, phase encoders to pick up the phase information from wave-shape conditioning, an optical-fibre transmission system and DLA calculation and display unit. The arrangement has been installed in a number of switchyards.

9.5.2 Online leakage current measurement

Most outdoor HV equipment has porcelain housings, e.g. CTs, VTs, bushings and surge diverters. Due to contamination, moisture or cracking of the porcelain housings, surface creepage discharges/currents may occur, which can significantly reduce the electric strength. Online monitoring of the leakage current can be used to detect

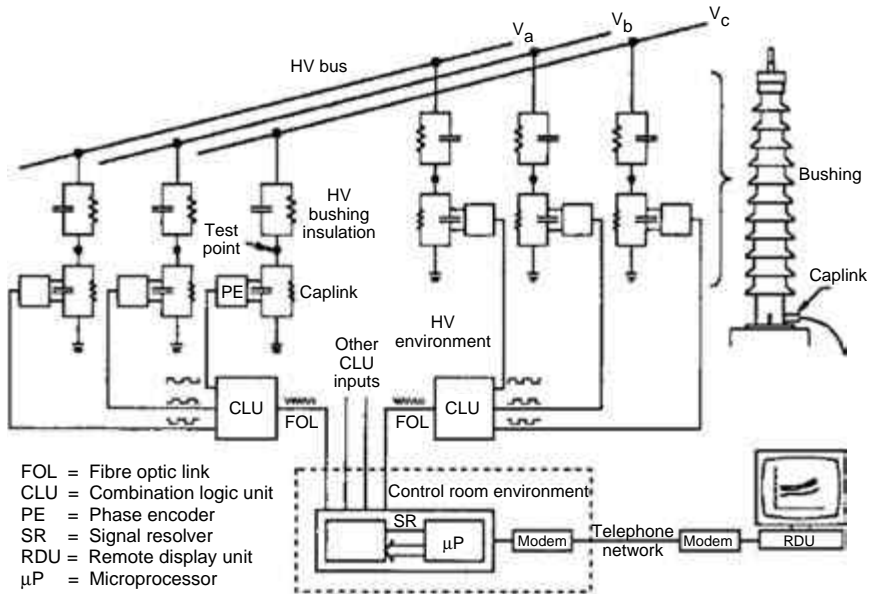


Figure 9.21 An online DLA monitoring system for CTs, CVTs and transformer bushings in a substation [6] [courtesy of Dave Allan]

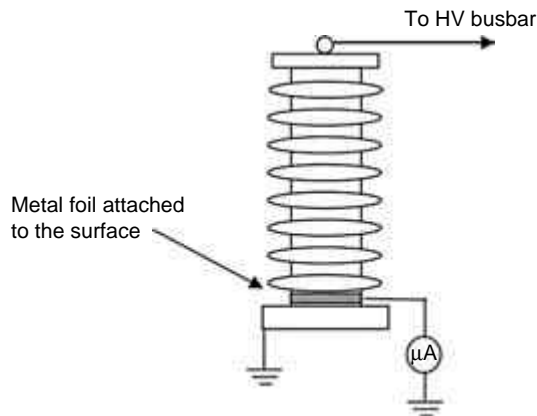


Figure 9.22 Online leakage current monitoring

incipient failure. The detecting circuit is depicted in Figure 9.22. If the low-voltage end of the porcelain housing is directly grounded, an additional electrode made of metal foil may be installed around the housing surface to detect the leakage current. Similar systems are used for monitoring high-voltage surge diverters.

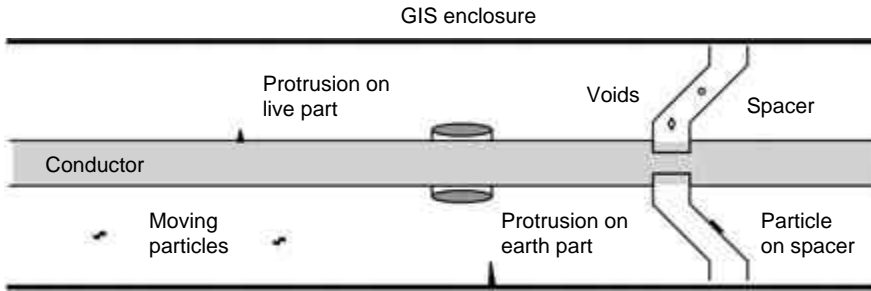


Figure 9.23 The main defects inside GIS resulting in PDs [18]

9.5.3 Electrical online PD detection

9.5.3.1 GIS PD detection

Due to the completely sealed HV circuit and the use of pressurized gas (SF_6) as the main insulation, GIS has the advantage of a compact structure and low maintenance requirements. Although GIS are usually very reliable, online PD detection is necessary for commissioning tests and condition monitoring for detecting any developing defects.

Metallic-particle contaminants are the most critical defects in GIS. They may develop from:

1. mechanical abrasions;
2. movement of conductors under load cycling;
3. vibrations during shipment and in service.

Defects and particles may be created during the production of the unit in the factory or during assembly at site. In normal operation, particles could also be produced by fast-earthing switches or disconnecter switches. The main defects in GIS are depicted in Figure 9.23.

Conventional test methods (IEC 60270) are usually applied during commissioning but these tend to be insensitive due to the poor coupling between the sensors and the PD sites. To obtain the required sensitivities of <5 pC, UHF sensors and associated systems, including remote monitoring, have been developed [18]. The frequency band might be up to the GHz range depending on different design and sensitivity requirements. At such high frequencies, each sensor can cover only a certain distance of the compartment/busbar. Therefore multiple sensors have to be installed to monitor the whole GIS. Typical UHF sensors used in GIS are shown in Figure 9.24.

9.5.3.2 Transformer PD detection using VHF and UHF sensors

In addition to online acoustic location of PDs in transformers, as indicated earlier, a number of organizations have developed systems for measuring the PD values on line. These are based on:

1. single-ended measurements using the bushing tap only and advanced signal processing including phase resolved analysis for identification and separation of interference [19];

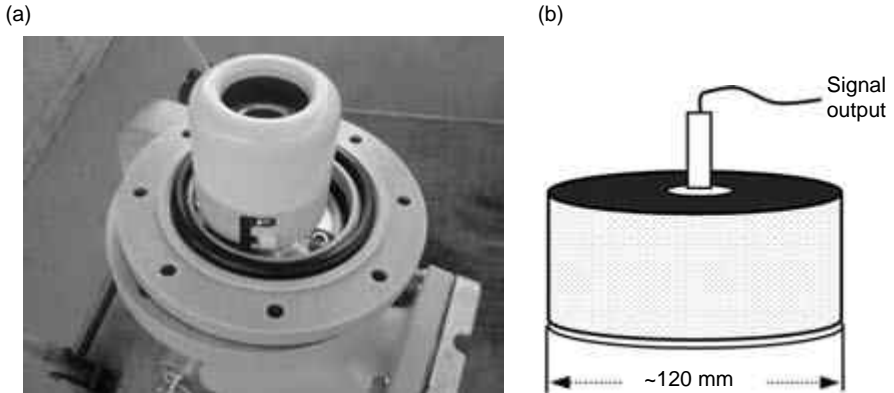


Figure 9.24 UHF sensors used for PD detection in GIS: (a) the sensor attached to the earthing switch inside GIS; (b) the sensor used externally on the observation window [18]

- multiple-terminal measurements including neutral and tank ground connections and appropriate signal processing to isolate interference effects [20].

Recent techniques aimed at reducing interference problems have applied the knowledge acquired from GIS investigations involving UHF detection methods. The KEMA patented system [21] includes capacitor-type sensors, as does that developed by the University of Strathclyde [22]. The latter studies show that at UHF it should be possible to locate PDs and characterize them in respect of energy and phase position.

9.5.3.3 Online PD detection on power cables

There are mainly two types of power cable – paper/oil and XLPE. These have significantly different PD levels. For XLPE cables, the allowed PD magnitude should be under 5–50 pC depending on the different voltage levels. On the other hand, paper/oil cables can tolerate larger PDs of even a few hundred pC. Therefore, online PD measurements at the terminal could be successful for paper/oil cables if appropriate techniques are used to discriminate against interference. For XLPE cables, more advanced techniques should be used to achieve a higher S/N ratio. Probably the most widely accepted technique for online PD detection is VHF/UHF sensing, which is specifically used for PD detection on cable joints. It has been found that cable joints and terminations are still the weakest part of a cable circuit.

In order to detect PDs in cable joints, prefabricated capacitive sensors imbedded inside the joint may be used, giving higher sensitivity and reducing noise problems. However, these internal sensors tend to make the cable structure more complicated and more expensive.

Sensors can also be installed outside the cable joint, such as the one developed by some Japanese companies [23]. The principle of this technique is shown in Figure 9.25. Two metal-foil electrodes are installed around the cable on each side of the joint. The capacitance between the foil and the conductor forms the coupling

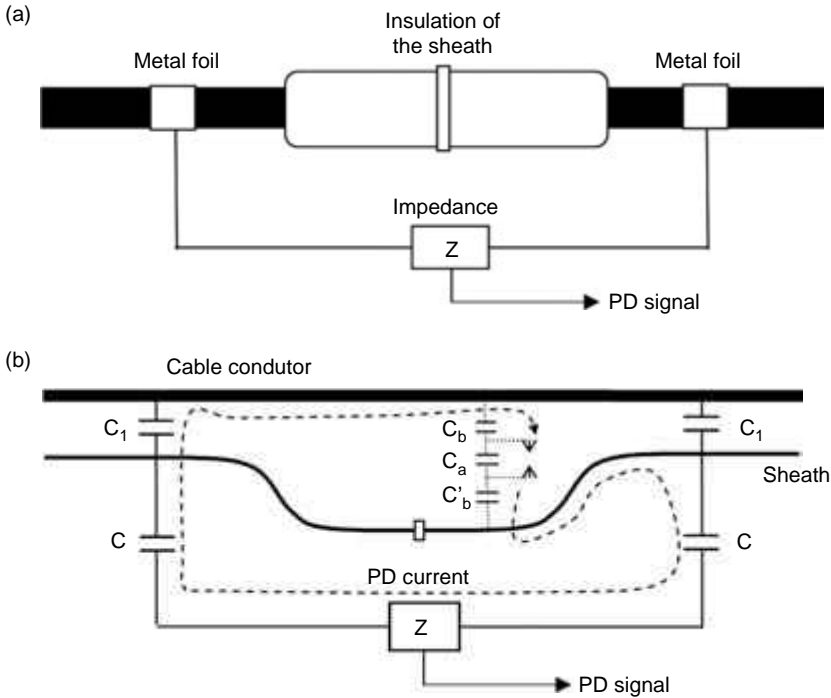


Figure 9.25 Online PD detection on cable joint: (a) schematic circuit connection; (b) the principle and main PD current flow path [23,24], where: C – capacitance between cable sheath and the metal foil which is installed on both sides of the joint; C_1 – capacitance between the conductor and cable sheath; C_a , C_b and C'_b – capacitances associated with a PD in the cavity in cable insulation; Z – impedance for PD detection

circuit for PD current to flow through the impedance connected to the two electrodes. A narrow frequency band of 100 kHz is used and the centre is approximately 25 MHz. Using this detector, a sensitivity of better than 5 pC has been achieved for PD measurements on in-service cable joints.

A similar system has been developed by Lemke Diagnostics (LDIC) with a maximum bandwidth of 2–600 MHz. Such methods are being applied experimentally by a number of research groups.

9.5.3.4 Online PD detection in large rotating machines

Generators have complicated winding structures. A simplified winding configuration and terminal connection are shown in Figure 9.26. Discharges and interference of various origins can produce impulsive currents in the neutral lead.

The high-frequency components of slot discharges (1) and those on the other end of the generator (2) will be significantly attenuated before reaching the neutral,

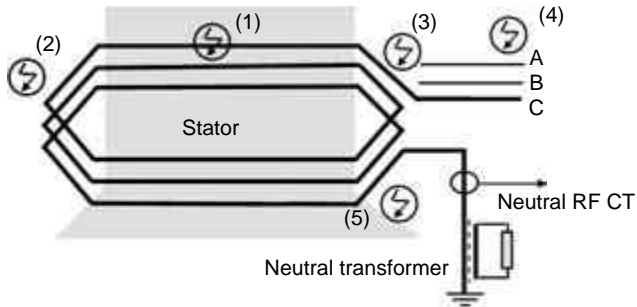


Figure 9.26 Discharge sources from inside and outside of the generator

whereas the low-frequency components do not remarkably reduce their magnitudes. High-frequency components of the discharges on the HV terminal end (3, 4) and interference (5) may easily be coupled through the overhang section to the neutral, resulting in a difference in the low- and high-frequency responses in the neutral currents.

9.5.3.5 RF current detector

A radio frequency current transformer mounted on the neutral grounding lead has successfully been used to detect internal generator arcing [25–27]. A prototype RF online monitor was developed by Emery *et al.* [27], which can continuously monitor the neutral current and alert the operator if the arcing level becomes destructively high. This technique may also be used for PD detection if the interference problem can be overcome.

Another method using RF techniques was described by Miller and Hogg in their paper [28]. Their results demonstrated that with the aid of Fourier transformation techniques the changing pulse shape may be used to locate the source and classify the type of discharges. Further investigations are necessary for the application to practical generators.

9.5.3.6 The Ontario Hydro Partial Discharge Analyser (PDA)

The Partial Discharge Analyser (PDA) developed by Ontario Hydro is a technique for the measurement of PD pulse-height distributions in rotating machines in the presence of static excitation and other common-mode noise [29,30]. The measurements are performed by connection to coupling capacitors permanently installed on the terminal's high-voltage conductors. Each phase has two capacitors connected as directional couplers. The length of the coaxial cable from each coupler is determined such that unwanted pulses emanating from the outside system arrive simultaneously at the differential input of the PDA, resulting in cancellation of the pulses, whereas pulses from within the generator arrive from each coupler with different delay times, resulting in a measurement. The circuit connection is depicted in Figure 9.27.

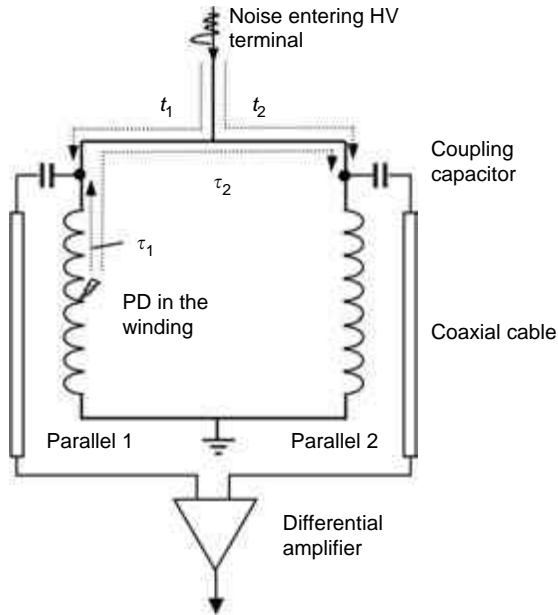


Figure 9.27 Ontario Hydro differential coupler installation [29] (note: for external noise $t_1 = t_2$ and PD in winding $\tau_1 \neq \tau_2$)

The PDA detects the steep pulses, which are considered to be capacitively coupled between the end windings of each turn, as little of the high-frequency components are conducted through the slots. From regular measurements on an individual machine and comparison with the historical data, the changes in discharge performance can be monitored and the insulation condition evaluated from previous knowledge of itself and similar units.

9.5.3.7 Ontario Hydro – IRIS Turbo-Generator PD Analyser (TGA)

Due to the different structural configurations of turbo-generators and larger interference levels, a stator slot coupler for sensing PDs in turbo-generators has been developed [31]. The sensor is essentially a directional electromagnetic coupler fitted in the slot, under the stator winding slot wedges between layers of wedge packing. Because of its location close to the slot conductors, the sensor is sensitive only to partial discharges but not the interference because of the filtering effect of the stator structure. Output voltages of the sensor have very high frequency (rise time being within a few ns), which are measured by a specially designed detector. The layout of the sensor is shown in Figure 9.28. The number of sensors is normally six in this system.

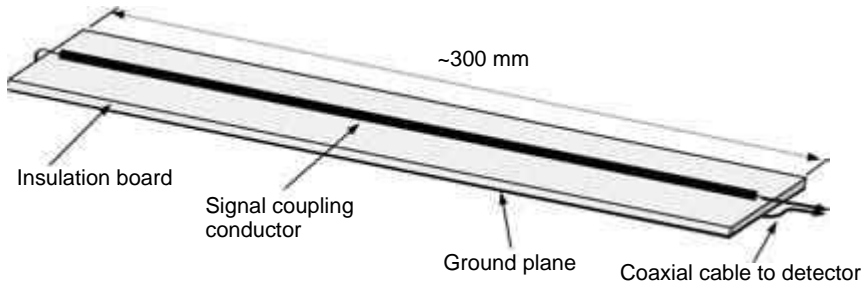


Figure 9.28 The simplified schematic of the stator slot coupler [31]

9.5.3.8 UNSW–SMHEA PD detector

In the late 1980s, a team at the University of New South Wales, in collaboration with engineers from Snowy Mountains Hydro-Electric Authority developed a PD detection method for hydraulic generators [32,33]. The method is based on the travelling wave and capacitively coupled PD signals detected at the HV terminal of the stator winding. The capacitively coupled part of a PD in the winding appears at the terminal almost instantaneously, whereas, the travelling wave part takes up to 7–8 μs to reach the same terminal depending on the PD source location and the stator winding structure and size. The time delay is then measured, which can be used to discriminate PD from noise as well as locate the discharge. The circuit connection is shown in Figure 9.29 and the PDs detected on a 200 MW hydro generator are shown in Figure 9.30.

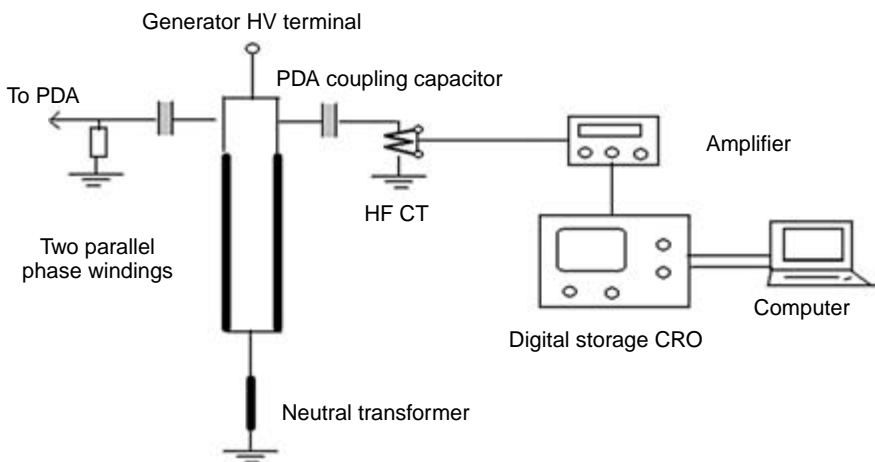


Figure 9.29 Test circuit connection (only one phase winding is depicted)

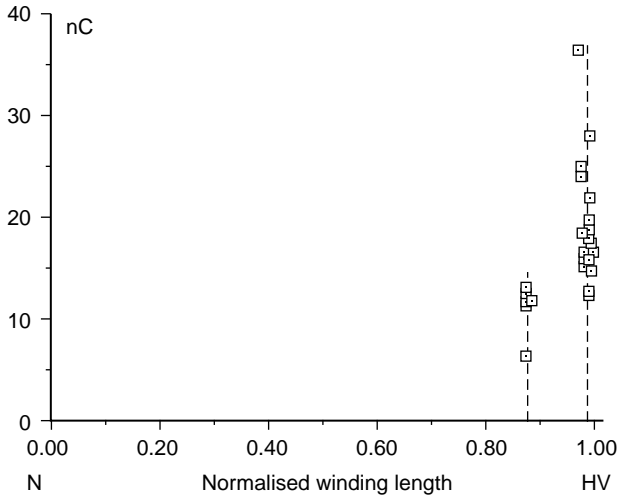


Figure 9.30 Apparent charge magnitudes versus estimated locations of the PDs detected on a 200 MW generator showing two possible PD sources at 87.4 per cent and 98.5 per cent of the winding [33]

9.6 Summary

Although condition monitoring on in-service equipment is difficult due to the noise problem, new techniques have been developed that make the operation of HV equipment safer and more reliable. There are two forms of online monitoring: (i) periodical measurements utilizing built-in sensors with portable instrumentation; and (ii) complete systems continuously recording the data. Online continuous condition monitoring should be integrated into a centralized monitoring system, which needs an advanced communication system using optical fibres, digital radio and even infrared techniques. This has placed a challenging task for future condition monitoring engineers who should be well equipped with knowledge in these areas as well as the operation and physical structure of the HV equipment.

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9.8 Problems

1. What are the advantages and disadvantages of online PD measurements on a generator? What are the differences of the electrical, mechanical and thermal stresses experienced by a generator during online and offline PD measurements?
2. What are the main techniques for noise mitigation in PD measurements? Take each from hardware and software approaches and explain the principle and implementation procedures for these techniques.
3. The dielectric loss is usually temperature-dependent, which may affect online DLA measurement and make it difficult to interpret the measurement results. What methods can be used to alleviate the problem?
4. A PD exists at the connection lead of the HV winding of a 500 kV 600 MVA transformer. The transformer is of paper/oil insulation and its HV bushings have capacitive taps. What techniques and sensors do you think will be promising to determine the type of fault (PD) and/or locate the discharge?

Chapter 10

Artificial-intelligence techniques for incipient fault diagnosis and condition assessment

- Database and expert systems for fault diagnosis
- Transformer DGA fuzzy-logic diagnosis
- Fuzzy-logic condition assessments and ranking

In general, fault diagnosis may be defined as a problem of pattern recognition. The pattern vector consisting of detected parameters can be correlated with its counterpart – a set of classes or types of incipient fault and no-fault. From the observed symptoms or/and test results (data) of equipment, an expert could make a general reasoning to derive the cause or causes using his/her knowledge and experience. However, it may be more objective and accurate when artificial intelligence is employed to establish the links between the cause and results behind the observations. An artificial-intelligence technique could consolidate the knowledge and experiences from a number of experts. It could even learn and improve itself from the cases it examines. During the last decade, many applications of artificial intelligence for incipient fault diagnosis of HV equipment have been developed in the world. It is not within the scope of this book to include all different methods and techniques. This chapter concentrates only on some of the techniques and applications developed by the authors. Interested readers can refer to relevant technical papers and books for detailed information.

10.1 Database for condition assessment

The number of HV devices in an electrical utility runs into several thousands. The devices need to be tested periodically for the monitoring of their insulation conditions. Many diagnostic tests can be carried out on each device, which produces an enormous number of data. Without a suitable computer database, manual storage and analysis of the data would be very difficult as well as time-consuming. Also, when a piece of HV

equipment is in question, it is often required to provide the management board with a sound and economic basis for the major decisions that will have to be made concerning possible refurbishment, life extension or replacement. Although condition monitoring can give an early warning about the insulation condition, there is no single technique that alone can guarantee to detect all the range of faults and give a reliable estimation of remnant life. For this reason, combined monitoring systems are required to provide a pool of data that will be analysed thoroughly so that an integrated assessment of equipment condition may be achieved. The accurate assessment also depends on the historical test record to establish a trend associated with normal operating conditions.

10.1.1 *A computer database and diagnostic program*

In most cases, accurate diagnosis of a piece of HV equipment or a cable needs the application of a number of techniques. The analysis of combined diagnostic test results and their trends can be made easier with the aid of a computer database.

A database to meet all the above requirements should have the following features:

- can store and retrieve a large number of data;
- is easy to use and fast in data retrieving;
- can process data and present results in graphical and tabular forms;
- can be incorporated within expert systems and other artificial intelligence;
- is reliable and secure.

The database software package developed by Monash University HVICM Group in the 1990s fulfils most of the above requirements. The front page of the ICMT-2.0 program is shown in Figure 10.1. Some advantages of the database – fuzzy logic – expert system are listed below.

- **Ease of use and large storage:** All options on the screen are in pull-down form with appropriate instructions. Information about all HV equipment in each power station of a utility (rated voltage, current, power and years in service, etc.) can be stored.
- **Graphical presentation:** Trends of test results can be illustrated graphically, which gives a better assessment of the insulation condition. Figure 10.2 shows the trend of dielectric loss angle ($\tan\delta$) of an HV motor presented in graphical form in ICM-2.0.
- **Searching for abnormal test results:** The test results over a certain limit can be determined and displayed on the screen in tabular forms. A number of queries have been designed, e.g. asking to show all transformers with one or more gases exceeding the guided values.
- **Reporting:** The test results can be printed out in a report.
- **Security:** There is a security system. The low-level password is for general users who can only *view* the data. To add to or change the data, a high-level password must be used, which may be issued to authorized personnel only.



Figure 10.1 The database and expert system ICM-2.0 developed at Monash University

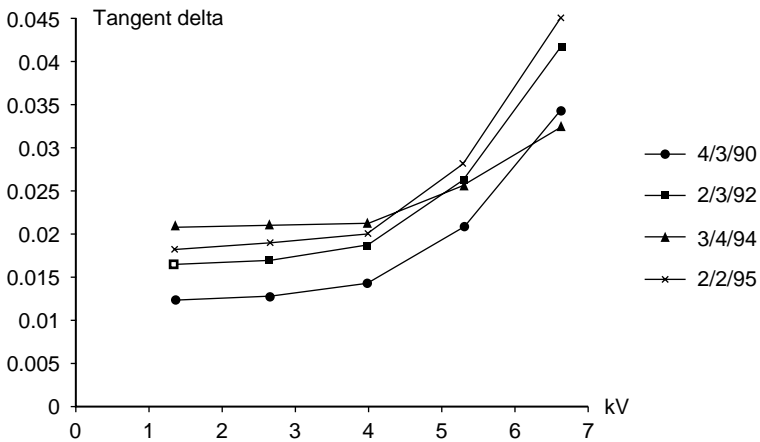


Figure 10.2 The trend of dielectric loss angle ($\tan\delta$) of an HV motor against voltage presented in graphical form in ICM-2.0

10.1.2 A combined method for DGA diagnosis

Large power transformers are probably the most important equipment in an electrical transmission system. Correct diagnosis of their incipient faults is vital for safety and reliability of an electrical network. An in-service transformer is subject to electrical and thermal stresses, which can break down the insulating materials and release

Expert diagnosis of equipment T8–45D

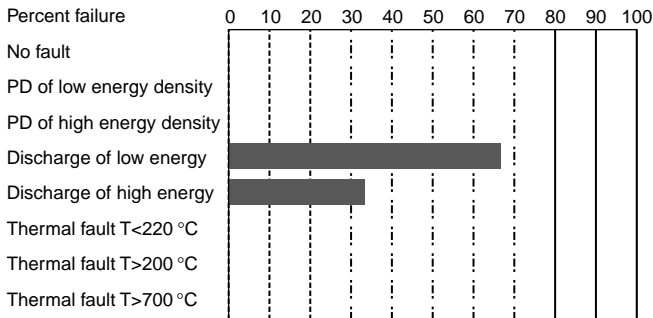


Figure 10.3 DGA interpretation using a combined diagnostic method

gaseous decomposition products. Overheating, partial discharge and arcing are three primary causes of fault-related gases. There are many interpretative methods based on DGA to diagnose the nature of transformer deterioration, such as the IEC ratio codes, Rogers and triangle methods [1–3], which were developed from intensive investigations on gases generated from individual faults.

It has been found for a long time that the interpretation of DGA results using different conventional methods can be different and confusing. Each of these methods may have its own features in fault diagnosis. It is therefore useful to combine these methods and derive the results statistically. For example, the IEC code, Rogers and triangle methods may bear 40 per cent, 30 per cent and 30 per cent of weight respectively. The interpretation will be based on the normalized total value as calculated from these three methods based on the last three tests. The combined method can then determine the possibility for each fault in an isobar format. As shown in Figure 10.3, the diagnostic results using this method clearly show that the transformer tested is most likely to have a fault of low-energy discharge.

10.2 Fuzzy-logic fault diagnosis

Although DGA has been widely used in the industry, in some cases the conventional methods fail to provide a diagnosis. This normally happens to those transformers that have more than one type of fault. In practice, the conventional diagnostic methods are based on the ratio of gases generated from a single fault or from multiple faults but with one of dominant nature in a transformer. When gases from more than one fault in a transformer are collected, the relation between different gases becomes too complicated and may not match the predefined codes. For instance, the IEC codes are defined from certain gas ratios, which increase across the defined limits (boundaries); the code changes suddenly between 0, 1 and 2 (Table 10.1). In fact, the gas ratio boundary may not be clear (i.e. fuzzy), especially when more than one type of fault exists. Therefore, between different types of fault, the code should not

Table 10.1 IEC ratio codes

| IEC codes | | | |
|---|-------------------------------|--------------------|-------------------------|
| Sharply defined ranges of the gas ratio | Codes of different gas ratios | | |
| | $\frac{C_2H_2}{C_2H_4}$ | $\frac{CH_4}{H_2}$ | $\frac{C_2H_4}{C_2H_6}$ |
| <0.1 | 0 | 1 | 0 |
| 0.1–1 | 1 | 0 | 0 |
| 1–3 | 1 | 2 | 1 |
| >3 | 2 | 2 | 2 |

change sharply across the boundaries. New methods based on fuzzy logic and neural networks may improve the accuracy of DGA diagnosis.

10.2.1 The conventional methods

In dissolved gas analysis, the IEC codes have been used for several decades and considerable experience accumulated in the world to diagnose incipient faults in transformers. Early interpretations were concentrated on specific gas components such as hydrogen and methane for the determination of discharges in the oil. This simplistic approach was refined by a number of researchers [1–3] who investigated the ratios of certain gases to establish more comprehensive diagnostic techniques. These techniques were standardized by IEC in 1978 in *Guide for Interpretation of the Analysis of Gases in Transformer and Other Oil Filled Electrical Equipment in Service* and its revision IEC 60599-1999 [8]. The individual gases used to determine each ratio and its assigned limits are shown in Table 10.1. Codes are then allocated according to the value obtained for each ratio and the corresponding fault characterized, as shown in Table 10.2.

Although the IEC code method is useful for the assessment of transformer insulation, it cannot determine the possibility of a fault. Also, in some cases, the DGA results cannot be matched by the existing codes, making the diagnosis unsuccessful. In multiple-fault conditions, gases from different faults are mixed, resulting in confusing ratios between gas components. This can be dealt with only with the aid of more sophisticated analysis methods such as the fuzzy-logic diagnostic method presented in this section.

10.2.2 A fuzzy-logic method

During the last two decades, several methods have been developed in the world to use artificial intelligence for more accurate diagnosis [4–7]. These methods are mostly suitable for transformers with a single fault or a dominant fault. In principle, these methods are still based on the specific set of codes defined from certain gas ratios, as

Table 10.2 Fault classification according to the IEC Gas Ratio Codes

| No. | Fault type | $\frac{C_2H_2}{C_2H_4}$ | $\frac{CH_4}{H_2}$ | $\frac{C_2H_4}{C_2H_6}$ |
|-----|---|----------------------------|--------------------|-------------------------|
| 0 | No fault | 0 | 0 | 0 |
| 1 | Partial discharges of low energy density | 0 (but not significant) | 1 | 0 |
| 2 | Partial discharges of high energy density | 1 | 1 | 0 |
| 3 | Discharges of low energy | 1 or 2 | 0 | 1 or 2 |
| 4 | Discharges of high energy | 1 | 0 | 2 |
| 5 | Thermal fault of low temperature, <150 °C | 0 | 0 | 1 |
| 6 | Thermal fault of low temperature, 150–300 °C | 0 | 2 | 0 |
| 7 | Thermal fault of medium temperature, 300–700 °C | 0 | 2 | 1 |
| 8 | Thermal fault of high temperature, >700 °C | 0 | 2 | 2 |

shown in Table 10.1. In addition, there are also some other limitations in the previous fuzzy diagnosis methods.

In general, in order to diagnose more accurately the incipient faults in a transformer, the key gases should be analysed and the trend of individual faults determined. These could be achieved by the fuzzy-logic method presented in this section. It employs fuzzy boundaries between different IEC codes (i.e. the fuzzy IEC code) with demi-Cauchy distribution function. The critical level of key gases is also treated with the same fuzzy method and combined with the fuzzy IEC codes. Each fault in a transformer can then be assessed by the fuzzy vector and the trend of fault development with time can be closely monitored. For multiple faults in a transformer, this technique can be used to monitor the trend of each fault.

10.2.2.1 Fuzzy IEC codes

According to the IEC codes in Table 10.1, the three gas ratios $r_1 = \frac{C_2H_2}{C_2H_4}$, $r_2 = \frac{CH_4}{H_2}$ and $r_3 = \frac{C_2H_4}{C_2H_6}$ can be coded as 0, 1 and 2 for different ranges of ratios (note, r_1 , r_2 and r_3 are larger than or equal to 0). Table 10.1 is rearranged to give a clear relationship between the range of each gas ratio and the corresponding IEC code, as shown in Table 10.3. For example, the codes for a set of gas concentration $\frac{C_2H_2}{C_2H_4} < 0.1$, $\frac{CH_4}{H_2} > 1$ and $1 \leq \frac{C_2H_4}{C_2H_6} \leq 3$ are $\text{Code}(r_1) = 0$, $\text{Code}(r_2) = 2$ and $\text{Code}(r_3) = 1$. According to Table 10.2, the transformer is diagnosed to have a No. 7 fault, i.e. thermal fault of medium temperature 300–700 °C.

Table 10.3 Gas ratios and corresponding IEC codes rearranged from Table 10.1

| Ratio \leftrightarrow Code(<i>r</i>) | 0 | 1 | 2 |
|--|-------|-------|----|
| $r_1 = \frac{C_2H_2}{C_2H_4}$ | <0.1 | 0.1–3 | >3 |
| $r_2 = \frac{C_2H_4}{H_2}$ | 0.1–1 | <0.1 | >1 |
| $r_3 = \frac{C_2H_4}{C_2H_6}$ | <1 | 1–3 | >3 |

In the IEC code diagnosis, actually the conventional logic AND and OR are used. For example, the seventh fault is represented by

$$f(7) = code_{zero}(r_1) \text{ AND } code_{two}(r_2) \text{ AND } code_{one}(r_3),$$

where $code_{zero}(r_1)$, $code_{two}(r_2)$ and $code_{one}(r_3)$ are the logics of coded values of gas ratio r_1 , r_2 and r_3 respectively. They are either one (true) or zero (false) according to Table 3.

For example, $code_{zero}(r_1) = \begin{cases} 1 & \text{for } r_1 < 0.1 \\ 0 & \text{for } r_1 \geq 0.1 \end{cases}$. Therefore, fault $f(7)$ will be either one (true) or zero (false) by means of the logic operation $code_{zero}(r_1) \text{ AND } code_{two}(r_2) \text{ AND } code_{one}(r_3)$.

In the fuzzy-diagnosis method developed, however, the IEC codes 0, 1 and 2 are reconstructed as fuzzy sets ZERO, ONE and TWO. Each gas ratio r can be represented as a fuzzy vector

$$[\mu_{ZERO}(r), \mu_{ONE}(r), \mu_{TWO}(r)],$$

where $\mu_{ZERO}(r)$, $\mu_{ONE}(r)$, $\mu_{TWO}(r)$ are the membership functions of fuzzy code ZERO, ONE and TWO respectively. The membership function is represented by a descending or/and an ascending demi-Cauchy distribution function [11]:

$$\mu_d(r) = \begin{cases} 1 & \text{if } r \leq A \\ \frac{1}{1+(\frac{A-r}{a})^2} & \text{if } r > A \end{cases} \tag{10.1}$$

$$\mu_a(r) = \begin{cases} 1 & \text{if } r \geq A \\ \frac{1}{1+(\frac{A-r}{a})^2} & \text{if } r < A \end{cases} \tag{10.2}$$

where a and A are a pair of parameters that can be selected to give appropriate membership functions [4]. In diagnostic tests, A and a can be regarded as the boundary parameter and distribution parameter respectively. From (10.1) and (10.2), the fuzzy IEC codes ZERO, ONE and TWO are formed. For each set of ratios, the corresponding fuzzy IEC codes can then be determined.

The fuzzy-diagnosis vector $F(i)$ ($i = 0-8$) is then determined by replacing the logic ‘AND’ with the minimization operation and the logic ‘OR’ with the

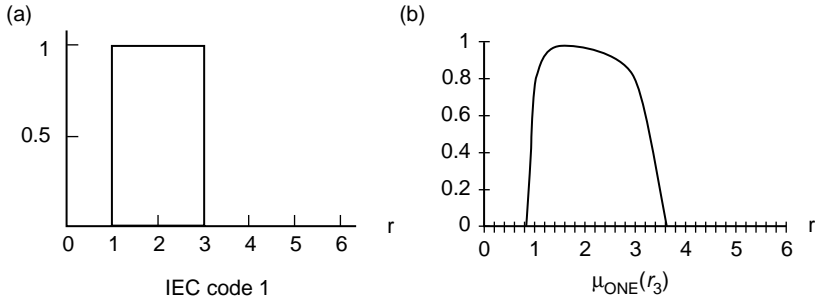


Figure 10.4 Comparison between IEC code 1 and fuzzy IEC code ONE for the gas ratio $r_3 = \frac{C_2H_4}{C_2H_6}$

maximization operation. In other words, the fuzzy multivalued logic is used to substitute for the conventional true-false logic [9]. Based on the IEC rules, different faults (from No. 0 to 8 in Table 10.2) can be diagnosed by the following equations:

$$\begin{aligned}
 F(0) &= \min[\mu_{ZERO}(r_1), \mu_{ZERO}(r_2), \mu_{ZERO}(r_3)] \\
 F(1) &= \min[\mu_{ZERO}(r_1), \mu_{ONE}(r_2), \mu_{ZERO}(r_3)] \\
 F(2) &= \min[\mu_{ONE}(r_1), \mu_{ONE}(r_2), \mu_{ZERO}(r_3)] \\
 F(4) &= \min[\mu_{ONE}(r_1), \mu_{ZERO}(r_2), \mu_{TWO}(r_3)] \\
 F(5) &= \min[\mu_{ZERO}(r_1), \mu_{ZERO}(r_2), \mu_{ONE}(r_3)] \\
 F(6) &= \min[\mu_{ZERO}(r_1), \mu_{TWO}(r_2), \mu_{ZERO}(r_3)] \\
 F(7) &= \min[\mu_{ZERO}(r_1), \mu_{TWO}(r_2), \mu_{ONE}(r_3)] \\
 F(8) &= \min[\mu_{ZERO}(r_1), \mu_{TWO}(r_2), \mu_{TWO}(r_3)] \\
 F(3) &= \max\{\min[\mu_{ONE}(r_1), \mu_{ZERO}(r_2), \mu_{ONE}(r_3)], \\
 &\quad \min[\mu_{ONE}(r_1), \mu_{ZERO}(r_2), \mu_{TWO}(r_3)], \\
 &\quad \min[\mu_{TWO}(r_1), \mu_{ZERO}(r_2), \mu_{ONE}(r_3)], \\
 &\quad \min[\mu_{TWO}(r_1), \mu_{ZERO}(r_2), \mu_{TWO}(r_3)]\}
 \end{aligned}$$

The equations are then normalized as:

$$F_r(i) = \frac{F(i)}{\sum_{j=0}^8 F(j)}, \quad i = 0-8 \tag{10.3}$$

A comparison between the conventional IEC code 1 $code_{one}(r_3)$ and the fuzzy membership function $\mu_{ONE}(r_3)$ for gas ratio $r_3 = \frac{C_2H_4}{C_2H_6}$ is shown in Figure 10.4.

10.2.2.2 Fuzzy key gases

Three key gases are commonly used to identify particular faults according to the following rules:

C_2H_2 – Arcing (discharge of high energy)

H_2 – Corona (partial discharge)

C_2H_2 – High temperature oil breakdown

(thermal fault of high temperature $> 700^\circ C$)

Each fault is indicated by the excessive generation of the relevant gas above its designated threshold. For different voltage levels, winding structures and types of transformer, the threshold may be different. The threshold can be determined from previous experience for a certain type of transformer. From fuzzy logic theories [9], the membership functions of the fuzzy set 'LOW', 'MEDIUM' and 'HIGH' for each key-gas can then be represented as descending demi-Cauchy distribution function $\mu_L(x)$ or ascending demi-Cauchy distribution function $\mu_H(x)$ or their combination $\mu_M(x)$. For every given key gas concentration x , the corresponding fuzzy vector is therefore $[\mu_{LOW}(x), \mu_{MED}(x), \mu_{HIGH}(x)]$.

The fuzzy-diagnosis vector $F_k(i) (i = 0-8)$ is then determined in the same way as the fuzzy IEC code.

10.2.2.3 The fuzzy IEC code – key gas method

The fuzzy IEC code – key gas method (FIK) – developed is a combination of fuzzy diagnoses using the IEC codes and key gases. The combined fuzzy-diagnostic vector is represented by

$$F(i) = w_1 F_r(i) + w_2 F_k(i) \quad i = 0-8 \quad (10.4)$$

where w_1 and w_2 are the weights to relate the fault with the fuzzy IEC codes and key gases respectively. w_1 and w_2 can be 0.5/0.5 or determined from previous experience. $F(i)$ is normalized to make the total fuzzy component equal to 1.

10.2.2.4 Applications

Using the FIK method, a number of 110–330 kV power transformers were diagnosed and some typical results are given in Table 10.4. It can be seen from sample No. 1 that the new method is generally in agreement with the IEC method for transformers of a single or a dominant fault. Compared with the IEC method, the FIK method also has some advantages. For example, due to no matching codes, 13 transformers could not be diagnosed by the IEC method but are diagnosed by the FIK method, as shown in Table 10.4, Nos. 2–3, for some typical results. In some cases, the faults may be only at the early stage or intermittent, which did not produce sufficient gases to give a stronger indication, such as F(2) in No. 2 and F(6–8) in No. 3. However, the information obtained should be useful for future trend analysis. Transformer No. 4 was diagnosed by the IEC method to have a thermal fault of medium temperature

Table 10.4 Comparison of diagnosis results from the FIK method and the conventional IEC method

| No. | Conventional IEC method | | Fuzzy IEC code – key gas method (FIK) | | Comments |
|--------------|-------------------------|---------------------------|---------------------------------------|----------------------------------|--|
| | IEC code | Explanatory note | Fuzzy fault components | Explanatory note | |
| 1 | 020 | Thermal fault (150–300°C) | F(0) = 0.479 | Normal ageing | Both FIK and IEC diagnose a thermal fault (150–300°C), indicating a general agreement between these two methods. |
| | | | F(1) = 0.006 | PD of low energy | |
| | | | F(2) = 0.006 | PD of high energy | |
| | | | F(3) = 0.000 | Discharge of low energy | |
| | | | F(4) = 0.005 | Discharge of high energy | |
| | | | F(5) = 0.000 | Thermal fault (<150°C) | |
| | | | F(6) = 0.496 | Thermal fault (150–300°C) | |
| | | | F(7) = 0.000 | Thermal fault (300–700°C) | |
| F(8) = 0.009 | Thermal fault (>700°C) | | | | |
| 2 | 100 | No match | F(0) = 0.525 | Normal ageing | IEC cannot diagnose but FIK indicates a high-energy PD fault which could be at an early stage. |
| | | | F(1) = 0.053 | PD of low energy | |
| | | | F(2) = 0.231 | PD of high energy | |
| | | | F(3) = 0.045 | Discharge of low energy | |
| | | | F(4) = 0.050 | Discharge of high energy | |
| | | | F(5) = 0.000 | Thermal fault (<150°C) | |
| | | | F(6) = 0.047 | Thermal fault (150–300°C) | |
| | | | F(7) = 0.000 | Thermal fault (300–700°C) | |
| F(8) = 0.050 | Thermal fault (>700°C) | | | | |

| | | | | |
|---|----------------------|--|--|---|
| 3 | 121 | <p>No match</p> <p>F(0) = 0.005 F(1) = 0.052 F(2) = 0.052 F(3) = 0.000 F(4) = 0.408 F(5) = 0.000 F(6) = 0.161 F(7) = 0.161 F(8) = 0.161</p> | <p>Normal ageing</p> <p>PD of low energy</p> <p>PD of high energy</p> <p>Discharge of low energy</p> <p>Discharge of high energy</p> <p>Thermal fault (<150°C)</p> <p>Thermal fault (150–300°C)</p> <p>Thermal fault (300–700°C)</p> <p>Thermal fault (>700°C)</p> | <p>IEC cannot diagnose probably due to the existence of more than one fault. The fuzzy component of the early thermal fault indicated by FIK is useful for future trend analysis. Actual fault was an arc damage to the core.</p> |
| 4 | 021 | <p>Thermal fault (300–700°C)</p> <p>F(0) = 0.007 F(1) = 0.026 F(2) = 0.026 F(3) = 0.000 F(4) = 0.030 F(5) = 0.000 F(6) = 0.003 F(7) = 0.477 F(8) = 0.431</p> | <p>Normal</p> <p>PD of low energy</p> <p>PD of high energy</p> <p>Discharge of low energy</p> <p>Discharge of high energy</p> <p>Thermal fault (<150°C)</p> <p>Thermal fault (150–300°C)</p> <p>Thermal fault (300–700°C)</p> <p>Thermal fault (>700°C)</p> | <p>IEC diagnoses medium temperature fault, but actually both medium- and high-temperature faults existed as indicated by FIK. Two locations of overheating damages were found due to eddy currents and a bad contact.</p> |
| 5 | Below nominal values | <p>F(0) = 0.479 F(1) = 0.005 F(2) = 0.057 F(3) = 0.441 F(4) = 0.013 F(5) = 0.000 F(6) = 0.000 F(7) = 0.000 F(8) = 0.005</p> | <p>Normal</p> <p>PD of low energy</p> <p>PD of high energy</p> <p>Discharge of low energy</p> <p>Discharge of high energy</p> <p>Thermal fault (<150°C)</p> <p>Thermal fault (150–300°C)</p> <p>Thermal fault (300–700°C)</p> <p>Thermal fault (>700°C)</p> | <p>Although the gas level is below the guide value, an early indication of low-energy discharge by FIK should be useful for trend analysis in the future.</p> |

Table 10.5 Gas concentration for the transformers listed in Table 10.4 (in ppm)

| No. | H ₂ | CH ₄ | C ₂ H ₂ | C ₂ H ₄ | C ₂ H ₆ | IEC ratio codes |
|-----|----------------|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------|
| 1 | 95 | 110 | <0.1 | 50 | 160 | 020 |
| 2 | 120 | 17 | 4 | 23 | 32 | 100 |
| 3 | 300 | 490 | 95 | 360 | 180 | 121 |
| 4 | 200 | 700 | 1 | 740 | 250 | 021 |
| 5 | 25 | 3 | 0.1 | 0.1 | 0.1 | below guide level |

(300–700 °C). In comparison, the FIK method indicates that both high (>700 °C) and medium temperature (300–700 °C) faults existed. The likelihood of each fault is given by the fuzzy components of 0.477 and 0.431 respectively. The analysis results of another transformer (No. 5) show that, although the gas level is below the guide value, the FIK method can still be used and a low-energy discharge is diagnosed. The fuzzy vector ranges from 0 to 0.441, which could be useful for future trend analysis when the gas level increases.

The gas concentrations for the samples in Table 10.4 are given in Table 10.5. Most transformers have shown a medium or low level of gases and lower increasing rates, such as transformers No. 1, No. 2 and No. 5. Therefore they are closely monitored. Transformer No. 3 was dismantled and an arc damage in the insulation was found in the core. In the inner inspection of another transformer, No. 4, two locations were identified with high-temperature damage due to eddy currents and a bad contact. More transformers can be investigated when certain criteria for individual gases are met. Laboratory tests can also be carried out to fine-tune the fuzzy-diagnosis technique.

The details of the transformers and the DGA results are stored in the database and fuzzy-logic software package, as shown in Figure 10.5. After a transformer is selected, by pressing a button ‘Fuzzy Logic Diagnosis’, the likelihood of fuzzy elements will be displayed on the screen giving an advice on the predicted incipient fault. Using this computer analysis tool, a number of 110–330 kV power transformers in Victoria, Australia, were diagnosed and some typical results are given in Figure 10.6. For the new transformer, the fuzzy-logic method indicated an 87 per cent diagnosis index for no fault, as shown by Figure 10.6(a), whereas two faults were diagnosed for the second transformer (Figure 10.6(b)). The transformer was eventually untanked and two faults were found in the winding.

The combined DGA diagnosis method (Section 10.1.2) is found useful because it uses three different methods and the last three test results, which involves the trend of faults. When there is more than one fault in a transformer, the fuzzy-logic method may be more effective. The methods have been successfully used for the diagnosis of a number of transformers in Australia. It has been proved that, using the fuzzy-diagnosis method, more detailed information about the faults inside a transformer can be obtained. This is an improvement over the conventional IEC code method, which

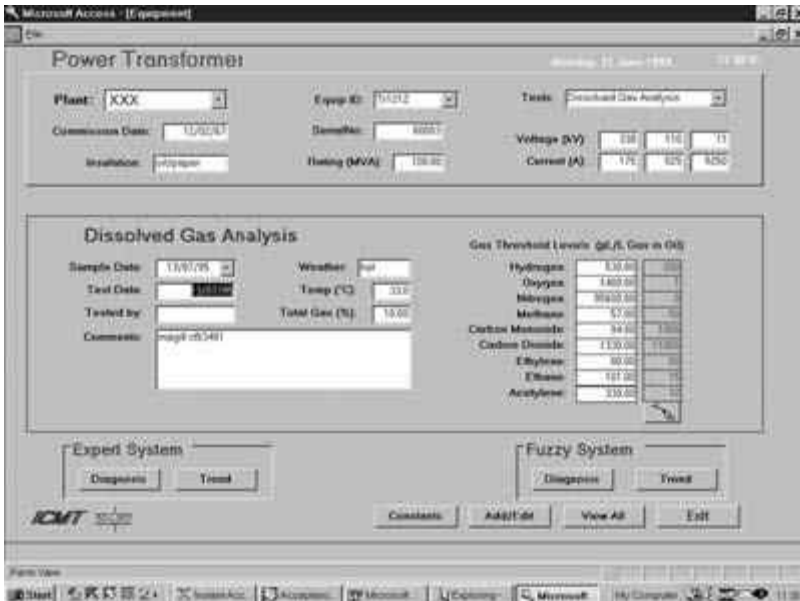


Figure 10.5 The computer program ICM-2.0 works as a comprehensive database and a fuzzy-logic diagnosis tool for transformers

may be due to the more realistic representation of the relationship between faults and dissolved-gas ratios with the fuzzy membership functions. Also, using this method, multiple faults can be diagnosed and their trends determined, which is an important feature.

10.2.2.5 Trend analysis for individual faults

In FIK diagnosis, a fault can be more accurately determined by its fuzzy component, which indicates the likelihood or dominance of the fault. Deterioration of the fault may therefore be closely monitored through trend analysis. This technique has been used for a transformer that was tested over a 15-month period. Thermal faults of medium and high temperature (300–700 °C and >700 °C) were diagnosed by the FIK method and their fuzzy components against the test time are plotted in Figure 10.7. The graph clearly shows the development of each thermal fault in this transformer. It can be seen that at the beginning of this monitoring period, the medium temperature thermal fault F(7) was the main problem of this transformer and the fuzzy component of high-temperature thermal fault (>700 °C) was very small, i.e. below 0.05. The high-temperature thermal fault F(8) was diagnosed from Day 114 onwards and then became stable until Day 406, when the oil was degassed. After degassing, because the thermal faults remained, the fuzzy components F(7) and F(8) went up again from Day 453. It took a few weeks for the gases to be released and dissolved in the oil to

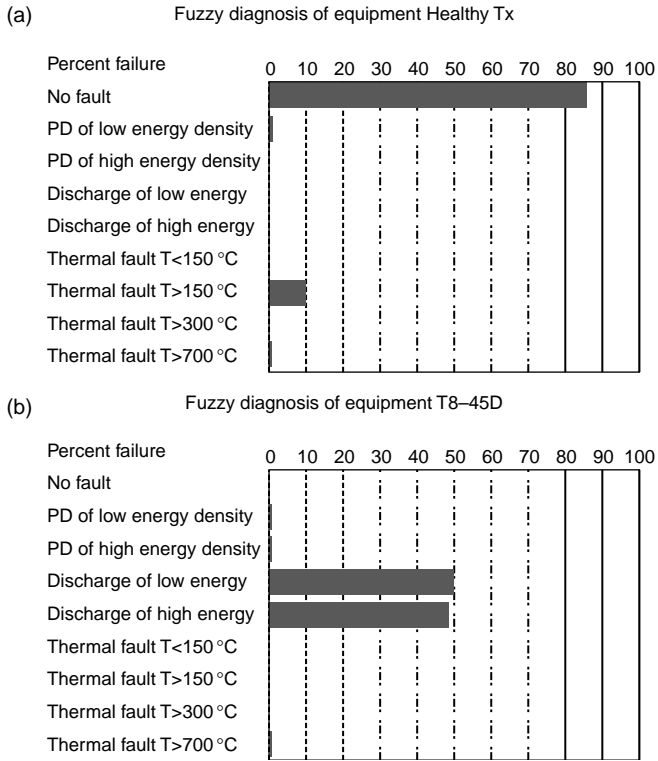


Figure 10.6 Fuzzy-logic diagnosis for transformers using ICM-2.0: (a) a new 'healthy' transformer; (b) a transformer with two types of incipient fault

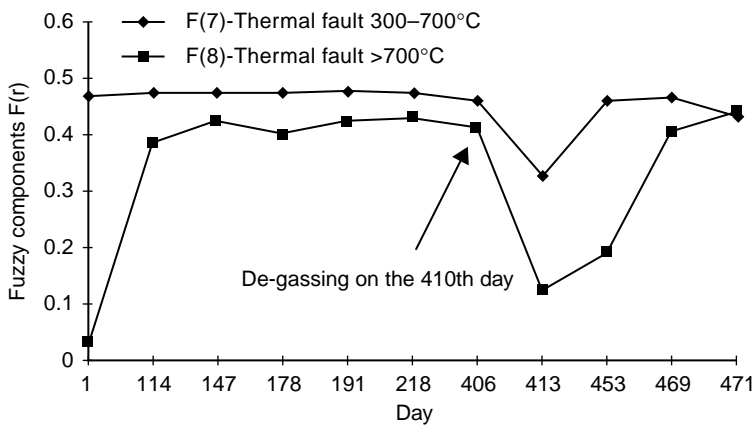


Figure 10.7 The trend of two types of thermal fault in a 330 kV transformer determined by the FIK method

a sufficient level for accurate diagnosis. A small fluctuation of $F(8)$ was recorded on Day 178, which might be due to the lighter load during the specific time period.

It must be noted that, if a transformer has no fault, the fuzzy component $F(0)$ always gives a large value in the range of 0.6–1. For example, the DGA results for a healthy transformer are (in ppm) $H_2 - 95$, $N_2 - 73\,000$, $O_2 - 11\,000$, $CO - 1\,000$, $CH_4 - 20$, $CO_2 - 8400$, $C_2H_4 - 25$, $C_2H_6 - 45$ and $C_2H_2 - 2$. The fuzzy component of no-fault $F(0) = 0.863$, which indicates that no fault exists in the transformer. The IEC codes are 0, 0, 0, also indicating no fault. From our experience, when the value of $F(0)$ is between 0.3 and 0.6, an incipient fault at its earlier stage may have occurred. When the fault is getting worse, $F(0)$ will decrease to <0.1 .

10.3 Asset analysis and condition ranking

Under the current economical climate, no utility could afford to replace all aged equipment according to its designed lifetime. Priority has to be given to those that have already reached or are close to their critical point of failure. A thorough study of the asset condition and correct ranking of the equipment would be essential for the decision making. This will ensure that the worst equipment can be replaced or refurbished in time.

10.3.1 Equipment ranking according to the insulation condition

Conditions of a piece of equipment can be assessed in terms of its failure probability. Preferably, the whole history of the equipment since commissioning can be retrieved and analysed thoroughly. The following are some important factors to be considered in the equipment ranking:

- failure rate at different ages for a particular type of equipment;
- trend and deterioration rate indicated by diagnostic test results;
- severity of failure consequence;
- value and maintenance costs of equipment;
- working environment, loading and impact of electrical, mechanical and chemical overstresses.

From a combined evaluation of various factors with certain weights attached, the priority list for a type of equipment can be determined.

10.3.2 Insulation health index

The insulation health or failure index may be determined from various test results, quality of equipment, operating condition (e.g. temperature), load, overvoltage impacts and so on. Because there are too many factors that affect the probability of insulation failure, it may not be possible to include every factor in the evaluation. Starting from some important factors, an evaluation system using fuzzy logic has been developed [12–15].

Taking a type of HV motor as an example, three parameters from conventional insulation tests were used: partial discharge (P), dielectric dissipation factor $\tan \delta$ (T) and its knee-point voltage (K). The absolute value and increase/decrease rate of each parameter would form an array of six components (P_a , P_r , T_a , T_r , K_a and K_r) and can be analysed with a fuzzy-logic tool. According to the scalar, the fuzzy sets of every parameter are defined as low (L), medium (M) and high (H):

P_a – partial discharge magnitude, its fuzzy set is low (L) for $P_a < 5,000$ pC, medium (M) for $5,000 < P_a < 50,000$ pC and high (H) for $P_a > 50,000$ pC.

P_r – the trend of partial discharge represented by the ratio between PDs measured in subsequent 6 months $P_r = \frac{Q_{n+1}}{Q_n}$. It is divided into three groups: low (L) for $P_r < 1.2$, medium (M) $1.2 < P_r < 2.0$ and high (H) $P_r > 2.0$.

T_a – the level of dielectric dissipation factor $\tan \delta$. The three groups are low (L) for $T_a < 0.01$, medium (M) for $0.01 < T_a < 0.05$ and high (H) $T_a > 0.05$.

T_r – the trend of dielectric dissipation factor $\tan \delta$ represented by the ratio between PDs measured in subsequent 6 months $T_r = \frac{\tan \delta_{n+1}}{\tan \delta_n}$. The three groups are low (L) for $T_r < 1.2$, medium (M) for $1.2 < T_r < 2.0$ and high (H) for $T_r > 2.0$.

K_a – the normalized knee-point voltage, i.e. $V_t = kV_p$ where V_t is the knee-point voltage and V_p the rated voltage. K_a is divided into three groups: low (L) for $K_a < 0.2$, medium (M) for $0.2 < K_a < 0.5$ and high (H) for $K_a > 0.5$.

K_r – the trend of knee-point voltage (measured once a year), $K_r = 1 - \frac{V_k(n+1)}{V_k(n)}$. K_r is divided into three groups: low (L) for $K_r < 0.1$, medium (M) for $0.1 < K_r < 0.75$ and high (H) $K_r > 0.75$.

It should be noted that the high, medium and low levels of the above six variables are selected according to previous test results and condition assessment experience for the particular motor. They can be very different depending on the type of equipment.

10.3.3 Membership functions of fuzzy set

In fuzzy diagnosis, the fuzzy sets of the six parameters need to be established. According to the fuzzy-set theory and the diagnostic experience, the membership functions of fuzzy sets ‘LOW’, ‘MEDIUM’, ‘HIGH’ are represented as descending demi-Cauchy distribution function $\mu_L(x)$ or ascending demi-Cauchy distribution function [4] $\mu_H(x)$ or their combination. The two functions $\mu_L(x)$ and $\mu_H(x)$ are represented by

$$\mu_L(x) = \begin{cases} 1 & \text{for } x \leq A \\ \frac{1}{1+(\frac{x-A}{a})^4} & \text{for } x > A \end{cases} \quad (10.5)$$

$$\mu_H(x) = \begin{cases} 1 & \text{for } x \geq A \\ \frac{1}{1+(\frac{A-x}{a})^4} & \text{for } x < A \end{cases} \quad (10.6)$$

where x is the variable and the values of a and A are given in Table 10.6, which are determined from previous experience [4].

Table 10.6 Coefficients 'a' and 'A' of Equations (10.5) and (10.6) for various fuzzy sets

| Fuzzy set | | P_a | P_r | T_a | T_r | K_a | K_r |
|-----------------|---|----------|-------|--------|-------|-------|-------|
| $\mu_{LOW}(x)$ | A | 5 000.0 | 1.2 | 0.01 | 1.2 | 0.2 | 0.1 |
| | a | 1 200.0 | 0.3 | 0.0025 | 0.3 | 0.05 | 0.025 |
| $\mu_{HIGH}(x)$ | A | 50 000.0 | 2.0 | 0.05 | 2.0 | 0.5 | 1.0 |
| | a | 8 300.0 | 0.34 | 0.0083 | 0.34 | 0.083 | 0.17 |

We take the membership functions of fuzzy sets LOW, MEDIUM, HIGH, as follows:

$$\mu_{LOW}(x) = \mu_L(x)$$

$$\mu_{HIGH}(x) = \mu_H(x)$$

$$\mu_{MED}(x) = \min[\mu_{H1}(x), \mu_{L1}(x)]$$

where

$$\mu_{L1}(x) = 1 - \mu_{LOW}(x)$$

$$\mu_{H1}(x) = 1 - \mu_{HIGH}(x)$$

Thus, every membership function can be constructed from descending demi-Cauchy function $\mu_L(x)$ and/or ascending demi-Cauchy function $\mu_H(x)$ given by (10.3) and (10.4).

For $x = P_a$, the membership functions of fuzzy sets LOW, MEDIUM, HIGH are shown in Figure 10.8.

For $x = P_r$, the membership functions of fuzzy sets LOW, MEDIUM, HIGH are shown in Figure 10.9.

From fuzzy-logic analysis, the total failure index based on these test results can be derived.

$$F = F1(P_a) + F2(P_r) + F3(T_a) + F4(T_r) + F5(K_a) + F6(K_r)$$

where

$$F1(P_a) = w_1 w_{11}[\alpha \mu_{LOW}(P_a) + \beta \mu_{MED}(P_a) + \gamma \mu_{HIGH}(P_a)]$$

$$F2(P_r) = w_1 w_{22}[\alpha \mu_{LOW}(P_r) + \beta \mu_{MED}(P_r) + \gamma \mu_{HIGH}(P_r)]$$

$$F3(T_a) = w_2 w_{11}[\alpha \mu_{LOW}(T_a) + \beta \mu_{MED}(T_a) + \gamma \mu_{HIGH}(T_a)]$$

$$F4(T_r) = w_2 w_{22}[\alpha \mu_{LOW}(T_r) + \beta \mu_{MED}(T_r) + \gamma \mu_{HIGH}(T_r)]$$

$$F5(K_a) = w_3 w_{11}[\alpha \mu_{LOW}(K_a) + \beta \mu_{MED}(K_a) + \gamma \mu_{HIGH}(K_a)]$$

$$F6(K_r) = w_3 w_{22}[\alpha \mu_{LOW}(K_r) + \beta \mu_{MED}(K_r) + \gamma \mu_{HIGH}(K_r)]$$

and w_1, w_2, w_3, w_{11} and w_{22} are weights for the parameters.

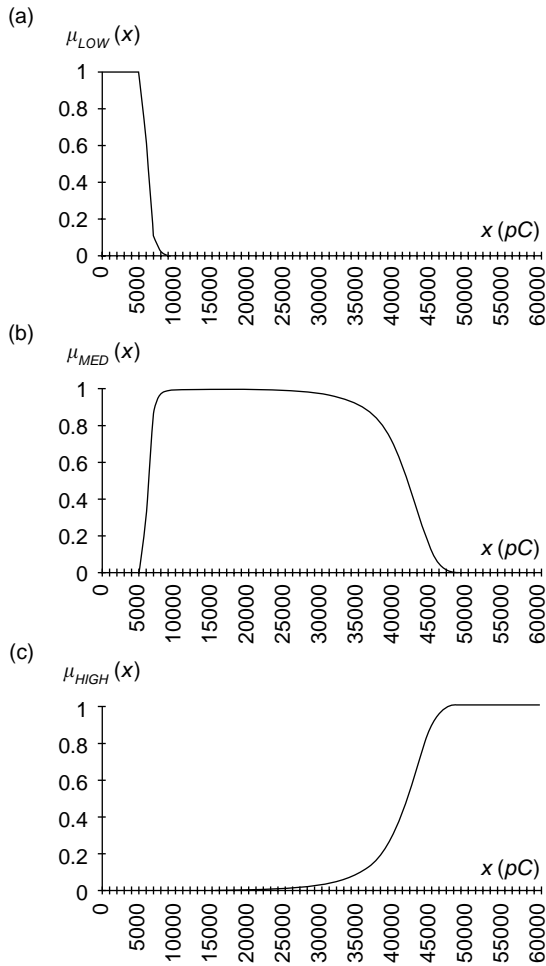


Figure 10.8 The membership functions of fuzzy sets of P_a (LOW, MEDIUM, HIGH)

10.3.4 Example of fuzzy logic condition ranking

In order to check the failure index analysis using the proposed fuzzy-logic technique, 14 hypothetical HV motors and their test results are used, as shown in Table 10.7.

(1) P_a , P_r AND THEIR FUZZY SETS

The level of partial discharge (P_a), its trend (P_r) and their fuzzy sets LOW, MEDIUM, HIGH are calculated as shown in Table 10.8.

(2) T_a , T_r AND THEIR FUZZY SETS

The level of dielectric dissipation factor $\tan \delta$ (T_a), its trend (T_r) and their fuzzy sets LOW, MEDIUM, HIGH are calculated as shown in Table 10.9.

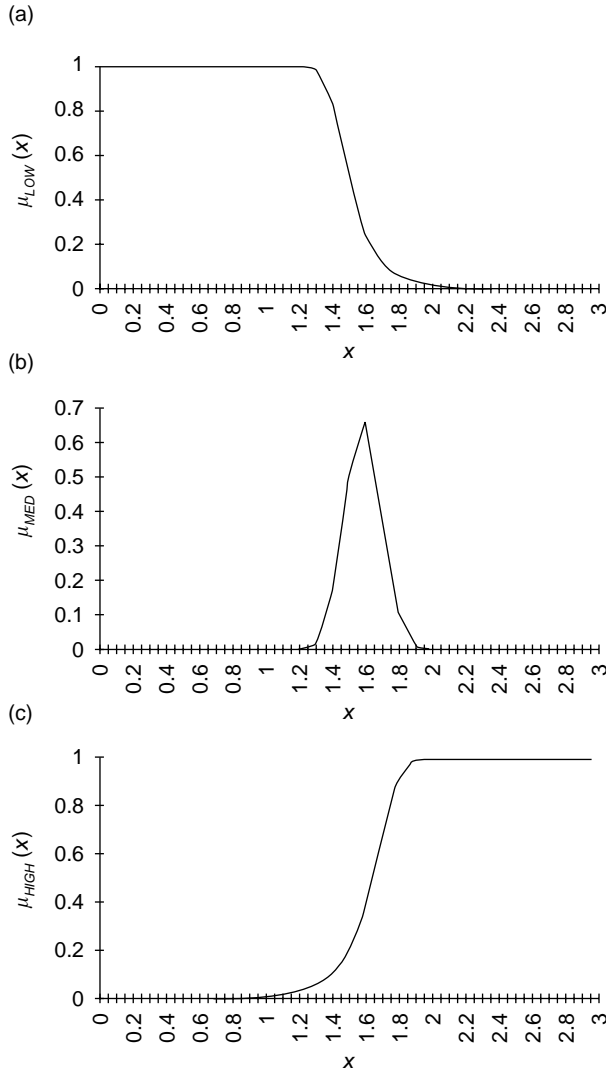


Figure 10.9 The membership function of fuzzy sets of P_r (LOW, MEDIUM, HIGH)

(3) K_a , K_r AND THEIR FUZZY SETS

The level of knee-point voltage (K_a), its trend (K_r) and their fuzzy sets LOW, MEDIUM, HIGH are calculated as shown in Table 10.10.

Using the fuzzy sets of P_a , P_r , T_a , T_r , K_a , K_r and specified weights, the 14 hypothetical motors are examined to give their failure indexes, as given in Figure 10.10. The weights may be selected from experience and can be tuned up in the analysis. It can be seen that motors No. 8 and No. 12 have the highest failure indices and should

Table 10.7 *Six important parameters of the hypothetical HV motors*

| No. | P_a (pC) | P_r | T_a | T_r | K_a | K_r |
|-----|------------|-------|-------|-------|-------|-------|
| 1 | 3 000 | 1.4 | 0.01 | 1.3 | 0.8 | 0.2 |
| 2 | 5 000 | 1.3 | 0.015 | 1.4 | 0.75 | 0.15 |
| 3 | 8 000 | 1.35 | 0.012 | 1.2 | 0.75 | 0.5 |
| 4 | 10 000 | 1.4 | 0.015 | 1.3 | 0.7 | 0.65 |
| 5 | 20 000 | 1.6 | 0.02 | 1.1 | 0.7 | 0.5 |
| 6 | 25 000 | 1.8 | 0.01 | 1.2 | 0.7 | 0.5 |
| 7 | 10 000 | 1.3 | 0.008 | 1.6 | 0.7 | 0.75 |
| 8 | 30 000 | 1.3 | 0.015 | 2 | 0.65 | 0.9 |
| 9 | 40 000 | 1.5 | 0.01 | 1.2 | 0.65 | 0.5 |
| 10 | 50 000 | 1.4 | 0.03 | 1.4 | 0.65 | 0.75 |
| 11 | 60 000 | 1.3 | 0.02 | 1.3 | 0.7 | 0.6 |
| 12 | 10 000 | 2 | 0.005 | 1.1 | 0.7 | 0.9 |
| 13 | 35 000 | 1.1 | 0.015 | 1.2 | 0.65 | 0.5 |
| 14 | 80 000 | 1.4 | 0.012 | 1.1 | 0.65 | 0.8 |

Table 10.8 *P_a , P_r and their fuzzy sets of the hypothetical HV motors*

| No. | P_a (pC) | LOW | MED. | HIGH | P_r | LOW | MED. | HIGH |
|-----|------------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 3 000 | 0.999 | 0 | 0.001 | 1.4 | 0.764 | 0.151 | 0.085 |
| 2 | 5 000 | 0.999 | 0 | 0.001 | 1.3 | 0.938 | 0.012 | 0.05 |
| 3 | 8 000 | 0.025 | 0.974 | 0.002 | 1.35 | 0.88 | 0.055 | 0.065 |
| 4 | 10 000 | 0.003 | 0.995 | 0.002 | 1.4 | 0.764 | 0.151 | 0.085 |
| 5 | 20 000 | 0 | 0.994 | 0.006 | 1.6 | 0.194 | 0.53 | 0.277 |
| 6 | 25 000 | 0 | 0.988 | 0.012 | 1.8 | 0.056 | 0.101 | 0.843 |
| 7 | 10 000 | 0.003 | 0.995 | 0.002 | 1.3 | 0.938 | 0.012 | 0.05 |
| 8 | 30 000 | 0 | 0.971 | 0.029 | 1.3 | 0.938 | 0.012 | 0.05 |
| 9 | 40 000 | 0 | 0.678 | 0.322 | 1.5 | 0.425 | 0.425 | 0.15 |
| 10 | 50 000 | 0 | 0 | 1 | 1.4 | 0.764 | 0.151 | 0.085 |
| 11 | 60 000 | 0 | 0 | 1 | 1.3 | 0.938 | 0.012 | 0.05 |
| 12 | 10 000 | 0.003 | 0.995 | 0.002 | 2 | 0.019 | 0 | 0.981 |
| 13 | 35 000 | 0 | 0.914 | 0.086 | 1.1 | 0.98 | 0 | 0.02 |
| 14 | 80 000 | 0 | 0 | 1 | 1.4 | 0.764 | 0.151 | 0.085 |

be put on the first priority for maintenance or replacement. These two motors have the highest change rate of PD level, DDF or knee-point voltage, which indicates that their rate of insulation condition deterioration is high. Although motor No. 14 has

Table 10.9 T_a , T_r and their fuzzy sets of the hypothetical HV motors

| No. | T_a (pC) | LOW | MED. | HIGH | T_r | LOW | MED. | HIGH |
|-----|------------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 0.01 | 0.998 | 0 | 0.002 | 1.3 | 0.938 | 0.012 | 0.05 |
| 2 | 0.015 | 0.059 | 0.938 | 0.003 | 1.4 | 0.764 | 0.151 | 0.085 |
| 3 | 0.012 | 0.708 | 0.29 | 0.002 | 1.2 | 0.969 | 0 | 0.031 |
| 4 | 0.015 | 0.059 | 0.938 | 0.003 | 1.3 | 0.938 | 0.012 | 0.05 |
| 5 | 0.02 | 0.004 | 0.99 | 0.006 | 1.1 | 0.98 | 0 | 0.02 |
| 6 | 0.01 | 0.998 | 0 | 0.002 | 1.2 | 0.969 | 0 | 0.031 |
| 7 | 0.008 | 0.998 | 0 | 0.002 | 1.6 | 0.194 | 0.53 | 0.277 |
| 8 | 0.015 | 0.059 | 0.938 | 0.003 | 2 | 0.019 | 0 | 0.981 |
| 9 | 0.01 | 0.998 | 0 | 0.002 | 1.2 | 0.969 | 0 | 0.031 |
| 10 | 0.03 | 0 | 0.971 | 0.029 | 1.4 | 0.764 | 0.151 | 0.085 |
| 11 | 0.02 | 0.004 | 0.99 | 0.006 | 1.3 | 0.938 | 0.012 | 0.05 |
| 12 | 0.005 | 0.999 | 0 | 0.001 | 1.1 | 0.98 | 0 | 0.02 |
| 13 | 0.015 | 0.059 | 0.938 | 0.003 | 1.2 | 0.969 | 0 | 0.031 |
| 14 | 0.012 | 0.708 | 0.29 | 0.002 | 1.1 | 0.98 | 0 | 0.02 |

Table 10.10 K_a , K_r and their fuzzy sets of the hypothetical HV motors

| No. | K_a (pC) | LOW | MED. | HIGH | K_r | LOW | MED. | HIGH |
|-----|------------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 0.2 | 0.994 | 0 | 0.006 | 0.2 | 0.004 | 0.994 | 0.002 |
| 2 | 0.25 | 0.494 | 0.494 | 0.012 | 0.15 | 0.059 | 0.94 | 0.002 |
| 3 | 0.25 | 0.494 | 0.494 | 0.012 | 0.5 | 0 | 0.987 | 0.013 |
| 4 | 0.3 | 0.057 | 0.915 | 0.028 | 0.65 | 0 | 0.947 | 0.053 |
| 5 | 0.3 | 0.057 | 0.915 | 0.028 | 0.5 | 0 | 0.987 | 0.013 |
| 6 | 0.3 | 0.057 | 0.915 | 0.028 | 0.5 | 0 | 0.987 | 0.013 |
| 7 | 0.3 | 0.057 | 0.915 | 0.028 | 0.75 | 0 | 0.824 | 0.176 |
| 8 | 0.35 | 0.012 | 0.903 | 0.085 | 0.9 | 0 | 0.107 | 0.893 |
| 9 | 0.35 | 0.012 | 0.903 | 0.085 | 0.5 | 0 | 0.987 | 0.013 |
| 10 | 0.35 | 0.012 | 0.903 | 0.085 | 0.75 | 0 | 0.824 | 0.176 |
| 11 | 0.3 | 0.057 | 0.915 | 0.028 | 0.6 | 0 | 0.968 | 0.032 |
| 12 | 0.3 | 0.057 | 0.915 | 0.028 | 0.9 | 0 | 0.107 | 0.893 |
| 13 | 0.35 | 0.012 | 0.903 | 0.085 | 0.5 | 0 | 0.987 | 0.013 |
| 14 | 0.35 | 0.012 | 0.903 | 0.085 | 0.8 | 0 | 0.657 | 0.343 |

the largest PD level and low knee-point voltage, because its PD level is stable and knee-point change rate is not the largest, it is not ranked to the worst motor.

From this example, it can be seen that visual examination of the test results may not be sufficient to determine the condition ranking of a type of equipment. Using fuzzy-logic analysis and suitable weights in the calculation, the failure index could be more accurate in terms of the total condition assessment. Of course, the coefficients

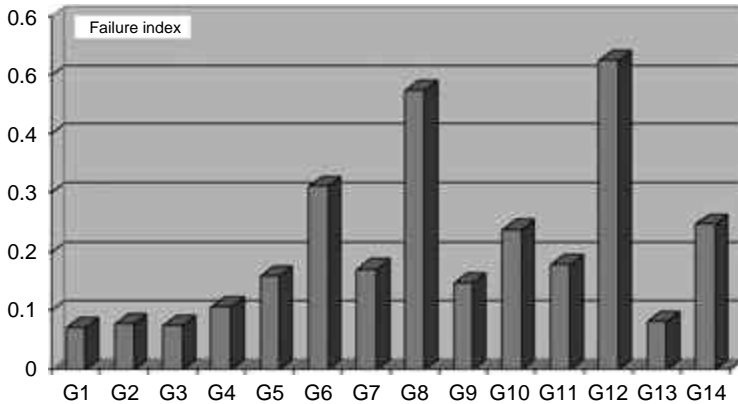


Figure 10.10 The failure index of 14 hypothetical HV motors determined from their PD and DDF test results using a fuzzy-logic analysis technique

of membership function and weights should be adjusted according to the experience of individual utility and analysis results from time to time.

10.4 Summary

The rapid development in artificial-intelligence techniques has led to a wide range of applications in insulation condition monitoring areas. Expert systems, neural networks and fuzzy logic have been used in maintenance, diagnosis and condition ranking of electrical plant. With the aid of neural networks and fuzzy logic, pattern recognition is now used for identification of partial discharge sources and suppression of interference. As an example, the fuzzy-logic DGA and key gas analysis technique presented in this chapter has been successfully used for the diagnosis of transformers in Australia. It has been proved that, using the fuzzy diagnosis method, more detailed information about the incipient faults inside a transformer can be obtained. Also, multiple faults can be diagnosed using this method, which may not be possible by other known techniques.

Another advantage of the fuzzy-diagnosis method is its quantitative indication of the fault likelihood/dominance by means of the fuzzy diagnostic vector. This has been used to identify the main faults and determine their severity in comparison with each other. It has been found from our experience [12,13] that the larger the fuzzy component, the more dominant, active and severe the fault. After a certain period of monitoring, the trend of each fault in a transformer can also be determined from its fuzzy diagnostic vector. This information is important for any decision regarding the replacement or/and refurbishment of a suspect transformer. In the current economic climate, there is an increasing demand to extend the service life and reduce maintenance costs of HV equipment. With the aid of more accurate insulation-condition-assessment techniques, such as the fuzzy-logic condition ranking method

discussed in this chapter, the maintenance schedule can be optimized and a longer service life in HV equipment and cables achieved. This would delay the investment in new equipment and, at the same time, keep the network performance at an acceptable level. The fault-diagnosis technique has been implemented in a computer program ICM-2.0 with a large data-storage capacity. With a PC Pentium IV 2.0 GHz, the analysis of each set of DGA results takes about 1 second. The program also has a user-friendly interface and has been used by several utilities in Australia and New Zealand.

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10.6 Problems

1. Based on the fuzzy-logic method explained in this chapter, derive the IEC ratio codes and calculate the fuzzy logic elements F(0)...F(7) for the transformers whose DGA test results are given in the following table. Fill in the derived and calculated results in the following tables.

| No. | H ₂ | CH ₄ | C ₂ H ₂ | C ₂ H ₄ | C ₂ H ₆ | IEC ratio codes |
|-----|----------------|-----------------|-------------------------------|-------------------------------|-------------------------------|-----------------|
| 1 | 95 | 110 | <0.1 | 50 | 160 | |
| 2 | 120 | 17 | 4 | 23 | 32 | |
| 3 | 300 | 490 | 95 | 360 | 180 | |

| No. | F0 | F1 | F2 | F3 | F4 | F5 | F6 | F7 |
|-----|----|----|----|----|----|----|----|----|
| 1 | | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |

2. Referring to technical papers and books, find the difference between the IEC code, Rogers and triangle methods. Is there any relationship between these methods in terms of the comparison between different gas concentrations?

Appendix 1
Abbreviations

| | |
|-------|---|
| CIGRE | Conseil International des Grands Reseaux Electriques (International Council on Large Electric Systems, Paris, France) |
| DEIS | IEEE Dielectrics and Electrical Insulation Society |
| EPRI | Electric Power Research Institute (Palo Alto, California) |
| ERA | ERA Technology Ltd (Leatherhead, Surrey, UK) |
| IET | Institution of Engineering and Technology (incorporating the former Institution of Electrical Engineers, UK) |
| IREQ | Institut de Recherche d'Hydro Quebec (Varenes, Quebec) |
| ISH | International Conference on High Voltage Engineering (bi-annual conference) |

Appendix 2

Major standards organizations

| | |
|---------------|---|
| ANSI | American National Standards Institute |
| ASTM | American Society for Testing of Materials (ASTM International) |
| BSI | British Standards Institute |
| CISPR | International Special Committee on Radio Interference (subcommittee of IEC) |
| DKE (DIN/VDE) | German Commission of Electrical, Electronic and Information Technologies (standards and regulations) |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronic Engineers (USA) |
| ISO | International Organization for Standardization |
| SA | Standards Australia (SAI GLOBAL) |
| WSSN | World Standards Services Network (www.wssn.net/WSSN/index.html) |

Appendix 3
Answers to problems

Chapter 1

No calculations.

Chapter 2

Q.1: See Chapter 6.

Q.2: (a) BDV 22.4 kV (RMS) $E_{\text{air}} = 2.12 \text{ kV/mm (RMS)}$ $E_{\text{resin}} = 0.6 \text{ kV/mm (RMS)}$.

(b) BDV 74.75 kV (RMS) $E_{\text{gas}} = 7.07 \text{ kV/mm (RMS)}$ $E_{\text{resin}} = 2.02 \text{ kV/mm (RMS)}$.

(c) BDV 84.3 kV (RMS) $E_{\text{oil}} = 7.5 \text{ kV/mm (RMS)}$ $E_{\text{resin}} = 4.72 \text{ kV/mm (RMS)}$. See Figures 2.2 and 2.3.

Q.3: $C_b = 0.0072 \text{ pF}$ $C_c = 0.0625 \text{ pF}$ $C_a \gg C_b$ $q_c = 285 \text{ pC}$ $q_a \approx 32 \text{ pC}$
 $V_i = 31.1 \text{ kV (RMS)}$.

Chapter 3

Q.1: Refer to Chapters 2, 4 and 5.

Q.2 Refer to Chapters 2, 4, 5 and 9.

Q.3: (i) $E_{\text{oil}} = 11.8 \text{ kV/mm (RMS)}$ $E_{\text{pbd}} = 5.9 \text{ kV/mm (RMS)}$.

(ii) $E_{\text{oil}} = 2.7 \text{ kV/mm}$ $E_{\text{pbd}} = 27 \text{ kV/mm}$. Note higher stress **in** solid.

Q.4: $C_{\text{oil}} = 27.8 \text{ pF}$ $C_{\text{pbd}} = 129 \text{ pF}$ -Total C = 22.9 pF.

$R_{\text{oil}} = 7 \times 10^{10} \Omega$ $R_{\text{pbd}} = 30 \times 10^{10} \Omega$.

Q.5: (i) 94 kV (RMS).

(ii) 127 kV (RMS). Reduced oil duct thickness allows higher V_i .

Chapter 4

- Q.1: $E_m = (V_0 - V_1)/r_0 \ln r_1/r_0 = (V_1 - V_2)/r_1 \ln r_2/r_1 = \dots\dots\dots C_1(V_0 - V_1) = Kl_1(V_0 - V_1)/\ln r_1/r_0$. Also $C_1(V_0 - V_1) = C_2(V_1 - V_2) = \dots\dots\dots$
 $K = 2\pi\epsilon_0\epsilon_r$ and l_1 is length of first foil (400 mm). From these equations and E_m being equal the foil length x radius is the same for each capacitor.
 (i) $l_1 = 400$ mm, $l_2 = 307$ mm, $l_3 = 250$ mm and l_4 (outer) = 210 mm.
 (ii) Capacitance values: $K / \ln r_n/r_{n-1}$. $C_1 = 296$ pF, $C_2 = 288$ pF, $C_3 = 283$ pF and $C_4 = 292$ pF
 Total capacitance C, HV – Earth = 73 pF. All in series.
 (iii) Voltages/section = CV/C_n ; $C = 73$; $V = 60$ kV (RMS); $(V_0 - V_1) = 73 \times 60/296 = 14.8$ kV; $(V_1 - V_2) = 15.2$ kV; $(V_2 - V_3) = 15.4$ kV; $(V_3 - V_4) = 15.0$ kV. Small variations in capacitance calculations.
 Maximum radial stress, $E_m = 2.8$ kV/mm. Similar in all interfoil insulation.
 (iv) Maximum radial stress without foils = $60/20 \ln 44/20 = 3.8$ kV/mm – at HV conductor.
 Notes: The design problems relating to axial and radial stresses are complex (see Chapter 12 of Reference 18 – Chapter 4).
 The average values between foil ends in this problem range from 0.16 kV/mm to 0.37 kV/mm. Approximately axial uniform distributions are often required.
- Q.2: See Reference 5 of Chapter 7.
- Q.3: For 2.0 kV/mm (RMS) applied, possible PDs for gap of 0.3/0.4 mm. PDs for gap of 0.5 mm. For 3.0 kV/mm (RMS) applied PDs for gap > 0.1/0.2 mm.

Chapter 5

- Q.1: (i) Speed differences. Internal water cooling in large turbine generators.
 (ii) Semiconducting tapes or similar.
 (iii) Refer to Chapter 9.
- Q.2: Air stress due to applied voltage following local erosion of the earthed screen = 6.6 kVpk/mm. The 0.5 mm air gap $b/d = 5.4$ kVpk/mm thus PDs are possible. Hydrogen stress in gap for $b/d = 10$ kVpk/mm, thus applied voltage required for PDs = 9.6 kV (RMS) to ground.
- Q.3: (ii) From equation (Figure 5.4) for $\alpha = 1$ voltage across line end discs = 11% of line voltage. For $\alpha = 4$ voltage is 26 per cent of line voltage.
 Oil b/d stress for 8 mm gap = 25 kV/mm (Figure 2.3(c)) requiring a voltage between the line discs of 225 kV.
 For $\alpha = 1$ line voltage expected to cause $b/d = 225 \times 100/11 = 2049$ kV. Assuming safety factor of approximately 1.3 choose test level <1 576 kV (525 kV class).
 For $\alpha = 4$ line voltage expected to cause $b/d = 225 \times 100/26 = 867$ kV. Assuming factor of 1.3 choose test level <667 kV (145 kV class).
- Q.4: Refer to tables in Chapters 9 and 10.

Chapter 6

- Q.1: Resistive divider – add matching resistor of Z_0 at receiving end of cable. Add series resistor at divider end in some cases to match cable and reduce possible reflections. Ratio 30×10^{-5} if no series resistor. Ratio 33×10^{-5} with series resistor.
 Capacitive divider – add series resistor, Z_0 , at divider – 50 per cent pulse input to cable but maintaining required time constant. High impedance at receiving end of cable allows doubling of the transmitted signal. Ratio 50×10^{-5} .
- Q.2: (i) Temperature critical. Parallel paths may mask result.
 (ii) Ratio arm bridge more versatile.
- Q.3: $C_x = 45 \text{ pF}$ and $\tan \delta = 0.0086$ As this value is above the acceptable value for a new bushing consider application of PD test.
- Q.4: Applying the simplified relationships, the relative values with (i) as reference are (i) 1, (ii) 7.3 and (iii) 67.
 Improvement may be achieved by increasing the coupling capacitor value (e.g. to 1000 pF) and/or adjusting the amplifier gain if its noise level is acceptable.

Chapter 7

- Q.2: Pulse separation between direct and reflected pulses $\Delta t = 2(L - x) / v$. For $v = 164 \text{ m}/\mu\text{s}$ and $(L - x) = 100$, $\Delta t = 1.22 \mu\text{s}$. The pulse velocity can be determined from measurements as in Figure 7.2. The reduced velocity of about 20% is due to the influence of the outer and inner semi-conducting layers in an XLPE cable. This has been confirmed in research investigations.

Chapter 8

No calculations.

Chapter 9

No calculations.

Chapter 10

No calculations.

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Condition Assessment of High Voltage Insulation in Power System Equipment

R.E. James and Q. Su

The book introduces the reader to the major components of a high voltage system and the different insulating materials applied in particular equipments. During a review of these materials, measurable properties suitable for condition assessment are identified. Analyses are included of some of the insulation fault scenarios that may occur in power equipment. The basic facilities for carrying out tests on the internal and external insulation structures at high and low voltages are described. Tests and measurements according to specifications, on-site requirements and research investigations are considered. Advances in the application of digital techniques for detection and analyses of partial discharges are discussed and methods in use, or under development, for service condition monitoring are described. These include the utilization of new sensors, the solution of online problems associated with noise rejection and the adaptation of artificial intelligence techniques for incipient fault diagnosis.

The subject matter of the book is suitable for final year courses in electrical power engineering, short courses in insulation condition assessment and postgraduate programmes. Power system engineers associated with high voltage equipment should find the book of value in relation to fault investigations, maintenance requirements, insulation testing and condition monitoring.

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ISBN 978-0-86341-737-5



9 780863 417375 >

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978-0-86341-737-5