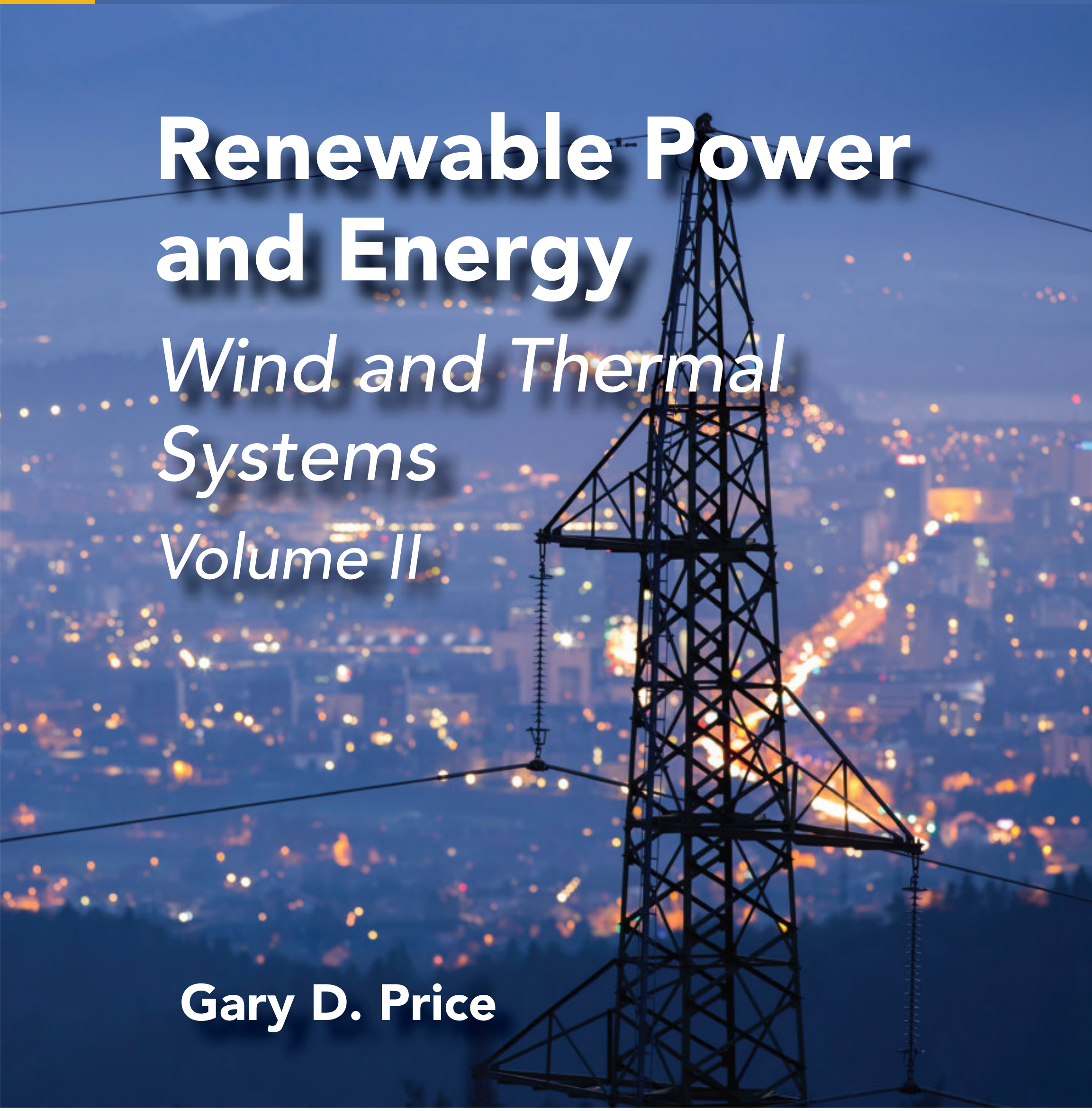
ELECTRICAL POWER COLLECTION

Hemchandra M. Shertukde, *Editor*



Renewable Power and Energy

Wind and Thermal Systems

Volume II

Gary D. Price

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RENEWABLE POWER AND ENERGY

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ABSTRACT

Wind and thermal power systems are becoming a significant source of energy in our energy resource mix today. It is essential these systems are reliable, safe, and secure. Precise engineering design is required to insure these new power systems meet these requirements. In particular, interconnected systems with existing utility power systems must operate in synchronism and improve overall quality of the electrical power grid.

This textbook is intended to identify and explain engineering procedures for the design and operation of renewable energy systems. The first chapters include a review of conventional electrical power systems as implemented in the United States and common to all electrical systems throughout the world. Several other types of renewable energy systems are introduced. The heart of the textbook is focused on the design of interconnected and stand-alone wind and thermal systems. Battery storage is becoming an integral part of renewables, and a significant portion of the textbook is dedicated to energy storage for stand-alone and back-up power systems. Economics considerations are included as an essential part of the engineering design process.

KEYWORDS

batteries, electric power systems, energy storage, energy, engineering economics, generators, induction motor, inverters, lithium-ion, net-metering, power factor, power, probability distribution, renewable, solar, synchronous machine, thermal, transfer fluid, wind turbine

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PREFACE

Renewable energy systems have flourished throughout the United States in the last few years because of public demand for cleaner air, environmental protection, and reduced dependence on foreign oil. Government programs have been established to meet the public demand. Many states have passed a legislation that requires electric utilities to include a portfolio of renewable energy sources in their generation mix. The public demand has stimulated the growth of an industry that now provides many renewable energy sources. Small businesses have developed into an industry to design and install these systems. Training programs and courses are now ubiquitous as the demand for designers and installers increases. Almost every educational institution offers renewable energy classes or curriculum.

The objective of this book is to provide a resource for engineering students interested in the design, installation, and operation of wind energy generation. In particular, this textbook provides challenging problems and solutions that stimulate engineering thinking. While there are many good reference books on power systems and renewable energy, the objective here is to integrate the engineering basics of existing power systems with design problems and solutions using renewable energy sources.

The organization of this book begins with concepts and terminology for power and energy—the basics needed to communicate and understand the subject. Conventional power systems are briefly discussed to understand the concepts used in the integration of renewable power systems. We apply these concepts to the design and installation of a small wind generator connected to the electric utility grid. With this background, the student is able to understand the concepts of large-scale wind generation.

The chapters following concepts and background review delve into the details of wind systems as interconnected or standalone designs. Estimating and predicting energy production is presented using industry distribution functions and online programs. Concepts of synchronization, power conversion, and system protection are explained and practiced.

These concepts are applied to residential and small commercial systems and later extrapolated to a large system design.

Economic analysis is presented using basic methodologies of payback, levelized cost of energy, and rate of return. A methodology to develop advanced analysis is introduced using spreadsheets. A course on engineering economic analysis is recommended for students to develop a sound understanding of investment risk, rate of return, and return on investment.

The text also explores related renewable technologies, including energy storage systems and thermal systems. This textbook is intended as a *hands-on* guide, and is structured to motivate the student to experience the design and installation process. Many thanks go to the students and faculty of the Metro State University of Denver who have helped with textbook content and presentation of this course.

CHAPTER 1

CONVENTIONAL ELECTRIC POWER SYSTEMS

Power and energy are important concepts that must be understood before beginning to explore the application of renewable energy systems. For example, a common misunderstanding is the confusion between *watt* and *watt-hour*. Watt is a power term, and watt-hour is an energy term. Adding to the confusion are shortcuts used by the power industry professionals who frequently use the power term *megawatt* when they really mean *megawatt-hour* (energy). A utility energy trader will almost universally use the term *megawatt* when buying or selling a *megawatt-hour* of energy. We begin this book with definitions and the relationship between energy and power, as used by electrical power engineers.

1.1 POWER ENGINEERING CONCEPTS AND TERMINOLOGY

Power is defined as the time rate at which work is done or energy emitted or transferred. *Energy* is the capacity for doing work. *Watt* is a unit of power equal to 1 joule per second—or in electric terms, 1 ampere under the pressure of 1 volt. (*joule* is the unit of mechanical power equal to a meter-kilogram-second or 0.7375 foot pounds). The important fact to remember from these definitions is that power is a rate, and energy is a quantity. Therefore a *watt (w)* is the rate at which energy is being produced or transferred. A *watt-hour (wh)* is the quantity of energy transferred or produced.

Electrical power equipment is typically rated in terms of watts. A 100-watt light bulb will use 100 watt-hours of energy when operated for 1 hour at 1 amp and 100 volts. A photovoltaic (PV) panel rated at 100 watts will generate 100 watt-hours in one hour when operated at a specified solar intensity and connected to an appropriate load. If these devices operate for 6 minutes, the resulting energy will be 10 watt-hours. A *kilowatt* (kW) is 1,000 watts, a *megawatt* (MW) is 10^6 watts, and a *gigawatt* (GW) is 10^9 watts.

Power plant generators usually are operated at a constant power near the nameplate rating. This makes it simpler for dispatch operators to communicate by referring to 100 MW and assuming the generator will operate at 100 MW for one hour to produce a 100-MWh block of energy. We cannot make that assumption with PV systems or wind generators because the output power is variable. Wind and solar power must be integrated over time to determine energy.

The *British thermal unit* (BTU) is a common measure of energy. One BTU is equal to the energy required to heat 1 pound (lb) of water 1 degree Fahrenheit (1°F). A BTU is also equal to 0.293 watt-hours (wh), and 3,412 BTUs equal 1 kWh. The BTU provides a useful conversion between electrical and solar thermal systems. The gas industry commonly uses the acronym MBTU to represent 1,000 BTUs and MMBTU to represent 1,000,000 BTUs. (The M is derived from the Roman numeral value.) This textbook will avoid using MBTU, as it causes frequent calculation errors and confusion. K represents 1,000 and M equals 1,000,000, as used in kW and MW.

A common energy term used in the natural gas industry is the *therm***.** One therm equals 100,000 BTUs and represents the heat or energy content of natural gas. A cubic foot (cu ft) of natural gas contains approximately 0.9 therms of energy. The energy content of natural gas is not consistent, depending on the chemical makeup of natural gas. Natural gas consists of several components: primarily methane, heptane, and propane. Small amounts of nitrogen, carbon dioxide, oxygen, and an odorant are also present in natural gas. The energy content varies from source to source. The energy content also depends on the delivery pressure. The price of natural gas that shows up in our utility bill is usually expressed in dollars per therm.

As aforementioned, a joule is equal to 0.7375 foot-pounds (ft-lbs), and a joule per second is equal to 1 watt. From these relationships, we can determine that 1 kWh of energy is equal to 2,655,000 ft-lbs. If a 150-pound person climbs a 17,700-foot mountain, the amount of energy expended is about 1 kWh! Most of us use that amount of energy for home lighting every day! Another reference to the value of 1 kWh is the content of energy in petroleum: approximately 3 ounces of oil contains 1 kWh of energy if we assume 1 gallon of oil contains 143,300 BTUs. By comparison, if we install 2 square meters (m^2) of PV on our roof, the array will generate about 1 kWh of electricity per day.[1]

Demand is defined as the amount of work to perform a desired function. In the electrical world, the term *demand* is used to measure the peak power required to operate all connected loads for a particular circuit. If a circuit consists of five 100-watt light bulbs, the peak demand is 500 watts. Demand is determined when the load is at maximum, or when all five lights are on. As utilities are concerned with the maximum load on their system, they measure peak energy in a specified time interval for demand. An instantaneous value is not as significant as the average value during this time interval, usually 15 minutes. For example, if the power on a circuit ranges from 5 to 15 kW during the 15-minute interval, the demand will be about 10 kW. The average value of 10 kW is more significant than the 15 kW peak value, because it more accurately represents the load that the generators must meet.

Capacity is the instantaneous ability to provide energy required to do work. Again, the electrical use of the term *capacity* usually refers to the size of the generator(s) required to maintain a circuit load. A 100-MW generator will provide the energy required to operate 100 MW of peak load. Capacity is also used to define the load capability of other electrical equipment on the system. A 115-kilovolt (kV) transmission line may safely transfer 100 MW of power without overheating and sagging. A 100-megavolt-ampere (MVA) transformer may safely transform 90 MW of power before it overheats. The safe operating rating of the equipment defines its capacity.

Using the electrical definitions of capacity and demand, *energy* can be defined as the demand times time-in-use ($D \times t$), or capacity times time-in-use ($C \times t$). These definitions are used when calculating the total consumption. For example, the United States consumed about 4 trillion kWh of energy in 2005.[2] That equates to about 13 MWh per year per person. The peak electrical demand for the United States is about 760 GW.

When scientists talk about global or national energy use, the term *quad* is frequently used. A *quad* is equal to one quadrillion BTUs. A quad is also approximately equal to the energy stored in 180 million barrels of crude oil. One quad equals 293 billion kWh. The total global primary energy production in 2004 was 446 quads.

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[1] Messenger, R.A., and J. Ventre. 2003. *Photovoltaic Systems Engineering*, 3rd ed. p. 3. Boca Raton, FL: CRC Press.

[2] Patel, M.R. 2005. *Wind and Solar Power Systems: Design, Analysis, and Operation*, 2nd ed. p. 3. Boca Raton, FL: Taylor & Francis Group.

Avoided costs are the incremental costs to an electric utility to generate electrical energy. These costs generally include fuel costs for generation, operational costs of transmission, and operational distribution costs per kWh. Fixed costs (e.g., capital equipment improvements, and franchise fees) are not included in avoided costs.

Net metering generally refers to buying and selling energy at the same rate. Net metering applies to small (<10 kW) systems, where the financial impact is relatively negligible to the utility. Under net metering rules, a renewable energy (RE) system is allowed to sell its generated energy at the same rate it is buying energy from the utility. However, utilities and public utility commissions set rules for net metering, which vary by jurisdiction. The utility may require the renewable energy entity to pay avoided costs for excess energy generated each month. More commonly, the utility will pay avoided costs for excess generation at the end of the year. Xcel Energy currently has an option to *bank* excess energy indefinitely. We will discuss the financial details of net metering in the economics chapter.

Renewable Energy Credit (REC) is an incentive for production of energy from renewable energy systems. Investors can accumulate RECs from the energy produced by their renewable systems. A political proposal has been suggested to impose carbon taxes on companies that generate carbon dioxide and other greenhouse gasses. RECs may be purchased to counter the carbon tax. Public utility commissions may also require utilities to include renewable generation in their mix of generation. The utility may then earn or purchase RECs to meet the portfolio requirements. The price on an REC varies because the value of carbon emission is difficult to monetize. The value we place on global warming and air pollution is controversial. In Colorado, the Public Utility Commission set the price of an REC for small residential systems at 10 cents/kWh in 2010. The latest REC contract price for small RE systems is 2 cents/kWh. The REC is primarily a subsidy or incentive.

Carbon footprint is a measure of greenhouse gas (GHG) emission or carbon dioxide (CO_2) equivalent. We can determine the carbon footprint for any individual, entity, or process if we can measure the amount and source of energy consumed. The source of energy determines the content of CO_2 emission for a quantity of fuel consumed. For example, in 2015, the Public Service Company of Colorado calculated that 1 kWh of electrical energy delivered is responsible for 1.338 pounds of CO_2, and 1 therm of natural gas is responsible for 11.7 pounds of CO_2. This calculation is based on a mix of 52.9% coal, 23.5% natural gas, 19.3% wind, 2.0% hydroelectric, 1.3% solar, and 1.0% other sources used in electric generation. If an individual's annual usage is 5,000 kWh of electricity and 200 therms of natural gas, the equivalent carbon footprint is 6,690 plus 2,340 = 9,030 lbs of $CO_{2.}$ That is a carbon footprint of 4.5 tons! The financial impact of carbon is also arbitrary. Recent estimates are 40 to 80 U.S. dollars per ton of carbon or 6 cents/kWh.

Production-based incentives (PBI) have replaced up-front payments for renewable energy installation incentives. Instead of up-front cash incentives based on system size, utilities may offer incentives based on energy production over a fixed number of years. For example, in 2010, Xcel Energy offered an REC in the form of a PBI of 10 cents/kWh over the first 10 years of operation of a small RE system. In 2016, PBI was reduced to 2 cents/kWh, and now is at ½ cent/kWh. This incentive will be eliminated soon. The advantage of PBI to the utility is improved cash flow for the rebate program. Incentives are paid out during the same time period that the utility is collecting renewable energy standard billing fees from the customers, which is called the renewable energy standard adjustment (RESA). PBI also insures the renewable energy systems are operating as designed. The utility does not need to enforce the REC production that is specified in operating contracts. Customers with renewable energy systems will insure the system is operating as designed to keep those PBI incentive checks coming. A disadvantage of PBI is the additional meter necessary to measure all renewable energy generation, and billing is more complex for customers with RE systems.

Production tax credit (PTC) for wind systems is a federal incentive that rewards investment in large wind generation. The current PTC rate is 2.2 cents/kWh. Because this is a federal incentive, it must be approved by Congress. Recently, the PTC incentive was extended for one year. As wind energy costs become more competitive with conventional power generation, the incentive will decrease and eventually dissolve.

Power purchase agreements (PPAs) are generally reserved for commercial and utility-scale projects. Energy rates are determined in the negotiation for contract. The interconnecting utility will offer rates based on the competitive sources of energy and the retail rates established within the jurisdiction by the regulatory agency. Power purchase agreements are used by independently owned utilities (IOUs) or publically owned facilities.

The *Federal Investment Tax Credit (ITC)* was extended by Congress in 2015 for another five years. The tax credit is 30% of capital investment in qualified RE systems. The credit is restricted to residential homeowners. It has been a major incentive for the RE industry.

Other acronyms are included in the *Acronym and Abbreviations* section at the back of this textbook. A glossary is also included with short definitions of terminology used in this textbook.

1.2 ELECTRIC POWER SYSTEM DESIGN

Conventional electric power systems in this country consist of generation, transmission, distribution, and loads. Generation is a mix of baseline, peaking, spinning reserve, offline reserve, and renewable (variable) equipment. Baseline refers to coal, nuclear, oil, and gas-fueled generators that run constantly except for scheduled maintenance. These are the largest generators that require relatively long start-up procedures to get them up to speed and online. Nuclear and coal facilities are usually baseline. Peaking generators are smaller and can be started and brought online in a relatively short time to assist with peak daily or seasonal loads. They are usually fueled with oil or natural gas. Spinning reserve units are large enough that it is more economical to keep them connected to the electrical grid and running at a low output, and increase output to match load conditions. Any generator that is running at low output is not as economical as at full load and is avoided by utilities if possible. Offline reserve generators are similar to peaking generators, but are usually larger and operated seasonally, or during scheduled maintenance times for baseline generators. Renewable systems, including wind and solar, are variable and must be supplemented with reserve or peaking generators when wind is low or solar energy is limited. For this reason, utilities try to limit the *penetration factor*, which is the ratio of grid-connected renewable power to conventional power.

Figure 1.1 is a one-line diagram of a power system, including generators, transformers, transmission lines, and a load distribution center. G1 and G2 generators provide system power that is stepped up to the transmission line voltage by transformer 1. T1 and T2 are transmission lines between two substation busses. Transformer 2 steps the voltage down for distribution and the load. Circuit breakers provide disconnect means and protection from system faults.

Transmission systems get electrical energy from the source (generation) to the load distribution centers. Transmission lines operate

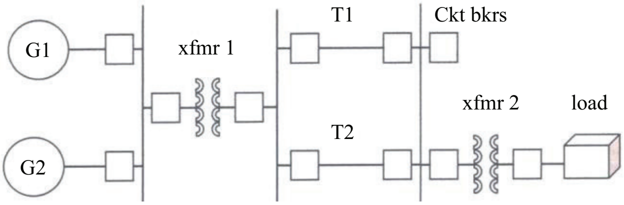

Figure 1.1. Conventional power system one-line diagram.

at much higher voltages than generation or loads to increase efficiency. A higher voltage means lower current for a given power. Lower current decreases power loss in the wire, and line capacity is proportional to the square of the voltage. With hundreds of miles of transmission lines, power loss is a significant factor in system operation. Typical AC transmission voltages are 230, 345, 500, and 765 kV.[3] A DC voltage of 1,000 KV is used for long-distance transmission, 350 miles or more. Transmission is a critical factor for many of our wind generation systems, because the wind farms are installed many miles from major cities and load centers. Also, some large PV systems are being installed far from major load centers and require additional transmission line capacity.

Distribution load centers use large step-down transformers to lower transmission line voltage for power lines and equipment that distributes power to the customer. Distribution voltages are typically from 4 to 13.8 kV. Circuit breakers are installed to provide switching and disconnect means for load control and system protection. System protection equipment has become very sophisticated in the last few years. Digital protection equipment can detect faults within one cycle (1/60 second) and open circuits before system damage or instability occurs. The addition of variable renewable energy systems to the grid increases the complexity of protection systems. Because most PV systems and wind generators have significantly less fault current capacity, the protection equipment must be more sensitive to voltage and power fluctuations. Electrical power engineers have been able to improve operation of the electrical grid to accommodate renewable generation systems to date. However, the caveat exists that higher penetrations of renewable systems may cause disturbances that the existing power grid cannot absorb and widespread outages may occur.

The fuel source for most of our conventional electric system generation is coal, which is the main contributor CO_2, pollution and other externality costs. Coal is the fuel for 41% of U.S. generation, followed by natural gas (21.3%), hydro (16%), nuclear (13.5%), and oil (5.5%).[4] By contrast, coal provides about 25% of the world primary energy, and oil contributes about 34%.[5] These fossil fuels contribute to worldwide pollution and CO_2 generation. Externalities are the consequences of activity that are

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[3] Stevenson, W.D., Jr. 1975. *Elements of Power System Analysis*, 4th ed. p. 4.

[4] IEA Key Statistics. 2010. *International Energy Agency*, 2008 data

[5] Freris, L., and D. Infield. 2008. *Renewable Energy in Power Systems*, 2. A. John Wiley & Sons, Ltd.

not normally part of the economic evaluation of electric generation. For example, the costs attributed to health problems caused by pollution are not directly paid by the generation provider (i.e., costs are external to the plant operator). Currently, new coal plants in the United States are required to include expensive pollution equipment (e.g., scrubbers) that mitigates pollution. However, CO_2 production continues to increase as more coal plants are built and pollution is generated, and environmental concerns are inevitable.

From 2008 to 2010, 16 new coal plants were built in the United States. Another 16 are now completed or under construction. They will generate 17.9 GW—enough to power for about 15.6 million homes. They will also emit 125 million tons of GHGs per year. The present federal administration has set aside 3.4 billion U.S. dollars in stimulus spending for the *clean coal* technology to capture and store GHGs. None of the new plants is built to capture CO_2 emissions, although the U.S. Department of Energy has spent 687 million U.S. dollars on clean coal programs, and 35 billion U.S. dollars has been invested in these traditional coal plants.

Another concern with our conventional fuel source is environmental damage caused by mining, drilling, and transportation. The Exxon tanker Valdez spill and the British Petroleum offshore drilling explosion and leak are highlights of externalities associated with the oil industry. The oil shale industry is also experiencing contamination problems with hydraulic fracturing (i.e., fracking)—the injection of fluids into deep geological formations to recover oil and gas reserves. Hydraulic fracturing enables the production of natural gas and oil from rock formations deep below the earth's surface (generally 5,000–20,000 feet). At this depth, there may not be sufficient porosity and permeability to allow natural gas and oil to flow from the rock into the well bore and be recovered. A fluid is pumped into the rock to facilitate release of the trapped reserves. The composition of the fluid is proprietary information that is not made readily available to the public. The fluid used in fracking may be spilled or work its way into water supplies. Although drilling companies report that the fluid and process are safe, there are many claims to the contrary. Another concern with the fracking process is the venting of unwanted natural gas from the well. As gas escapes from the fracking well, it is collected and burned at the site. The constant gas flares in the oil field are an unsightly view in areas of natural landscapes and national park locations. A good example of the visual pollution occurs at the Badlands in North Dakota near the Bakken oil fields. The night-time sky is filled with gas flares on the horizon. The emissions add to CO_2 production and global warming. Current studies are underway to determine whether environmentally dangerous gasses are also released in the fracking process.

1.3 ELECTRIC POWER ANALYSIS

Before we can explore renewable energy power systems, we must review voltage and current representation for conventional power systems operating under normal conditions. The conventional AC power system consists of purely sinusoidal voltage and current waveforms when in a steady state condition. This chapter reviews typical representations of voltage, current, and power values in single- and three-phase configurations.

The equations developed in this chapter will be used throughout the text to analyze renewable energy systems interconnected to conventional power systems. Power factor, real power, reactive power, and apparent power are particularly useful components that are used to analyze any power system. Per unit analysis, voltage drop calculations, distortion measurement, and power flow analysis are additional tools introduced in this chapter, which are useful in succeeding chapters to analyze power systems integration.

1.3.1 SINGLE-PHASE CIRCUITS

The AC voltage for a single-phase circuit is represented by a *sinusoidal time function* v(t) as shown in Figure 1.2.

$$v(t) = \mathrm{Vmax} \cos(\omega t + \theta_r) \tag{1.1}$$

$$v(t) = 141.4 \cos(377t + 0) \tag{1.2}$$

Vmax is the peak value of the waveform (141.4 volts). The Greek letter omega (ω) represents the *angular velocity* and is equal to 377 ($\omega = 2 \times \pi \times 60$) for a 60-cycle per second (Hz) system. The Greek letter theta (θ_r) indicates the *phase angle* between an instantaneous value and a reference time (e.g., $t = 0$). The phase angle for the voltage waveform shown is zero. θ_r must be expressed in radians because ωt is in radians (radians = degrees $\times\ \pi$ / 180).

A more convenient representation of voltages, currents, and power can be shown in a *phasor diagram* that shows the magnitude and instantaneous angle from a reference (usually voltage at 0° or 0 radians). Figure 1.3 shows the same voltage as in Figure 1.2, but with a 30° phase angle. The

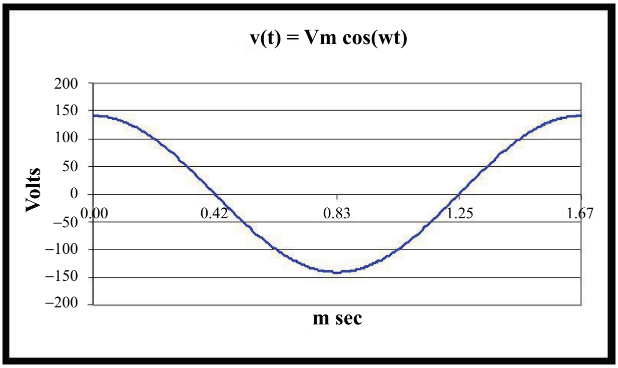

Figure 1.2. AC voltage waveform.

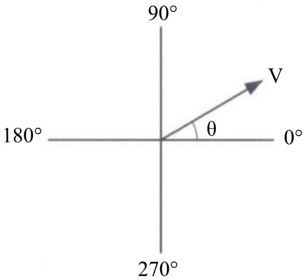

Figure 1.3. Phasor representation of voltage.

common electrical convention for phase angle is 0° on the positive x-axis and 180° on the negative x-axis. The phasor voltage V is represented by the rms magnitude |V| and a phase angle θ as shown in equation 1.3.

$$V = |V| \angle \theta = 100 \angle 30° \qquad (1.3)$$

Phasor representation of the voltage waveform is given as a magnitude and phase angle. Phasor voltages are the root-mean square (rms) value of voltage or Vmax/√2. The bars enclosing the phasor (|V|) indicate rms values of the voltage or current. RMS values are the effective values of voltages, currents, and power. The *effective value* of power is the average power expended in a resistor ($P = |I^2|\ R$). These are the values read by ordinary voltmeters and ammeters.

Another common representation for voltage, current, and impedance is the *rectangular* format as shown in Figure 1.4.

$$V = A + j\,B \text{ volts} = 86.6 + j50 \text{ volts} \qquad (1.4)$$

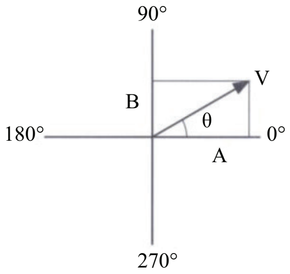

Figure 1.4. Rectangular representation of voltage.

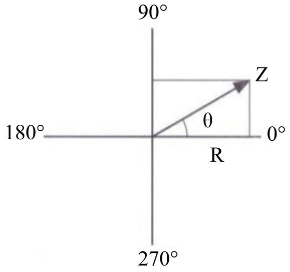

Figure 1.5. Rectangular representation of impedance.

where A = |V| × cos (θ), and B is |V| × sin (θ)

The rectangular format as shown in Figure 1.5 may also be used to represent impedance:

$$Z = |Z|\llcorner 30° = |100|\llcorner 30°$$

$$Z = R + j\,X \text{ ohms} = 86.6 + j50 \text{ ohms} \tag{1.5}$$

where R = |Z| × cos (θ), X = |Z| × sin (θ)

Now, let us look at the current waveform, which is similar to the voltage sinusoidal waveform. The maximum peak value of the current waveform is 14.4 amps and the phase angle in Figure 1.6 is zero (maximum value at ωt = 0). A cosine function is used in this example.

If we combine voltage and current time function waveforms and add a lagging phase angle of 30° to the current, the result is given in Figure 1.7. Note the zero crossing of the current waveform is 0.14 millisecond (ms) after the voltage zero crossing, which corresponds to 30° lagging current.

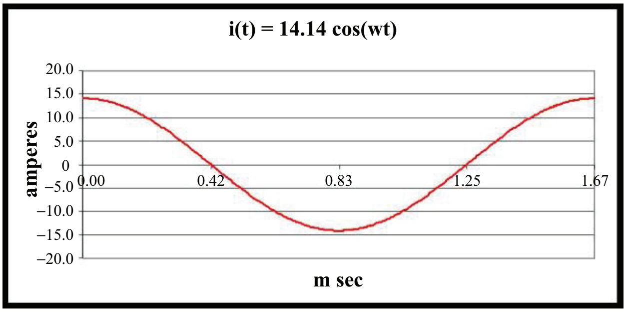

Figure 1.6. Time representation of current.

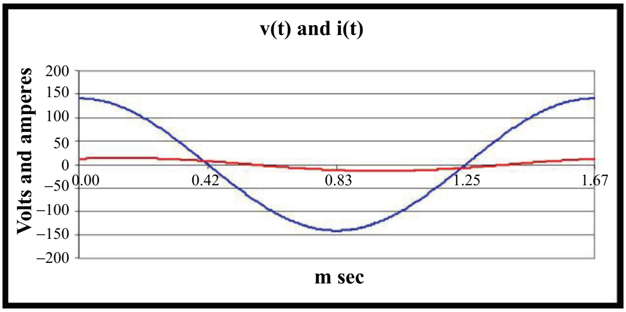

Figure 1.7. Time representation of voltage and lagging current.

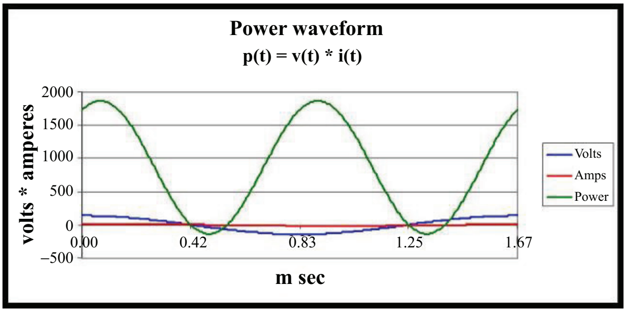

Figure 1.8. Time representation of power.

Now we can talk about power and power factor. Power is equal to the product of voltage and current. In the time waveform, power p(t) = v(t) × i(t) is shown in Figure 1.8. The 30° lagging current creates a power waveform that is not in phase with the voltage. Instantaneous power is negative when the polarity of current and voltage is opposite.

If the voltage and current are in phase (i.e., $\theta = 0$), the power waveform is in sync with the voltage and current, but twice the frequency.

This means the load is purely resistive and power is all real watts. It can be easily shown if the voltage and current are 90° out of phase, the resulting power would average out to be zero, and no real watts are used by the load. A lagging current is caused by an inductive component of load and creates a lagging power factor. Similarly, a leading current is caused by a capacitive component of load and creates a leading power factor. Leading or lagging is relative to the applied voltage.

1.3.2 POWER CALCULATIONS

Power factor (PF) is calculated from the cosine of the angle (θ) between voltage and current (PF = cos (θ)). For our 30° phase angle, PF = cos (30) = .866. PF is defined as the resistive component of power divided by the total apparent power. *Apparent power* (S) is the product of rms voltage and current ($|V| \times |I|$). *Real power* (P) is product of rms voltage and current times the power factor or cosine of the phase angle. $P = |V| \times |I| \times \cos(\theta)$ or $P = |V| \times |I| \times PF$. *Reactive power* (Q) is the component of apparent power that flows alternately toward or away from the load. $Q = |V| \times |I| \times \sin(\theta)$. Keeping in mind that S, P, and Q are rms values, we may simplify the power equations as:

$$S = V \times I \tag{1.6}$$

$$P = V \times I \cos\theta \tag{1.7}$$

$$Q = V \times I \sin\theta \tag{1.8}$$

The derivations of P, Q, and S using trigonometry can be found in basic power textbooks.[6] Cosine laws are used to convert equation 1.9 to equation 1.10, which shows the real and reactive components of the apparent power (p).

$$p(t) = Vm \cos wt \times Im \cos(\omega t - \theta) \tag{1.9}$$

$$\begin{aligned} p = {} & [Vm \times Im/2] \cos\theta\, (1 + \cos 2\omega t) \\ & + [Vm \times Im/2] \sin\theta \sin 2\omega t \end{aligned} \tag{1.10}$$

where the real component is $[Vm \times Im/2] \cos\theta\, (1 + \cos 2\omega t)$, and the reactive component is $[Vm \times Im/2] \sin\theta \sin 2\omega t$.

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[6] Stevenson, W.D., Jr. 1975. *Elements of Power System Analysis*, 4th ed. p. 15.

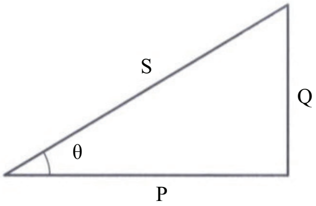

Figure 1.9. The power triangle.

Real and reactive power can be shown with much more clarity using a power triangle. Figure 1.9 shows a power triangle and the relationships of P, Q, and S:

$$S^2 = P^2 + Q^2 \tag{1.11}$$

$$P = [S^2 - Q^2]^{1/2} \tag{1.12}$$

PF can be obtained from P and S: PF = P / S. Trigonometric functions can also be used to determine PF:

$$PF = P / [P^2 + Q^2]^{1/2} \tag{1.13}$$

$$PF = \cos [\tan^{-1} (Q/P)] \tag{1.14}$$

If the phase angle is zero, the load is purely resistive and P = S. Similarly, if the phase angle is 90° or 270°, the load is purely inductive or capacitive.

By convention, a positive value of Q is an inductive load, and a negative value of Q is a capacitive load. The general engineering conception is that a capacitor generates positive reactive power, which supplies Q required by an inductive load. However, it is more convenient to consider the reactive power is positive when supplying an inductive load. The concepts of power factor, reactive power, and real power will become significant in future discussions concerning renewable energy sources and interconnection with conventional power systems. Reactive power does not require *coal off the coal pile* because reactive power flows back and forth, but reduces the capacity of the system and increases transmission losses. The effects of PF and reactive loads will be discussed later in relation to inductive wind generators and interconnected solar systems.

Another useful tool for calculating S, P, and Q is *complex power equations*. If the magnitude and phase angles for voltage (α) and current (β) are known, apparent power may be calculated using the complex conjugate:

$$S = P + jQ = VI^* \tag{1.15}$$

In this equation, I* is simply the magnitude of I and its conjugate (magnitude with negative phase angle). Apparent power is the product of the magnitudes of V and I and the sum of the voltage phase angle and the negative of the current phase angle.

$$S = V \times I \angle (\alpha - \beta) \tag{1.16}$$

1.3.3 PER UNIT ANALYSIS

Another tool that simplifies power calculations is per unit analysis. Instead of using the actual voltage in calculations, a base voltage and base apparent power are identified and set equal to 1.0 (PU). Then, all calculations may be expressed on the base reference. For example, if a base voltage of 120 kV is chosen, voltages of 108, 120, and 126 kV become 0.90, 1.00, and 1.05 (PU), respectively. We may also express these values as 90%, 100%, and 105%. However, percent becomes cumbersome when multiplying two quantities. The product of 1.2 PU voltage times 1.2 PU current becomes 1.44 PU volt-amperes. The product of 120% voltage and 120% current is 14,400, and we must divide by 100 to get the proper answer of 144%.

Voltage, current, kilovolt-amperes (KVA), and impedance are so related that selection for a base value for any two of them determines the base values of the remaining two. For example, if we select 12 kV as our base voltage and 100 KVA as our base apparent power, our base current may be determined by dividing apparent power by voltage:

$$\begin{aligned} \text{Base I} &= \text{base KVA / base KV} \\ &= 100 \text{ kVA} / 12 \text{ kV} = 8.3 \text{ amperes} \end{aligned} \tag{1.17}$$

Per unit calculation simplifies number crunching and allows relative comparisons of values of systems with varying voltages and power. One must be careful to separate single-phase systems from three-phase systems by identifying whether the base is a single phase quantity or the sum of all three phases.

1.3.4 EXAMPLE PROBLEMS

Example Problem 1.1
A commercial load is connected to the grid through a demand meter. The meter shows a load of 1,000 kW and 450 kvar of reactive power. What is the PF?

Solution:
As we are given real (P) and reactive power (Q), we may use equation 1.13 to determine the PF angle. The arctangent of Q/P is 24.2°, and the cosine of 24.2° is 0.912, which is the PF.

Example Problem 1.2
What is the apparent power (S) of the load in example problem 1.1?

Solution:
Applying equation1.11, S is equal to the square root of the sum of the squares of P and Q, or 1,096.6 KVA.

Example Problem 1.3
If the commercial load is offset with an RE system that generates 500 kW of real power (PF of 1.0), what is the new power factor at the meter?

Solution:
Recalculating the PF for P = 500 kW and Q = 450 kvars, PF = 0.74

Example Problem 1.4
If the utility requires a minimum PF of .85, how many kvars of capacitive correction must be added to the commercial system in Example Problem 1.3?

Solution:
Assuming the real power remains at 500 kW, and the PF is now 0.85, apparent power is $S = P / \cos\theta$ or $S = P / PF = 588$ KVA. $\theta = \arccos(.85) = 31.8°$. Reactive power (from the power triangle) $Q = S \sin\theta = 588 \times (0.527) = 310$ kvar. The capacitive bank must add 140 kvar (450 – 310) to the commercial system bus.

1.4 THREE-PHASE POWER SYSTEMS

The previous section analyzed single-phase power systems using basic mathematical and trigonometric methods. Now, we will apply those methods to a three-phase system. Utility generators, transmission, and distribution systems consist of three-phase equipment. Also, most commercial and industrial equipment is three phase. Three-phase motors and generators are more practical and efficient than single-phase machines. Utility generators are designed to produce balanced three-phase voltages that are 120° out of phase. The three windings of a generator are constructed with 120° mechanical orientation of the windings. Figure 1.10 shows a basic three-phase generator and load for a balanced system.

The generator is wound for a wye connection with a common neutral o. The load is also wye-connected with a neutral connection n. Zg is the generator internal impedance, which is inductive and with low resistance. Zl is the load impedance, which may consist of resistance, inductance, and capacitance. Figure 1.10 shows an inductive load with only resistance and inductance.

We will assume a *balanced* system to simplify calculations and simulate ideal operating conditions. This means the magnitude of generator phase voltages are equal |Va| = |Vb| = |Vc| and 120° in phase difference: Va = Vb ∟120° = Vc ∟240°. Current is also equal in magnitude with a 120° phase shift, and the sum of the three-phase currents is zero. In = Ia + Ib + Ic = 0. Any imbalance in the phase loads will create a neutral current, which is unwanted, and complicates system analysis.

Time-function voltage waveforms for phases a, b, and c are 120° out of phase, as shown is the Figure 1.11. The sum of the three voltages at any instant in time will equal zero (Vn = Va + Vb + Vc = 0). The current waveforms are also 120° out of phase for a balanced system and will sum to zero at the neutral point.

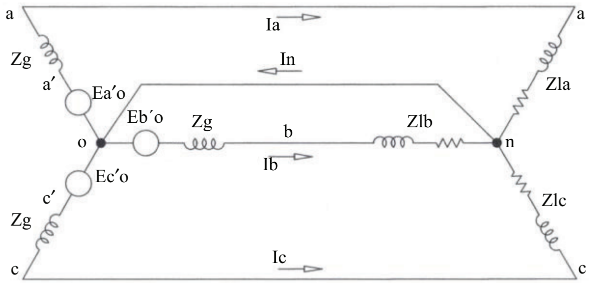

Figure 1.10. Three-phase system diagram.

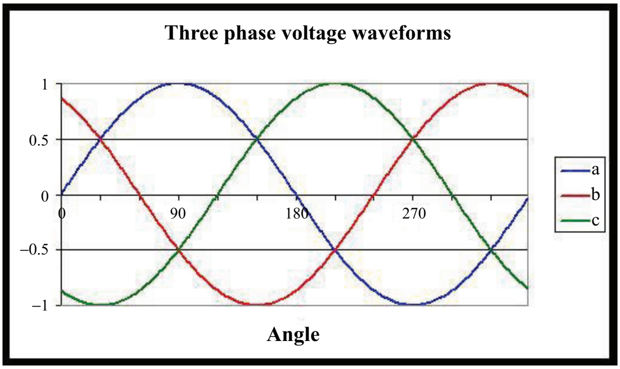

Figure 1.11. Three-phase waveforms.

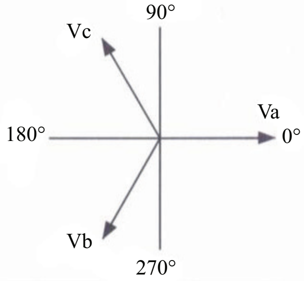

Figure 1.12. Voltage phasor diagram.

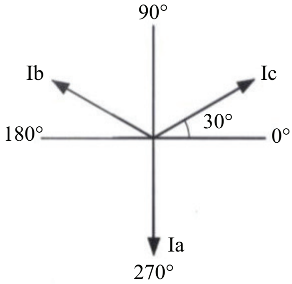

Figure 1.13. Current phasor diagram.

The phasor diagram represents the phase relation of the three-phase system more clearly, as shown in Figures 1.12 and 1.13. Conventional rotation of the generator will create a phase sequence of abc.

The phase relationships of Va and Ia are shown with a 90° phase difference. This would indicate the load is purely inductive. Normally, the phase current (Ia) would lag the phase voltage by a few degrees with a primarily resistive load with small inductance.

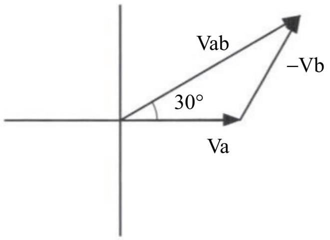

Figure 1.14. Line-to-line voltage.

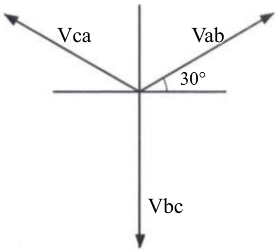

Figure 1.15. Three-phase line-to-line voltages.

We may also decide to use a line-to-line voltage (Vab) for the reference voltage instead of the line-to-neutral voltage (e.g., Va) shown earlier. As a phasor, Vab leads Va by 30°. Figure 1.14 shows the geometry for Vab and the line-to-neutral voltages Va and Vb. The magnitude of Vab is calculated using equation 1.18:

$$|Vab| = 2|Va| \cos 30° = \sqrt{3}\ |Va| \tag{1.18}$$

Figure 1.15 shows the line-to-line voltages (V_L) for a balanced three-phase system. Line-to-line voltage is commonly used as a reference for all three-phase systems. For example, a 115 kV transmission line and 480-volt commercial distribution system have line-to-neutral voltages of 66 kV and 277 volts, respectively. The magnitude of line voltage is equal to the phase voltage times the square root of 3. The phase current is the conventional reference for line current for wye-connected systems.

$$V_L = \sqrt{3}\ V_\varphi \tag{1.19}$$

$$I_L = I_{\varphi W} \tag{1.20}$$

1.4.1 POWER IN BALANCED THREE-PHASE SYSTEMS

Using the conventions of the previous section, we calculate *three-phase power* using the line references[7]:

$$P = \sqrt{3}\ V_L I_L \cos \theta_p \tag{1.21}$$

The power phase angle (θ_p) is the angle by which the phase current lags the phase voltage. *Apparent power* (S) is total volt-amperes, and *reactive power* (Q) is the inductive or capacitive component of apparent power. They are calculated using equations 1.22 and 1.23, respectively:

$$S = \sqrt{3}\ V_L I_L \tag{1.22}$$

$$Q = \sqrt{3}\ V_L I_L \sin \theta_p \tag{1.23}$$

Equations 1.21, 1.22, and 1.23 are commonly used to calculate P, Q, and S, respectively. Unless identified otherwise, voltages are assumed to be line-to-line, currents are line, and power is for all three phases. Again, balanced conditions are assumed unless specified otherwise.

A *power triangle* in Figure 1.16 shows the trigonometric relationship of apparent power, real power, and reactive power. The relationships are identical to those given in Section 1.3 for single-phase circuits.

$$S^2 = P^2 + Q^2 \tag{1.24}$$

$$P = [S^2 - Q^2]^{1/2} \tag{1.25}$$

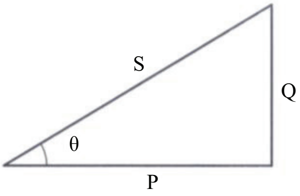

Figure 1.16. Power triangle.

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[7] Stevenson, W.D., Jr. 1975. *Elements of Power System Analysis*, 4th ed. p. 29.

1.4.2 WYE AND DELTA CONNECTIONS

For simplicity, the preceding discussion used wye connections at the generator and load. Delta connections are common in three-phase generators and transformers. If the load shown in Figure 1.10 is replaced by a delta-connected load, the load is represented by Figure 1.17. Although the currents in the delta windings are not the same as the line currents, the power calculations have not changed, if care is taken to correctly identify line current (Ia) and line voltage (Vab). Also, note that a neutral connection is not available with delta windings. Therefore, neutral current cannot flow between generation and load.

When solving three-phase *balanced* circuits, it is not necessary to work with the entire three phase circuit, as shown in Figure 1.10 or Figure 1.17. The circuit may be solved using Kirchhoff's voltage law around a closed path, which includes one phase and neutral. If the load is connected in delta, it is easy to convert the delta connection to its equivalent wye and proceed with the calculation of a single phase. The impedance of each phase of the equivalent wye will be one-third the impedance of the delta that it replaces. The equivalent circuit is shown in Figure 1.18 for phase *a* of Figure 1.10

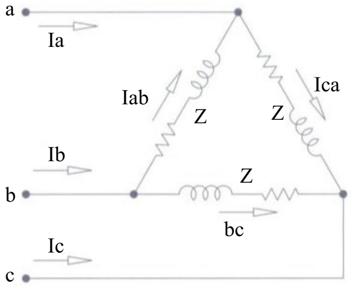

Figure 1.17. Delta connection.

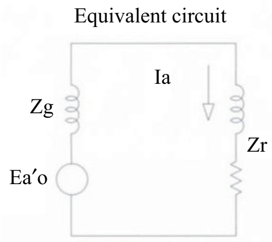

Figure 1.18. Equivalent circuit.

Voltage, current, and power calculations may now be easily done using the equivalent circuit. When converting back to three-phase power, add the power in each of the three (balanced and equal) phases. Remember to include the phase relationship and power angle in the calculation. Total three-phase power is given in equation 1.21.

1.4.3 UNBALANCED SYSTEMS

Unbalanced systems require analysis by more sophisticated tools, as the trigonometric functions we have discussed become complex in an unbalanced three-phase system. In 1918, a powerful tool called *symmetrical components* was developed by C. L. Fortescue.[8] According to Fortescue's theorem, three unbalanced phasors can be resolved into three balanced systems of phasors. The positive sequence of components consists of three phasors equal in magnitude and displaced by 120°, with the same sequence as the original phasors. The negative sequence differs, in that the sequence is opposite, and the zero-sequence phasors have zero displacement from each other.

A fault or disturbance on the system can be analyzed using balanced system techniques for each sequence. Symmetrical component analysis is used universally by modern system protection equipment to identify faults and control switching equipment. Further description of this technique is beyond the scope of this text, and balanced systems will be assumed.

1.5 PROBLEMS

Problem 1.1
A 100-MW coal-fired power plant generator runs continuously at rated output (100 MW) for 30 days. How much energy (kWh) is produced in the 30 days?

Problem 1.2
If a home uses 20,000 BTUs per day for heating, what is the equivalent energy used in kWh?

Problem 1.3
A 10-kW RE system is expected to generate about 15,000 kWh per year. If the customer has a net metering agreement with the utility, and uses all

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[8] Stevenson, W.D., Jr. 1975. *Elements of Power System Analysis*, 4th ed. p. 276.

the energy generated, what are the savings if energy is valued at 10 cents/kWh? If this customer also receives a PBI of 9 cents/kWh, what is the PBI revenue per year?

Problem 1.4
What is the electric generation mix for the utility serving you?

Problem 1.5
A single-phase voltage of 240 volts is applied to a series circuit with an impedance of $10 \angle 60^\circ$ ohms. Find R, X, P, Q, and the PF of the circuit.

Problem 1.6
If a capacitor is connected in parallel with the circuit of problem 1.5, and the capacitor supplies 1,250 vars, find the new P and Q supplied by the 240-volt source. What is the new PF?

Problem 1.7
In a balanced three-phase system, the line-to-line voltage is 480 volts. Y-connected impedance is $10\angle 30^\circ$ per phase. What is the line-to-neutral voltage ($V\varphi$) and phase current ($I\varphi$)? Express the current in rectangular and polar format.

Problem 1.8
Determine the current in a three-phase motor when voltage is 480 and the motor is running at full rated output of 15 HP. Assume the efficiency is 100% and PF is unity.

Problem 1.9
If the PF is 80% lagging, calculate P and Q for the voltage and current given in Problem 1.8.

Problem 1.10
In a balanced three-phase distribution line, the line-to-line voltage is 13.8 kV. The line is Y-connected at source and load. What is the phase-to-neutral voltage ($V\varphi$)?

Problem 1.11
The distribution line of Problem 1.10 is 15 miles long. The impedance of the line per phase is $0.2 + j0.5$ ohms/mile. A load of $50 + j20$ ohms is connected in Y. What is the phase current ($I\varphi$)? What is the total apparent, reactive, and real power provided by the source (generator)?

Problem 1.12

Determine the power factor at the generation source in Problem 1.11. Calculate the voltage drop from generator to load.

Problem 1.13

(a) A utility power feeder supplies a customer with a load of 1,000 kW and 450 kVar. Using the power triangle and three-phase power equations, solve for the apparent power. What is the PF at the customer's load?

(b) The customer installs a 500-kW RE system at the utility point of interconnection. What is the new power and apparent power when the RE system is operating at full output (500 kW, 0 kVar)? What is the new PF?

(c) The utility points out a lower PF at the point of interconnection and claims the customer is causing system inefficiency because of the lower PF caused by connecting a PV system to their power system. Is the claim valid?

Hint: Using per unit analysis, calculate the voltage drop on a feeder that connects the PV array and load to the utility. Use the following assumptions:

1.0 PU (apparent power) = 1,000 KVA
R (line resistance) = 0.05 PU (5%)
X (line reactance) = 0.142 PU (14.2%)

Calculate the line voltage drop with and without the RE system connected. Do your results support the claim by the utility that an RE connection is detrimental to the utility system?

CHAPTER 2

RENEWABLE ENERGY TECHNOLOGIES

Wind and photovoltaic systems are the most recognizable types of renewable energy systems we see today. There are many more sources of energy that are considered renewable, including hydroelectric, solar thermal, marine, geothermal, and bioenergy. These types of systems have been implemented for many years, such as hydroelectric systems. Hydro plants continue to supply large amounts of power to our electrical grid, and there is potential for limited growth. Other systems are still in infancy, although they have a huge potential, such as marine energy, which includes tidal power and wave power. This textbook will briefly describe some of the potential and limitations of the *other* renewable sources and provide references to some very good textbooks and documents that describe these technologies in detail.

Hydroelectric power plants currently supply about 20 percent of the world's electric generation.[1] Hydro generation is a very essential part of the electrical grid, because output can be controlled to compliment variable generation sources such as wind. Hydro plants are efficient at low generation levels and can be used to follow the predicted and unpredicted changes in consumer demand. Hydro generators can respond within minutes to a change in demand. Pumped storage systems are also used to meet the demand changes. Water is pumped to an upper storage reservoir at night when the demand is low, and released for generation during high demand times. Although many of the most attractive sites have been tapped with hydroelectric systems, there are locations where this technology may be developed. Figure 2.1 shows a typical hydroelectric facility.

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[1] Freris, L., and D. Infield. 2008. *Renewable Energy in Power Systems*, 24. John Wiley and Sons.

Figure 2.1. Hydroelectric facility.
Source: Photo courtesy of the National Renewable Energy Laboratory (NREL).

Marine systems are composed of tidal and wave power generators. Tidal power has the potential to provide a large portion of world energy use, but efficient systems have not been developed. A problem with tidal power is variability. Output generation depends on tidal frequency, which is approximately twice per day. Spring (in phase relation of the moon and sun) and neap (out of phase relation) tides also cause further variability in power. Low head turbines and two-way generation are features that have not been developed for tidal power. Wave power systems also have a large potential to generate energy, but the technology and capital needed to capture the energy from oceanic waves has not developed. Some of the problems include the low frequency of large waves and the variability of wind by season. Scientists have projected that wave energy in our oceans has the potential of 2,000 tera-watts, or about twice the present world capacity.

Bioenergy or biomass systems are similar to fossil fuel systems in construction and operation. A boiler and steam turbine produce power from the energy supplied by stored fuel with limited energy density. Fuel density limits the distance bio power plants can be located from the source, and the size of the plants is generally limited to 100 to 500 kW. Although direct combustion biomass systems may decrease the demand for imported oil, the process has several disadvantages. The fuel competes with food crops and may cause shortages or increased food prices. The environmental impact of CO_2 production and pollution also exists.

Solar thermal electric systems are in use at several locations in the United States. A large-scale plant near Barstow, California, has been in operation for about 20 years. The system uses mirrors to concentrate direct solar radiation for a boiler (see Figure 2.2), which drives the electric

Figure 2.2. Solar thermal plant.
Source: Photo courtesy of the NREL.

generator. As the system requires direct radiation, the southwest is the preferred location for similar plants. Cloudy skies and diffuse radiation is unsuited for this technology. Parabolic trough collectors are also used to force radiation on a piped system, which transfers heat to a heat exchanger/boiler where steam is produced to drive a generator. Xcel Energy is currently adding a solar thermal system to one of its coal-fired plants to supplement plant-auxiliary power requirements. Smaller systems use parabolic concentrators that work at high temperatures and are suitable for distributed electric generation. Figure 2.2 shows a solar thermal plant.

Wind power is the fastest-growing energy source in the United States. In 2008, the U.S. wind industry installed 8,358 MW of new generation and took the lead in global installed wind energy capacity with a total of 25,170 MW.[2] In 2009, the United States added another 10 GW of wind capacity to reach a total of 35 GW. In 2012, 13.1 GW of wind energy was installed, which was more than natural gas generation. The U.S. Energy Information Agency (EIA) estimates U.S. electric consumption will grow to 3,902 billion kWh by 2030. If the United States is to meet 20% of that demand, the U.S. wind generation capacity will have to be greater than 300 GW. Much of this growth is attributed to the Renewable Energy Portfolio Standard (RPS) and the renewable energy production act (PTC) bill passed by congress in 2002. Utilities were required to produce 10% of their energy from renewable sources by 2010.[3] The PTC provided a 1.8 cent/kWh incentive,

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[2] Energy Efficiency and Renewable Energy, U.S. Department of Energy, prepared by the NREL, April 2009.

[3] Patel, M.R. 2005. *Wind and Solar Power Systems*: *Design, Analysis, and Operation* 2nd ed. 17. CRC Press.

Figure 2.3. Wind turbine generator at the National Wind Test Center.
*Sourc*e: Courtesy of the NREL.

indexed to inflation, for the first 10 years of wind plant production. The PTC increased to 2.2 cents/kWh since 2010. Figure 2.3 shows a typical large wind generator.

Geothermal systems use extreme hot water from deep wells for heating purposes or to generate electricity when the pressure is high enough to drive a turbine. These systems are limited to areas where geothermal sources can be reached economically with drilling equipment. Many areas in the rocky mountains have large untapped geothermal resources, but temperatures over 200°F are several thousand feet below the surface. Figure 2.4 is a remote geothermal plant in operation.

Ground source heat pumps (GSHPs) are sometimes confused with geothermal systems. GSHP systems can be efficiently used for residential heating and cooling. A network of piping 10 to 20 feet underground transfers heat from the ground in the winter when earth temperatures are relatively warm, and transfers heat from the home to the cool earth in the summer. The piping may also consist of 200 feet of vertical supply and return piping in the ground. Electric power is needed to run pumps and heat exchangers, which offsets some of the savings. A backup heating system may also be required during periods of very cold temperatures. Some utilities will subsidize GSHP systems to replace natural gas with electrical use. A solar electric system can supplement the electrical use with net metering or a storage (battery) system.

Figure 2.4. Geothermal plant.
Source: Courtesy of the NREL.

Solar electric systems using photovoltaic (PV) modules are also growing rapidly as the cost for PV modules drops, and residential and small commercial systems are subsidized by state government programs. A good measure of the growth of PV installations is the volume of PV shipments in the world. In 1980, less than 10 MW were shipped, and in 2006, more than 1,000 MW of PV modules were shipped.[4] In 2007, about 93% of the PV modules were manufactured in Europe and Japan, and now, China is a leader in PV manufacturing. The United States installed 3.2 GW of PV in 2012. Figures 2.5 and 2.6 show typical remote and residential PV installations.

The U.S. Energy Information Administration (EIA) provides yearly reports concerning energy generation. Nonhydro renewable generation increased 12.8% from 2011 to 2012. In 2017, nonhydro renewable generation accounted for 10% of all U.S. electric generation sources. Coal fuel generation has decreased from 12.5% to 37.4% of the total mix. Nuclear energy is below 19% of the U.S. electric generation. Natural gas generation increased to 30.3% of electric generation in 2011 and 34% in 2017. Solar and wind was a small portion of overall electric generation (0.11 and 3.46% respectively) in 2011. However, in 2017, solar PV reached 2% and wind 8% of the total electric generation.[5]

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[4] Messenger, R., and J. Ventre. 2010. *Photovoltaic Systems Engineering*, 3rd ed. p. 15. Boca Roton, FL: CRC Press, Taylor and Francis Group.
[5] U.S. EIA: Electric power monthly.

Figure 2.5. Remote standalone PV system.

Figure 2.6. Residential PV system.

Solar PV systems are now the fastest growing source of electrical energy. Totally, 7.5 GW of solar was installed in the United States in 2015, and the total installed solar generation reached 29 GW. The number of solar PV systems grew to 1 million in 2016. The portion of all generation due to solar is predicted to grow to 3.5% by 2020. The cost to install solar has decreased from 7.50 U.S. dollars per watt in 2009 to below 2.50 U.S. dollars per watt in 2016.

CHAPTER 3

THE WIND RESOURCE

Until recently, wind energy was the fastest growing renewable energy source in the United States, only taken over by the growth of photovoltaic electric systems. However, wind energy systems now generate more renewable energy than any other renewable source. Large-scale wind farms have taken over the industry that once consisted of small, standalone wind generators that charged batteries for remote homes. Reliability and electrical performance have improved to the point where the annual production of wind farms can be more accurately predicted and managed by the interconnected utilities. Wind prediction techniques have also improved, so utilities can coordinate wind energy production with conventional power plants. This chapter will describe the wind resource in this country and the basics of analyzing wind speed data and how it is converted to power.

3.1 WIND SPEED ASSESSMENTS

Wind energy is an indirect form of solar energy. Thermal gradients caused by solar radiation cause air mass movements. Rising air at the equator is replaced by air movement from the north and south latitudes. Rotation of the earth creates trade winds east to west in some parts of the world, and west to east in other regions. Diurnal winds are created by land and sea thermal gradients. Weather systems create synoptic winds that are less predictable. Turbulence is a characteristic of synoptic winds, which is not a favorable component of wind when extracting energy. Turbulence disrupts the Bernoulli effect and causes airfoils to lose lift and efficiency. The best wind resources are areas of consistent and uniform wind characteristics.

The wind resource for the United States has been mapped in terms of wind speed and wind power density in watts per square meter. The U.S. Department of Energy (DOE) and National Renewable Research

Table 3.1. Wind energy classification

Hub height:	30 m		50 m			
	Power density	**Wind speed**	**Power density**	**Wind speed**	**Power density**	**Wind speed**
Wind class	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s
1	100	4.4	160	5.1	200	5.6
2	150	5.1	240	5.9	300	6.4
3	200	5.6	320	6.5	400	7.0
4	250	6.0	400	7.0	500	7.5
5	300	6.4	480	7.4	600	8.0
6	400	7.0	640	8.2	800	8.8
7	1,000	9.4	1,600	11.0	2,000	11.9

Laboratory (NREL) have developed a wind speed map from wind speed records (mostly airport data) throughout the country. These maps are available on the Internet at www.nrel.gov/wind. Seven wind classes categorize average wind speed and power density.

Table 3.1 shows the wind classifications, wind power density, and average wind speed for three hub heights. Hub height is the distance above the ground where an anemometer is installed to measure wind speed.

The U.S. wind resource is large enough to produce more than 3.4 trillion kWh of energy each year.[1] Almost 90% of the available wind resource lies in the Great Plains area. North Dakota has about 36% of the Class 4 wind resource area that is available for wind generation development. However, much of this resource is located far from the urban areas where electricity is needed. Transmission lines must be added to make wind energy feasible in these areas. Other constraints to wind development include public acceptance, institutional constraints, access, and technological problems.

3.2 WIND POWER CALCULATION

Kinetic energy of an air mass (m_a) moving at speed V (m/s) is given by the following equation:

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[1] Patel, M.R. 2006. *Wind and Solar Power Systems*, 2nd ed. p. 48. CRC Press.

$$KE = ½\, m_a\, V^2 \text{ joules} \tag{3.1}$$

Power is the flow rate of kinetic energy per second in watts:

$$P = ½\, (\text{mass flow per second})\, V^2 \tag{3.2}$$

From these relations, we can determine the power from a volumetric flow of air mass, which is given by equation 5.3:

$$P = ½\, (\rho\, A\, V)\, V^2 = ½\, \rho\, A\, V^3 \tag{3.3}$$

where P = mechanical power in watts (kg-m^2/sec^3)
ρ = air density (kg/m^3)
A = area swept by the rotor blades (m^2)
V = velocity of air (m/s)

If specific sites are being evaluated, it follows that the wind resource should be expressed in terms of the wind power per square meter (W/m^2). Equation 3.4 represents the *specific wind power density (SP)* for the wind resource:

$$SP = ½\, \rho\, V^3 \tag{3.4}$$

Obviously, a wind generator cannot extract all the energy from the wind, because that would give claim to an efficiency of 100% and defy a number of physical laws. A number of books are available on the subject of aerodynamic efficiency, which we will not get into in this text. The efficiency of any rotor is customarily expressed as a coefficient and included in the power equation for *net power extracted from wind turbine blades*.

$$P = ½\, \rho A\, V^3\, C_p \tag{3.5}$$

C_p is called the *power coefficient* of the rotor, or rotor efficiency. It varies for different types of blades, rotor design, wind speed, and rotor speed. It has a maximum theoretical value of 0.59, but in practical designs, it remains in the range of 0.4 to 0.5 for modern two-blade turbines. Higher-density rotors (more than two blades) usually have a C_p between 0.2 and 0.4.

Wind power varies linearly with the *air density (ρ)* in Equation 3.4. Air density is dependent on pressure and temperature according to the gas law:

$$\rho = p / RT \tag{3.6}$$

where p = air pressure (lbs per square inch or psi)
T = temperature (absolute °K)
R = gas constant

The air density at *sea level* (ρ_o) at 1 atmosphere pressure (14.7 psi) and 60°F is 1.225 kg/m^3. Air density at other elevations (Hm) in meters is corrected by the equation 3.7.

$$\rho = \rho_o - (1.194 \times 10^{-4}) \times \text{Hm kg/m}^3 \tag{3.7}$$

At an elevation of 2,000 meters, air density is 0.986 kg/m^3, which corresponds to a 20% difference in the power density calculation. We can roughly predict a 10% loss in power density for each 1,000 meters of elevation gain.

The swept area of a rotor is the area of a circle in which the rotor rotates. The output power of a wind turbine varies linearly with the swept area. For a *horizontal axis machine*, the swept area (A) calculation is simply the area defined by the rotor diameter:

$$A = (\pi/4)\, D^2 \tag{3.8}$$

where D is the rotor diameter

If the wind turbine is a vertical-axis design (i.e., Darrieus), the area is (2/3) × (width at center) × (height).

The wind turbine intercepts the wind energy flowing through the entire swept area, regardless of the number of blades. *Solidity* is defined as the ratio of the area of the blades to the swept area. A modern two-bladed wind turbine has a solidity ratio of 5% to 10%. As we will discuss later, the two-bladed machine is more efficient at high winds and less costly due to the lower blade material. The three-blade design boasts a 5% power performance increase, improved balance, and smoother operation than the two-blade design at the same angular speed. However, the third blade increases cost, weight, and installation work.

3.3 WIND SPEED PREDICTION TECHNIQUES

Wind speed measurements and methods of evaluation need further study because the average wind speed is the most critical data needed to estimate power production for a particular site. Wind is highly variable by the minute, hour, day, season, and even by the year. Weather patterns generally repeat over a period of one year, and a one-year site evaluation for average wind speed is a minimum. 10-year evaluations are preferred and give more confidence in future energy potential. However, most projects cannot be put on hold for long wind evaluations, and one-year wind speed data is often used to compare potential sites. This process is known as the *measure, correlate, and predict technique*.

Wind speed variations are best represented by a *probability distribution function*. The Weibull probability distribution is usually used to predict variability in wind speed. Weibull uses a shape parameter (k) and scale parameter (c) as given by the following expression:

$$h(v) = [k/c][v/c]^{(k-1)}\, e^{-(x)} \text{ for } 0 < v < \infty \tag{3.9}$$

where $x = (v/c)^k$

By definition of the probability function, the summation or integral of all wind speeds between zero and infinity must be equal to one:

$$\int_0^\infty h\, dv = 1 \tag{3.10}$$

The *shape parameter* (k) defines the wind characteristics of a potential site, as shown in Figure 3.1. If the site has many windless days, the Weibull distribution curve with k = 1 best represents the wind speed data. Most wind distributions take the form of the curve with k = 2, with a small number of windless days and a diminishing number of high-wind days. This special distribution curve (k = 2) is called a Rayleigh distribution and is used for most wind site analyses. The Weibull distribution curve with k

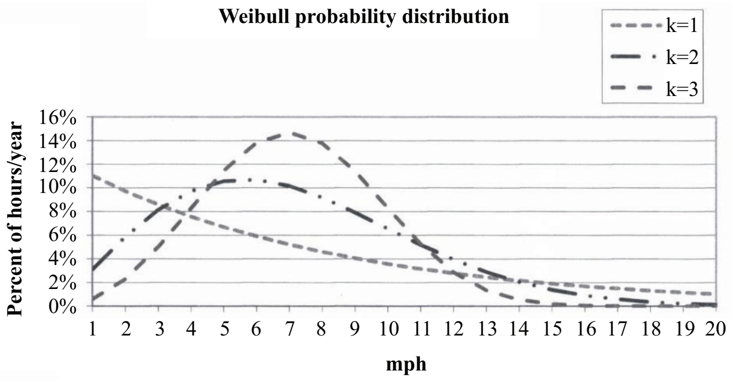

Figure 3.1. Weibull distribution and shape parameter (k).

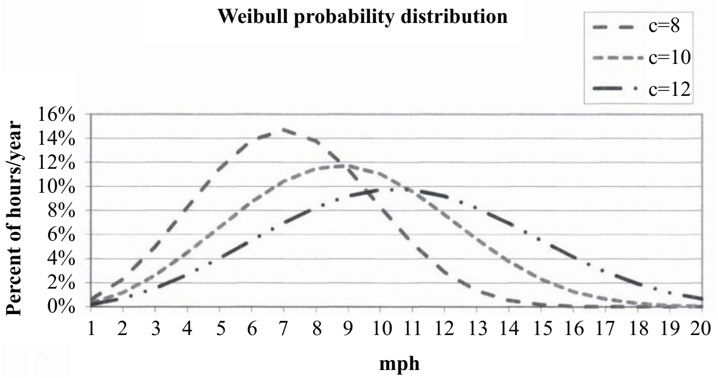

Figure 3.2. Weibull distribution and scale parameter (c).

= 3 is closer to a bell-shaped curve with an equal number of high- and low-wind days. The bell-shaped curve (k = 3) is sometimes called a *Gaussian distribution*.

The *scale parameter* (c) shifts the wind speeds to a higher speed scale (the hump moves to the right for a larger c value). Usual values of c are 10 to 20 mph. Figure 3.2 shows the effect of increasing c from 8 to 12 mph, while the shape factor k is held constant at 3.

Most site data is reported in terms of mean wind speed, which is used to evaluate potential wind sites. If a more accurate prediction of power density is needed, root mean cube (rmc) wind speed may be used. Vrmc is calculated by taking the cube root of the integral of hv^3 dv. If the data is from a one-year evaluation with hourly average wind speed values, the integral is divided by 8,760 hours.

$$Vrmc = [\ (1/8760) \int hv^3 dv)\ ]^{1/3} \tag{3.11}$$

Using Vrmc in the power formula (Equation 3.4) gives us the annual power generation in watts/m^2. The root mean cube wind speed calculation provides another look at potential wind sites when the average or mean wind speed provides insufficient information to decide whether the potential site is feasible.

Actual data from a wind site in North Dakota[2] is given in Table 3.2 and Figure 3.3. Instrumentation captured the time the wind speed was within 20 1-m/s intervals (called bins). The range of wind speed for each bin is ±0.5 m/s. Figures 3.3 and 3.4 show the corresponding frequency

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[2] Price, G.D. 1996. *Wind Energy Analysis, Wind Generation Project*, 28–30. North Dakota.

of wind speed in each bin (1 m/s = 2.24 mph). The duration of this test was 20 days of very consistent high wind and good variability of speeds, which provided accurate performance data. The data was used to create a power curve for a 10-kW wind generator installed at the site. Test data was obtained using the American Wind Energy Association (AWEA) performance standards that require a minimum duration in each wind speed bin. The data verifies the Rayleigh distribution probability curve with a shape parameter of about 2.5 and a scale parameter of about 20 mph. The data is not representative of the yearly wind speed distribution due to the short period of test data.

A Jacobs 23-10 WTG, installed at the North Dakota site, produced the data in Table 3.2 and Figure 3.3. Model 23-10 is a three-bladed wind turbine with a 23-feet rotor diameter and 10-kW alternator. The generator was utility-connected at 240 volts with a three-phase rectifier and line-commutated single-phase inverter. It was installed on a 120-feet tower. Site altitude is 1,600 feet above the sea level. The average annual wind speed was 14.05 mph (6.27 m/s). The average yearly energy generated was 22,000 kWh. The power curve for this machine is shown in Figure 3.5.

Mode speed is defined as the speed corresponding to the hump in the distribution function (or, in this case, the actual data). The mode speed in

Table 3.2. Wind speed (m/s) bins and frequency (%)

m/s	0	1	2	3	4	5	6	7	8	9	10
%	3.94	4.20	6.96	12.20	14.30	15.22	11.94	7.48	6.30	5.64	4.07
m/s	11	12	13	14	15	16	17	18	19	20	21
%	3.41	2.10	1.18	0.66	0.26	0.13	0.0	0.0	0.0	0.0	0.0

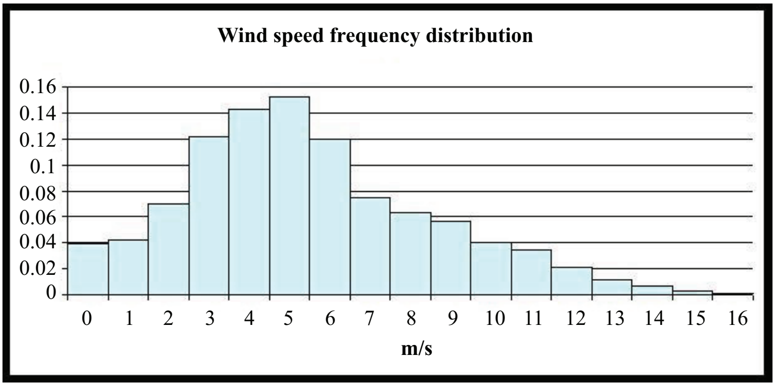

Figure 3.3. Frequency distribution of wind speed.

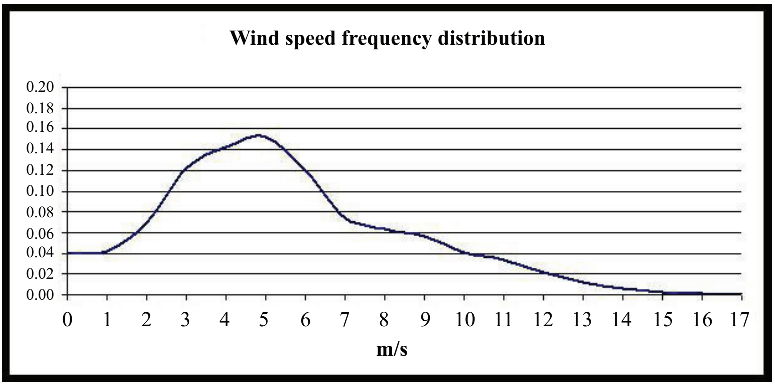

Figure 3.4. Smoothed frequency distribution of wind speed.

Figure 3.5. Cup anemometer.

Figure 3.3 is about 5 m/s or 11 mph. This is the speed of the wind most of the time. Figure 3.4 uses the same data as Figure 3.3, modified as a smoothed curve.

Mean speed is defined as the total area under the distribution curve integrated from zero to infinity and divided by the total number of hours in the period. If the period is one year, the area would be divided by the number of hours in a year (8,760).

$$\text{Vmean} = (1/8760) \int_0^\infty \text{hv dv} \qquad (3.12)$$

A thorough study of the probability of wind density distributions can involve some sophisticated mathematical approaches and three-dimensional analyses. We can avoid the math by making a few basic approximations that hold true for most wind distributions. The mean speed can be approximated by:

$$\text{Vmean} = 0.90 \times c \tag{3.13}$$

where c is the scale parameter described earlier for the Weibull probability distribution.

This relationship may be used for the Rayleigh distribution with a shape parameter of k = 2 with reasonable accuracy.

Mean wind speed is usually obtained using digital processing techniques. Wind speed is sampled by a data collection system every few seconds. This sample is averaged into minute averages. Minute averages are then averaged into hourly, daily, monthly, and yearly averages. The averaging algorithm is given in Equation 3.14, where n is the number of samples.

$$\text{Vave} = (1/n) \sum_{i=1}^{n} V_i \tag{3.14}$$

If the root mean cube velocity (Vrmc) is preferred for analysis, the following equations are used:

$$\text{Vrmc} = [\ (1/n) \sum_{i=1}^{n} V_i^3]^{1/3} \tag{3.15}$$

and

$$\text{Prmc} = (1/2n) \sum_{i=1}^{n} \rho_i\, V_i^3 \tag{3.16}$$

where ρ_i = air density (kg/m^3)
v_i = wind speed (m/s) for each sample i
n is the number of samples

3.4 WIND SPEED MEASUREMENT

The hub height of the anemometer used in making wind speed measurements must be corrected to the actual hub height of the proposed wind turbine. Many weather stations are located near airports where there are low-wind conditions, and the anemometer is installed 10 or 20 feet above the ground. Wind shear causes measurements to be lower near the ground level. The following relation corrects measurements at a lower level (h_1) to higher heights (h_2):

$$V_2 = V_1\,(h_2/h_1)^{\alpha} \tag{3.17}$$

where α is the ground surface coefficient

$\alpha = 0.1$ is smooth ground or a body of water
$\alpha = 0.4$ is in a city or around tall obstructions

Wind speed measurements are more reliable if using ultrasonic anemometers that are not affected by cold, ice, rain, or bearing wear. Common sensors used at airports and weather stations are cup or wind vane-type anemometers (see Figures 3.5, 3.6, and 3.7). Cup anemometers are the most common because they are relatively inexpensive and easy to install and monitor. They are best used to measure *wind run*, which is basically a count of revolutions for a specific time period. The data obtained can provide a good evaluation of the average wind speed for a site.

Vane-type anemometers are used when more accurate *wind gust* data is required. Propellers are more responsive to short bursts of wind and provide a better measure of turbulence. Vane anemometers are more expensive and require a more sophisticated data monitoring system due to the frequency and quantity of data.

Figure 3.6. Vane anemometer.

Figure 3.7. Ultrasonic wind sensor, courtesy of Lufft.

Ultrasonic anemometers are the preferred instrument when measuring turbulent wind and extreme weather conditions. They are more durable and have no moving parts. The data monitoring system must be able to measure and record the high-frequency output of the ultrasonic sensors.

3.5 PROBLEMS

Problem 3.1

What is the specific wind power density (SP) of a potential wind site at sea level with an average wind speed of 12 m/s? What is the SP if a site at an elevation of 2,000 meters and wind speed of 12 m/s?

Problem 3.2

If a horizontal-axis wind turbine with a rotor diameter of 20 meters is installed at the 12 m/s wind site and at 2,000-meter elevation, what is the net power at this wind speed if the rotor coefficient of power (Cp) is 0.4?

Problem 3.3

What is the net power output of Problem 3.2 if a vertical-axis wind turbine is installed with a diameter of 10 meters and height of 20 meters?

CHAPTER 4

WIND GENERATOR SYSTEMS

Large-scale wind farms have taken over the industry that once consisted of small, standalone wind generators that charged batteries for remote homes. The 10- to 20-kW wind machines of those times are now dwarfed by 1- to 3-MW wind turbines on 300-feet towers. Reliability and electrical performance has improved to the point where the annual production of wind farms can be more accurately predicted and managed by the interconnected utilities. This chapter will describe the basics of aerodynamics, generator operation, and balance-of-system equipment associated with interconnected wind turbines.

4.1 WIND POWER SYSTEM COMPONENTS

All wind systems have the following basic components: tower structure, rotor, nacelle, generator, speed controls system, and yaw control. Larger wind generators also have a gearbox, braking system, and power electronics. This section will describe these components and their general design and operation. Figure 4.2 identifies the components of a typical wind turbine.

The wind tower supports the rotor, generator, nacelle, and other components in the nacelle. Smaller wind turbines may use lattice or tubular towers, and large machines generally have concrete cylindrical towers. The height of the tower is usually equal to the rotor diameter for large machines to insure the blades are above any ground-induced turbulence or shear. Smaller wind turbines may have towers several times the rotor diameter in height to place the rotor in higher wind speeds and eliminate the effects of ground shear and turbulence. As described in the previous section, wind speeds increase with height by a factor dependent on ground surface smoothness. Tilt towers, with hinges at the base and a

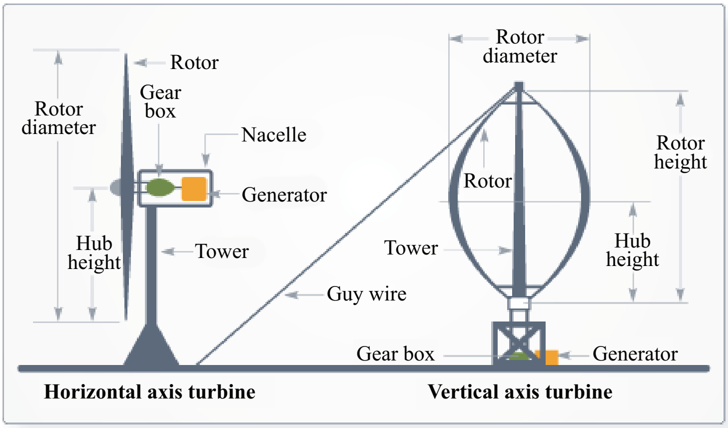

Figure 4.1. WTG towers.

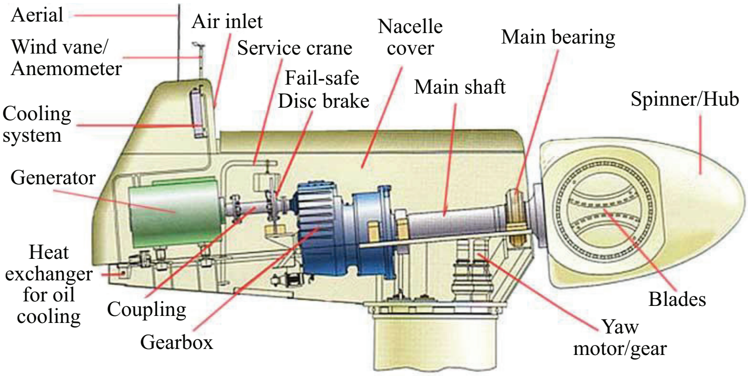

Figure 4.2. WTG components.

gin pole leverage arm, are sometimes used to install smaller wind turbines. The tilt tower is also useful for maintenance and repair. Large machines are installed at the top of the tower with large cranes. With the exception of blade replacement, maintenance of the equipment in the nacelle is accessed with an elevator or climbing ladder inside the tower. Figure 4.1 shows some basic WTG components and dimensions.

A primary concern in the design of wind turbine towers is structural dynamics. Wind speed fluctuations and rotor dynamics cause vibration at frequencies that may result in tower stress and fatigue. Resonant frequencies between the rotor, blades, and nacelle must be avoided as much as possible. Test facilities measure actual stress and strain caused from loads applied to the rotor and blades and determine the critical frequencies of each component. Modal analysis uses complex matrix equations to identify these frequencies, and the results determine the design of the rotor, blades, and tower. Some of the analysis can be done in the lab (large test facility), but much of the data is obtained from measurements on machines operating on site. Resonant frequencies also may cause objectionable noise when wind speeds change suddenly.

The weight of the rotor and nacelle has a significant impact on the cost and design of the tower. This weight is called the top head mass (THM) and is minimized using as much lightweight material in the rotor and nacelle as possible without compromising strength. The largest wind turbines (5 MW) made today have THM of 350 tons. The THM of the smaller Vestas wind turbine (3 MW) is 103 tons. The gearbox, electric generator, drive shafts, and rotor hub account for most of the THM, but steel must be used to withstand the stress on these components.

The nacelle houses the gearbox, generator, high—and low-speed shafts, brakes, and control equipment. A nacelle for large turbines also provides room for maintenance workers to access the components in a safe environment. It must be lightweight and strong to minimize THM and protect equipment from the environment.

The gearbox increases the rotational speed of the rotor (30 to 60 rpm) to the synchronous speed of the generator (1,200 to 1,800 rpm). As one can guess, the torque on the gearbox is very large, and cooling systems are usually required. The gearbox also contributes significantly to the THM. The gear ratio is usually fixed because shifting gears while a wind turbine is operating under large torque is all but impossible. Direct-drive generators are used with small machines, and variable speed generators are also being designed to reduce or eliminate the need for a gearbox.

Modern wind turbines have two or three blades, which are carefully designed aerodynamic airfoils. Gone are the old, water-pumping flat or cupped blades that operate on the principle of drag. Blades apply the Bernoulli's principle with a relatively flat bottom surface and longer upper-side surface. Lift is created on the airfoil by pressure difference in wind flow over the blade. Lift is increased by increasing the angle of attack slightly with pitch controls. The *angle of attack* is the angle between the wind direction and the chord of the airfoil (see Figure 4.3). A drag force is also created, which impedes the lift force. The lift-to-drag ratio varies along the length of the blade to maximize power output at various wind and rotor speeds. Pitch control rotates the blade as the rotor speeds-up to maximize lift and power to the shaft. Pitch control is also used to reduce lift and power as the turbine reaches maximum-rated power. When wind

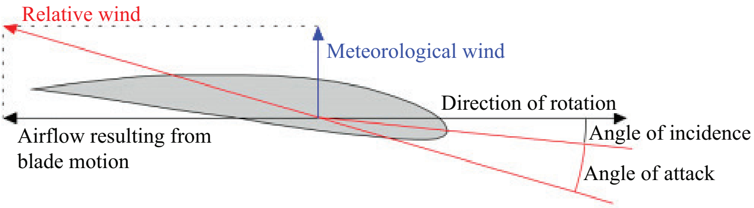

Figure 4.3. Angle of attack.

Figure 4.4. Small WTG with hinged tail.

speeds exceed rated values, the pitch is changed to stall the blade and act as a brake.

In addition to pitch control for rotor speed and power, other control systems are needed to maximize power output, prevent overspeed, and prevent exceeding the rated generator power. Yaw control continuously keeps the rotor facing directly into the wind. Many types of systems have been developed to control yaw, including the tail vane used by small wind turbines (see Figure 4.4). The tail vane also acts as a brake when high winds occur by rotating the rotor (axis) perpendicular to the wind direction. Downwind machines use the nacelle as a wind vane. Larger wind turbines use a combination of power monitoring and wind direction detectors to control yaw. Yaw changes must be dampened to prevent noise generated by rapid yaw movement in high winds. Tilt or teeter is the angle of the rotor shaft to horizontal. Although teeter angle is usually close to zero, it may be increased several degrees to reduce the noise caused by tower interference and prevent flexible blades from contacting the tower.

Wind turbine blades must withstand extreme mechanical stress, vibration, and fatigue. Centrifugal forces, combined with stress and strain from wind forces, may cause premature failure if there is any flaw in the fabrication process. Recent improvements in rotor blade technology allow construction of durable blades over 50 meters in length and rotor diameters over 100 meters. The emergence of carbon and glass–fiber–epoxy composites is one of the primary advances in this technology.

4.2 ELECTRIC MOTORS AND GENERATORS

Wind turbine generators have incorporated many types of electrical generators over the years. DC generators, alternators, induction motors, synchronous generators, and permanent magnet generators have been used, depending on the size and application of the wind turbine. Small wind turbines of early design used DC motors that generated voltage and current favorable to battery charging and standalone applications. Alternators replaced DC motors because the voltage and current output could be controlled to match loads and rotor speed. Early on, induction generators became the preferred interconnected wind turbine due to the rugged simplicity of design, cost, and availability. Synchronous generators are used in larger turbines and require a gearbox to step-up the rotor speed to 1,200 or 1,800 rpm. Although synchronous generators run at fixed speeds, electronic AC–DC–AC output systems allow variable speed operation. Doubly fed induction generators are now used in larger turbines to allow variable speed operation and decrease the size of electronic control systems. Permanent magnet generators allow variable speed operation and are used in small and medium-sized wind turbines. This section reviews the basic construction and operation of these types of machines as wind turbine generators.

4.2.1 DC GENERATOR AND ALTERNATOR

The DC generator produces direct current at a specific voltage range determined by the windings in the armature. The stator is the outer shell of the machine with windings on steel cores that produce the electromagnetic field. A DC field current is supplied to the stator, usually from a shunt connection from the armature. The rotor (armature) consists of a single coil of n turns wound lengthwise on a steel core along the shaft. (see Figure 4.5) The armature coil is connected to insulated bars around the end of the shaft, which makes up the commutator. Carbon brushes ride on the copper bars with spring tension and connect external output terminals

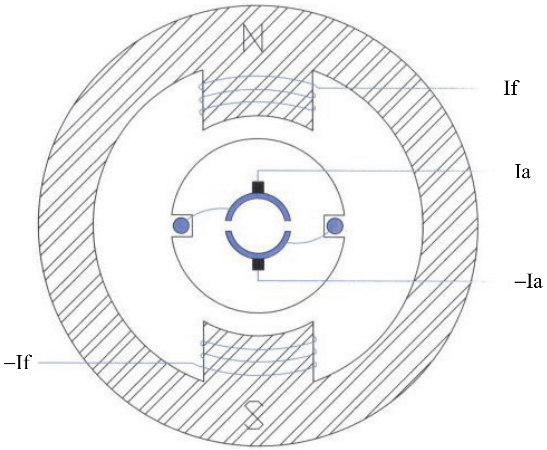

Figure 4.5. Elementary DC machine.

to the armature winding. As the rotor turns, the commutator rectifies the armature current by switching the polarity of the armature winding. As the output of the DC generator comes from the inside armature, this design is sometimes called *inside-out*. The output is controlled by increasing or decreasing the field current in the stator. The main disadvantage of the DC generator is the need for the commutator brushes that wear out, require maintenance, generate sparks, and add resistance to the output circuit. An advantage of the DC machine is precise speed control and DC output.

The alternator eliminates the need for the commutator and uses solid-state rectifiers to convert AC output to DC. The field current is supplied to the rotor (armature) coil through slip ring brushes. As the rotor turns, AC current is generated in the stator windings by the electromagnetic field produced by the rotor. The AC current is rectified to DC with a full-wave solid-state rectifier. Increasing or decreasing the rotor field current controls the output. This design is used in most automobile battery charging systems. The alternator is used by small wind turbines for DC battery charging and also in interconnected systems with a line-commutated inverter. The field current requirement can be eliminated by using permanent magnets in the rotor. The permanent magnet machine will be discussed later in this chapter.

4.2.2 THE SYNCHRONOUS GENERATOR

The synchronous machine is used in most utility power plants for system power generation. It runs at a precise speed and has the ability to provide real and reactive power to the grid. It also is well-suited to generate three-phase power. The stator is constructed similarly to the alternator and induction machine, with windings symmetrically placed in slots in the steel core. When connected to the grid as a motor, electromagnetic flux is generated at the utility frequency. The rotor, on the other hand, is wound to produce a north–south magnetic field proportional to the field current. The rotating stator flux *pulls* the rotor into synchronism so that the rotor magnetic field locks into the rotating field and no slip occurs. The rotor axis remains within a few degrees of the stator field axis. Any deviation from the synchronized position creates a large opposing torque until equilibrium is again maintained.

Synchronous speed (Ns) is determined by the number of poles (P) on the stator and frequency (f) of the utility-interconnected line (60 Hz).

$$Ns = 120 \times f / P \tag{4.1}$$

A two-pole machine (one-pole pair) has a synchronous speed of 3,600 RPM (Figure 4.6). Synchronous speed is 1,800 rpm for a four-pole machine (Figure 4.7), and Ns = 1,200 rpm for a six-pole machine.

As a generator, the synchronous machine must be brought up to the speed by the prime mover. When the rotor speed matches the stator field frequency, the stator winding contacts are closed. Increasing the field current maintains synchronism and is also used to control reactive component of power output. As the speed is fixed, the synchronous machine does not match the variable speed aspects of a wind turbine. A DC–AC–DC electronic converter is usually installed on the stator output to allow variable speed operation when connected to the fixed utility frequency grid.

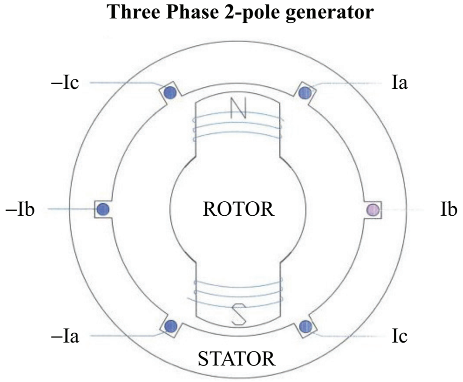

Figure 4.6. Two-pole synchronous generator.

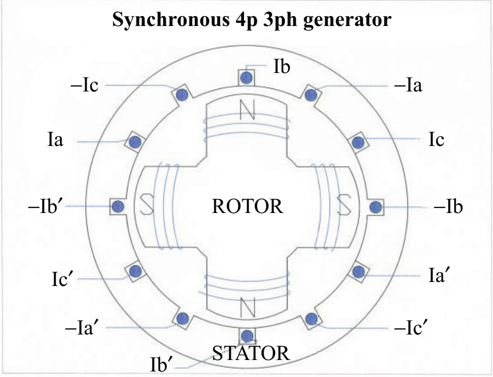

Figure 4.7. Four-pole synchronous generator.

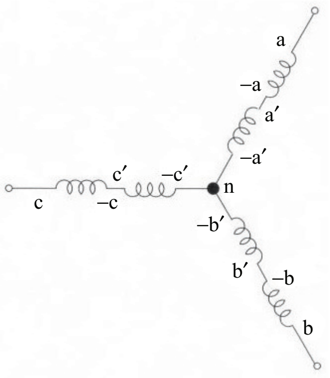

Figure 4.8. Synchronous generator stator winding.

The stator for a four-pole, three-phase synchronous machine is connected in wye, as shown in Figure 4.8. Two windings for each phase are connected in series. The polarity of the windings must be wired such that voltage is added for each phase. One end of each second winding is connected to a neutral point, which may be connected to the utility system neutral. Connections may also be made in delta configuration if the neutral is unnecessary.

4.2.3 THE INDUCTION GENERATOR

The induction generator eliminates two problems with the DC and synchronous machines: brushes and a separate field source. The stator poles are windings imbedded in slots and wound for single—or three-phase application. The output of the induction motor is the stator winding, instead of the armature in the DC machine. The rotor does not have slip rings or a commutator, but is constructed of parallel conducting bars around the rotor shaft with end rings. The end rings short the bars on each end. When power is applied to the stator, it acts as a transformer, inducing current in the rotor bars. The rotating flux in the stator brings the rotor up to speed determined by the frequency of the AC stator current. Torque is generated from the flux created in the air gap between the rotor and stator. If the rotor turns at the same speed as the rotating flux generated by the stator, no air gap flux is generated and no current flows in the rotor. As shaft load is applied and the rotor slows down, current flows in the rotor and torque is generated in the air gap, keeping the rotor speed (Nr) near the rotating flux speed (Ns) in the stator. The simple, rugged design of the *squirrel cage* induction motor makes it ubiquitous in the electric industry.

Synchronous speed of an induction machine is determined by the number of poles wound into the stator. If the machine is three-phase, the three phases represent a one-pole pair. The generator in Figure 4.9 shows one set of windings for each phase or one-pole pair. Synchronous speed is calculated as in equation 4.21, or Ns = 120 × 60/2 = 3,600 rpm. Slip (s) is the difference in rotor speed (Nr) and synchronous speed, expressed as a ratio.

$$S = (Ns - Nr) / Ns \tag{4.2}$$

If a four-pole induction motor is running at 1,750 rpm, the slip is 0.0278 (2.8 percent).

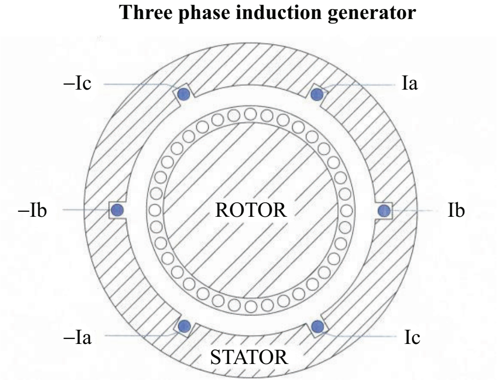

Figure 4.9. Induction generator.

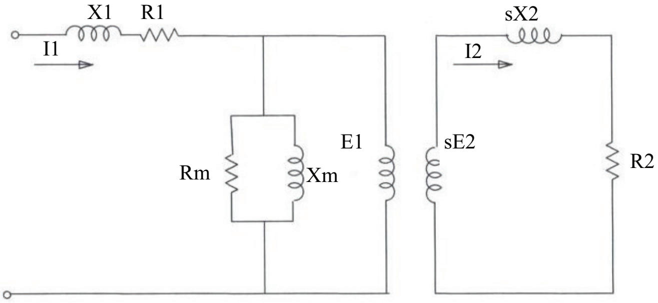

Figure 4.10. Induction machine equivalent circuit.

Induction motors become generators when torque is applied to the rotor shaft and the rotor speed is above synchronous speed (negative slip). If the four-pole induction motor is connected to a wind turbine rotor through a gearbox, the torque of the blades increases the speed of the rotor until it becomes a generator. If the rotor speed is 1,850 rpm, the slip becomes –0.0278 or –2.8 percent. If the induction machine is connected to the utility grid, it will feed power into the grid. If the grid connection opens and the wind turbine continues to apply torque, the machine will overspeed and may cause damage. The stator field and flux are necessary to operate an induction machine, as the flux will decay rapidly without a source. An emergency brake is needed to prevent an unloaded operation. The loss of grid connection and loss of induction generator power are also safety factors for the utility. Utility standards require that a nonutility generator stop producing power when the grid fails. Tests have shown that an induction machine will continue to produce power if capacitors are connected to the stator terminals. However, the resulting power is unstable in frequency and voltage, and may easily be detected with frequency relays in the wind turbine control system. The induction machine must be supplied with reactive power and will lower the power factor of the utility system.

The equivalent circuit[1] developed for the induction machine is similar to that of a transformer as shown in Figure 4.10. R1 and X1 are impedance elements of the stator (primary), R2 and X2 are rotor impedance components (secondary), and a magnetizing circuit is Rm and Xm. Slip (s) is the equivalent of the transformer-turns ratio.

Three-phase conversion power for the induction machine is given by equation 5.23:

$$P = 3\, I_2^2\, R_2\, (1-s) / s \text{ watts} \tag{4.3}$$

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[1] Fitzgerald, A.E., C. Kingsley, and S.D. Umans. 1983. *Electric Machinery*, 420. McGraw-Hill.

It is important to note that power is proportional to the rotor resistance R_2. If the rotor is at zero slip (synchronous speed), I_2 is 0 and power is 0. At standstill, slip is 1 and power is 0. Torque is also proportional to R_2, and given by $T = P \times \omega$ where ω is angular velocity (radians/second).

4.2.4 THE WOUND ROTOR INDUCTION GENERATOR

The induction generator may also be constructed as a *wound rotor* machine as shown in Figure 4.11. Such a machine is not as rugged and simple as the squirrel cage design, but adds a couple of important characteristics to operation. Slip rings are installed on the rotor shaft to allow access to the rotor windings. Resistance is added to the rotor circuit windings for improved starting torque characteristics and variable speed operation. The wound rotor is commonly used in streetcars and locomotives because of the high starting torque characteristic. A rheostat in the rotor circuit allows variable speed operation. It has also found use in wind turbines because of the variable speed characteristic.

The *doubly fed induction generator* uses a voltage source frequency converter to inject slip frequency power to the rotor. The result is a generator that runs in synchronism with the utility interconnection. Unlike the synchronous machine, only 20 to 30 percent of the output power goes through the frequency converter. The doubly fed generator has better start-up characteristics. One disadvantage of the large doubly fed induction machine is its tendency to drop out upon loss of utility power or a voltage dip. Utilities require that wind turbines ride through temporary outages to prevent a blackout if a large machine drops offline. Capacitors and control circuits have been developed to avoid this problem.

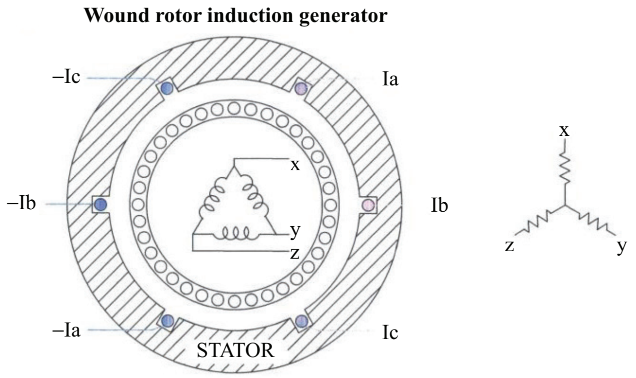

Figure 4.11. Wound rotor induction machine.

4.2.5 THE PERMANENT MAGNET GENERATOR

As mentioned earlier in this chapter, an alternator may be constructed with permanent magnets in the rotor, instead of a field winding. The magnetic field created by the magnets creates the air gap flux and output current in the stator, which is then rectified by solid-state equipment. Permanent magnet generators are used in small and some medium-sized (50 to 100 kW) wind turbines.

The permanent magnet generator is constructed with rare-earth magnets in the rotor. The magnets provide the magnetic field required to induce voltage in the stator. The advantage of this design is the elimination of slip rings that bring current into the rotor for synchronous, DC, and alternator machines. A disadvantage is the expense and weight of these magnets. Larger machines in the range of 100 to 200 kW are now being designed with permanent magnets, which have proven to be more efficient and durable.

4.3 WIND TURBINE RATING

Although there is no universal standard for rating performance of a wind turbine generator (WTG), there are a few generally accepted methods that manufacturers use in their specifications. The problem with rating wind generators arises because the output of a machine depends on the square of the rotor diameter and the cube of the wind speed. A rotor of a given diameter will generate different power at different wind speeds. The question is, at what wind speed should a WTG be rated? Some manufacturers use a higher wind speed than others to show greater output for the same design. Rotor diameter ratings also are not a good standard, because some wind turbines are designed to operate more efficiently at low wind speeds, while other machines are designed to withstand higher winds at the expense of low-speed efficiency. The best comparison of performance is a power curve that shows efficiency at a wide range of wind speeds, but these tests are difficult to control and expensive to perform on each machine design.

A comparative index known as the *specific rated capacity* is often used as a reference in a WTG design. It measures the capacity per square meter of the blade swept area and defined in units of kW/m^2:

$$\text{SRC} = \text{Generator electrical capacity/rotor swept area} \tag{4.4}$$

For example, a 300/30 (kW/m) wind machine has a 300-kW electrical generator and 30-meter diameter blade, and will have a SRC of:

$$\text{SRC} = 300 \text{ kW}/(\pi \times 15^2) = 0.42 \text{ kW/m}^2 \tag{4.5}$$

SRC ranges from 0.2 kW/m^2 for small machines to 0.5 kW/m^2 for large rotor diameter machines. SRC is a useful factor for the system integrator who needs to match the rated output of the generator to the interconnected power equipment, including transformers, cables, and substation equipment. It also provides a measure of the blade design that will capture the available wind energy for the specific site.

The power curve for a wind generator shows power output for wind speed range from cut-in to cut-out. *Cut-in wind speed* is the minimum wind speed when the generator begins to produce power, and *cut-out wind speed* is that at which the WTG begins shut-down for protection from overspeed damage. The power curve of Figure 4.12 is from a 10-kW wind turbine. Full rated output is not reached until the wind speed reaches 15 m/s. Rotor diameter is 7.0 meters, blade length is 3.5m, and the generator is rated 10 KVA for an SRC of 0.26.

A torque curve for the 10-kW wind generator is provided in Figure 4.13. Torque (T = P/ω) in foot-pounds per second is plotted versus angular velocity. The generator is rated at 10 kW at 25-mph wind speed (11 m/s) and 195 rpm. Torque levels at the rated output drop-off sharply at cut-out (not shown). The torque curve is typical of a variable speed WTG, as the generator is an alternator that produces power from 450 to 1,170 rpm. The alternator power output is rectified to DC and connected to the utility by an inverter. The AC–DC–AC design allows the WTG to operate at variable speed and capture energy over a wider range of wind and rotor speeds.

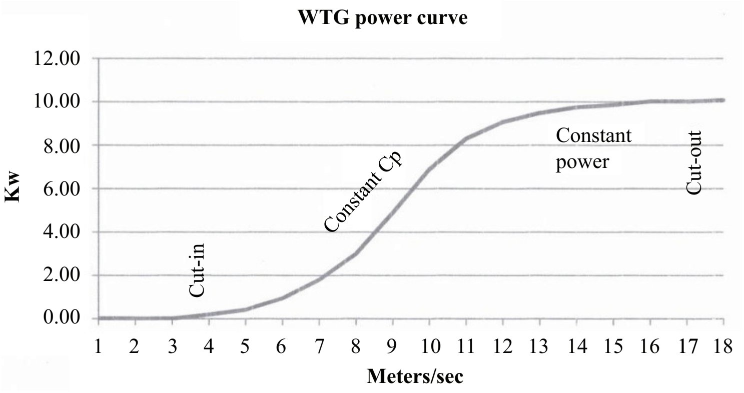

Figure 4.12. Wind turbine power curve.

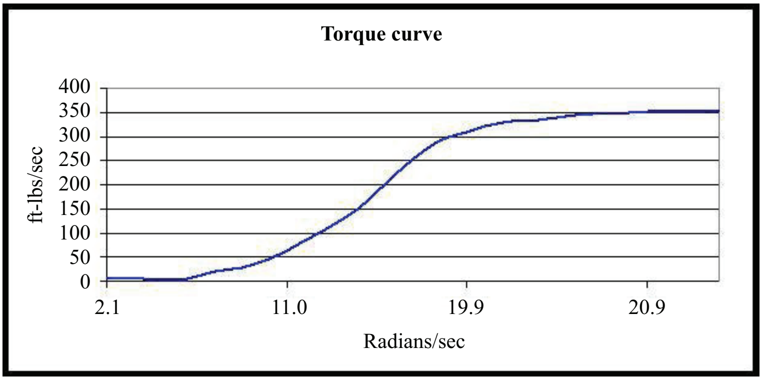

Figure 4.13. Wind turbine torque curve.

Power and torque curves show that it is very beneficial to match the angular velocity of the rotor to the wind speed. The power coefficient (Cp) is higher when the angle of attack maximizes lift versus drag. This happens when the effective wind direction is at the ideal angle of attack. Effective wind direction is determined by the orthogonal wind speed and blade speed. It follows that the blade and wind speeds have optimum values for maximum efficiency. This concept is embodied in a ratio called the *tip speed ratio (TSR)*.

$$\mathrm{TSR} = \omega\, r / v \tag{4.6}$$

where v = wind velocity (m/s)
r = blade radius (m)
ω = angular velocity (radians/sec)

The range for TSR is 1 to 6, depending on the blade design. Figure 4.14 shows several types of blade designs and the coefficient of power versus the range of TSR for several designs. The ideal rotor design operates at high efficiency over a wide range of TSR. This means the rotor/blades perform efficiently over a wide range of wind speeds and angular velocities of the rotor. Actual rotor designs operate efficiently only for a narrow range of TSR: the wind speed and angular velocity must be within limits.

The modern two-blade design has the highest coefficient of power (i.e., efficiency) at a TSR range of about 4.0 to 7.0. The multiblade rotor, which is of the *water-pumper* farm-style design, has the lowest efficiency and operates at a very small TSR range, which means the angular velocity, and the wind speed must be relatively constant (TSR = 1) to operate efficiently. The multiblade and Savonius rotors rely on drag, instead of

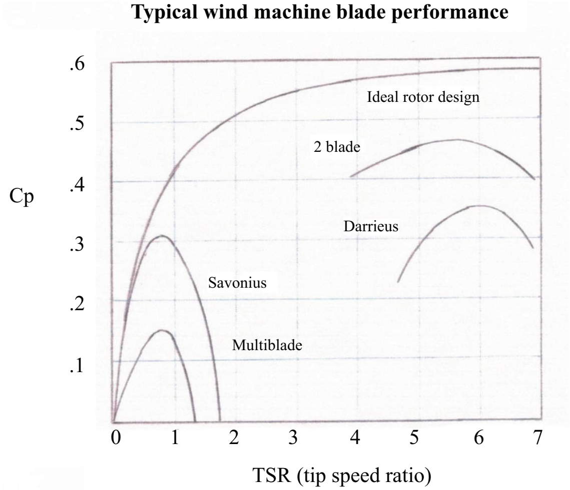

Figure 4.14. TSR and power coefficient.

lift. At low wind speeds, the drag component of wind provides the energy for this type of blade. At high wind speeds, efficiency drops-off sharply because drag-type machines do not operate at high shaft speeds. While the high wind efficiency and energy is low for multiblade machines, an advantage is overspeed protection at high winds. Low efficiency at high winds act as a brake to slow the rotor.

The Darrieus (vertical-axis) design operates well at high TSR numbers, but efficiency is very low in the low TSR range. At low wind speeds, a very small amount of lift is generated by the narrow blades, and a Darrieus rotor requires motor startup. As the rotor and blade speed approach wind speed, significant lift force is generated twice per revolution to maintain operation and generate significant power.

A three-bladed rotor design is the preferred option for some European manufacturers, as the added weight and cost of the third blade are not as significant to the additional 5 percent performance gain. A three-blade rotor has the advantage of smoother operation, improved balance, and lower harmonic and vibration issues. The TSR curve for the three-blade machine is slightly above and to the left of the two-blade curve.

4.4 WTG SPEED CONTROL SYSTEMS

The objectives of speed controls systems for a wind turbine are to a) capture maximum energy from the wind; b) protect the rotor, generator, and electronic equipment; and c) prevent runaway upon loss of electrical load to the generator. There are many methods and designs used to control the rotor speed. The method depends on the size of the machine, cost, reliability, and effectiveness of the design. Modern wind machines almost universally use pitch control as the primary method of rotor speed control. Blade pitch offers a wide range of torque control and power transmitted from the wind to the rotor. Maximum power and torque are achieved when the blade pitch is at the ideal lift angle for the instantaneous wind speed and rotor speed. This maximum operating condition is determined by TSR. Blade pitch may also cause stall condition, where power and torque are zero. Precise control of blade pitch can provide the optimum power for wind speeds from cut-in to cut-out.

There are five regions of operation for the wind turbine depending on the wind speed and turbine design. The first is *cut-in*, which is the wind speed where the wind has sufficient power to turn the blades and create measurable power output. Cut-in wind speed may be as low as 3 m/s for small machines to 8 m/s for large machines. The specified cut-in value, as determined by the manufacturer, is when the power in the wind is sufficient to overcome rotor inertia, mechanical losses, and power loss associated with the electronic equipment. If the machine turns on below this threshold, electrical losses in the generator and electronics make it uneconomical to operate.

Cut-out is the wind speed at which the wind turbine must shut down to prevent damage. The *constant Cp* region is wind speeds between cut-in and rated output as shown in Figure 4.15. Blade pitch controls operate to maintain maximum TSR and maximum power output at these wind speeds. As wind speeds are in this range most of the time, the wind turbine is designed to operate at a high coefficient of power to capture maximum energy.

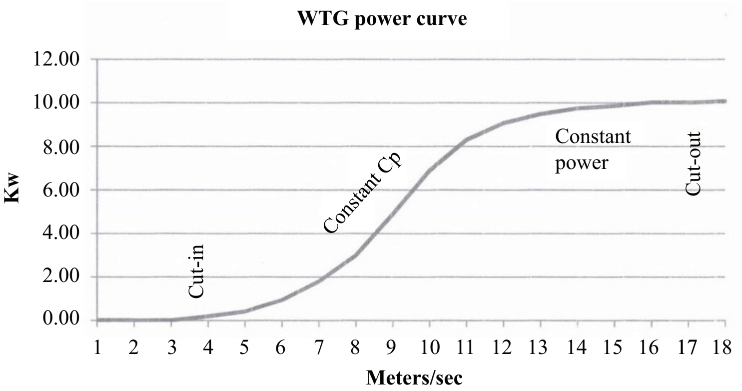

Figure 4.15. WTG power curve.

The *constant power* region is from rated output power at the end of the constant Cp region to cut-out. In this range of wind speeds, the wind is producing sufficient power to operate the wind turbine generator at maximum output. The blade pitch control will stall the blades when wind exceeds this limit. Therefore, the turbine is not operating at the maximum power coefficient or TSR in this region.

The last region is near cut-off, where the wind speed is too high for safe operation. The blade is *feathered* into stall condition in this region, and other types of braking may be applied. Mechanical brakes on the shaft and electrical eddy current braking to the generator may be used.

4.5 WIND TURBINE INSTALLATION

Ideal land locations for wind turbines are flat areas with strong consistent winds. Prevalent wind direction also benefits the layout of wind turbines in a wind farm. Turbulence caused by upwind turbines will decrease performance of downwind machines. Therefore, the recommended spacing between rows in a wind farm is 8- to 12-rotor diameters. Rows are orthogonal to the prevalent wind direction. Spacing between wind turbines in each row is usually 2- to 4-rotor diameters. This arrangement assumes the prevalent wind direction is significant and cross-winds (parallel to the rows) is infrequent. Figure 4.16 shows a typical wind farm installation. Tower height is a significant factor in performance, as the wind power density is proportional to hub height. Towers are also an expensive component of the turbine installation. Tower sizes of 80 to 100 meters are common for turbines that are rated from 1 to 3 MW. A rule of thumb is the tower height should be at least equal to the rotor diameter.

Figure 4.16. Wind farm orientation.

Other installation issues related to wind turbines are noise, electromagnetic interference (EMI), visual impact, and bird and wildlife impacts. Blade and generator noise has been mitigated by smooth airfoil design, nacelle construction, and mechanical improvements. Tubular tower design and slow rotor speed have shown to reduce bird fatalities. Studies on bird migration have also influenced the location of wind farms. Rotating blades have caused some EMI with local communication systems. This problem may be minimized by proper location of wind turbines and communication towers. The visual impact of wind turbines is of concern to many environmentalists. Many wind farms are located in remote locations, but the large towers and transmission lines associated with the farms are part of the landscape and reflective of the energy use of our society.

4.6 PROBLEMS

Problem 4.1

What is the generator rating and blade length for a 1,500/80 wind turbine? What is the SRC of this wind turbine?

Problem 4.2

A 10-kW wind turbine is designed to produce a rated output at 14 m/s wind speed, a generator-rated speed of 1,200 rpm, with a gearbox ratio of 6:1, and a blade radius of 5.135 meters. What is the TSR at rated speed and output?

Problem 4.3

A six-pole induction generator runs at a slip of –3.0 percent. What is the shaft speed in rpm? Assume the interconnected utility frequency is 60 Hz.

Problem 4.4

The generator of problem 4.3 is installed in a wind turbine with a rotor diameter of 10 meters. The average wind speed at the site is 6 m/s. If the desired TSR is 7.0, what is the optimum gearbox ratio to run the generator at a slip of –3.0 percent?

CHAPTER 5

ENERGY STORAGE AND STANDALONE WIND SYSTEMS

Storing energy has always been a challenge for renewable energy systems. As renewables are generally intermittent, a means of storing energy is critical to standalone systems. Conventional power systems may provide electrical power when renewable energy is not available. Electro-chemical storage (battery) is the prevalent means for electrical storage, but many other methods are becoming practical and economical. Flywheels, compressed air, superconducting coils, and hydrogen fuel cells are a few other methods being developed. Efficiency of conversion from thermal and mechanical energy into electrical energy has limited the development of most of these alternatives. This chapter will review battery and alternative storage methods used with wind energy generation.

Electricity is a highly ordered form of energy, which means it is easily converted into thermal or mechanical energy. Thermal energy is a disordered form of energy, and the conversion to electricity is inefficient. For example, conventional thermal conversion (e.g., coal power plant) is less than 50 percent efficient. The process of burning fossil fuels to create superheated steam and drive generators to create electricity is very inefficient, although it is the primary source of all electricity generated. Wind generators do not have the thermal conversion efficiency loss and are improving on the ability to capture the full potential of energy in wind. If an efficient method of energy storage is available, renewable sources could replace centralized power plants with local generation. Transmission lines could be minimized, pollution reduced, and the negative effects of fossil fuel combustion mitigated.

5.1 BATTERIES

Battery storage using electro-chemical means is a semiordered form of energy. Electricity generated from battery storage is easily converted into heat or light, but the conversion process within the battery is relatively inefficient. Battery types are categorized as primary and secondary. *Primary batteries* are nonreversible—they cannot be recharged and are discarded after the energy is consumed. Common alkaline cells are examples of this type. *Secondary batteries* are rechargeable. Lead–acid batteries are the most common type and used in automobile and backup systems. Efficiency of a secondary battery is typically 70 to 80 percent for the round-trip (charge and discharge) cycle. Energy is lost in the form of heat for both the charge and discharge cycle. Other common types of secondary batteries include nickel cadmium (NiCad), nickel metal hydride (NiMh), lithium ion, zinc air, and lithium polymer.

5.1.1 LEAD–ACID BATTERIES

A lead–acid battery consists of a lead (Pb) anode, lead oxide (PbO_2) cathode, and sulfuric acid (H_2SO_4) as the electrolyte. The acid requires a plastic case and other material, such as antimony or calcium, is added to the plates for added strength and performance. Deep cycle batteries used in renewable storage systems are sometimes called *traction batteries*, and use thicker plates and greater plate surface area than the typical auto battery. The typical auto battery is sometimes called an *ignition* or *starter* battery, because it is designed for short high-current duty. The classic lead–acid battery is commonly referred to as *flooded* if the electrolyte is in liquid form.

Recombinant technology allows lead–acid batteries to be sealed and eliminates the need to add water or vent hydrogen. These batteries are referred to as *valve regulated lead–acid (VRLA)*. The lead–acid battery is also available as a sealed *gel-cell* version, which has a nonspillable electrolyte, and can be mounted in any position. The *gel-cell* battery cannot be charged or discharged at high rates. The gel may *bubble* at high temperatures, causing permanent voids and reduced capacity. However, the advantages of the gel-cell battery have caused it to become a common replacement for flooded batteries.

An improvement to the gel-cell lead–acid battery is the *absorbed glass matt* (AGM) design. A porous matt composed of boron silicate contains the sulfuric acid electrolyte between the plates. The matt is 95 percent saturated with acid, and sometimes called *starved electrolyte*. The matt prevents spillage, eliminates freezing damage, eliminates water loss, and has a low self-discharge rate. The matt provides pockets that assist in the recombination of gasses generated during charging: Hydrogen and oxygen are recombined back into water. AGM batteries have a limited charge and discharge rate due to the restricted flow of ions in the electrolyte. The cost of AGM batteries is two or three times flooded lead–acid batteries. However, improvements have been made to increase efficiency, lower cost, and are now competitive with gel-cell batteries.

State of charge (SOC) is a measure of the remaining capacity of the battery. The most accurate method is measurement of the specific gravity (SG). A fully charged lead–acid battery has an SG of about 1.28, depending on the temperature. SG is the density ratio of the sulfuric acid electrolyte compared with water. Charge and discharge measurements with appropriate C/D efficiency factors based on battery temperature also provide a good estimate of SOC. SOC may also be estimated by measuring cell voltage: for example, 11.4 volts for a 12-volt battery (six cells at 1.9 volts per cell) indicates about 20 percent SOC.

The lifetime of a lead–acid battery is dependent on the number and depth of discharges. *Depth of discharge* (DOD) is the percentage of capacity that has been removed compared with the fully charged state. DOD is the complement of SOC. If the battery is discharged by 80 percent of full capacity, the DOD is 80 percent and the SOC is 20 percent. DOD is usually limited to 75 to 80 percent to protect from freezing and extend life. The lead plates eventually combine with the acid to create lead sulfate, leaving the capacity of the remaining plates too low to serve the load.

5.1.2 NICAD BATTERIES

NiCad, or nickel cadmium, uses a cadmium anode and nickel hydroxide cathode in a stainless steel case. The electrolyte is potassium hydroxide with a nylon separator. NiCad cells are almost half the weight of lead–acid cells. The sealed cell means no spilling or mounting issues. Two problems with the NiCad battery have caused it to be less popular. Cadmium is an environmentally dangerous metal and disposal is restricted. Cells also exhibit a memory problem, causing reduced capacity before reaching the expected life. Full discharge to zero capacity and recharge must be performed regularly to prevent memory failures.

5.1.3 LITHIUM-ION BATTERIES

Lithium-ion (LI) cells are the preferred battery for computers and electronics, because of their high energy density capacity. The atomic weight of lithium is 6.9, compared with 207 for lead. The LI cell voltage is 3.5 compared with 2.0 for lead–acid. Fewer cells for the same application voltage lower manufacturing costs. However, the plates must be thicker to maintain adequate life, which increases cost significantly for larger-capacity batteries. The LI battery also requires an elaborate charging circuitry to prevent damage by overcharging. LI batteries have been known to explode if not charged or discharged properly, or not adequately cooled.

LI batteries are the battery of choice for plug-in vehicles. Battery stacks typically consist of thousands of AA size cells. Each cell has a capacity of 2,700 to 2,900 milli-amp-hours (mAh). The voltage range is 3.6 volts to 4.2 volts (charging). The cell weight is 46.5 grams. The specific volume is 577 wh/liter, and the specific weight is 214 wh/gram. The Tesla model S car was built with 18,650 LI AA cells, which provide 50 to 70 kWh of energy storage.

There are six major types of LI batteries now in production, which are compared in Table 5.1. Lithium cobalt oxide (LCO) is a major type used in cell phones, computers, and cameras. It has a high specific energy, but low power output, as compared with other types of LI batteries. LCO batteries have also been prone to thermal runaway, which may cause fire if charge and discharge rates are not properly controlled.

Lithium titanate (LTO) has a good temperature range and is safer than the LCO battery. It has a longer life and can be charged at a fast rate.

Table 5.1. Lithium battery comparison (5 = favorable)

	Specific energy	Specific power	Life span	Safety	Performance	Cost
LCO	5	3	3	3	4	4
LTO	3	4	5	5	5	2
LFP	3	4	5	5	4	4
NMC	3	5	5	5	4	4
NCA	5	4	4	3	4	3
LMO	4	4	3	4	3	4

However, the LTO battery is more expensive than other types of LI batteries. It is used for remote street lighting applications, UPS systems, and in some electric vehicles, including the Honda Fit and Mitsubishi EV.

Lithium iron phosphate (LFP), LiFePO4, has a lower specific energy because of the iron component, but has a much better cycle life and high current characteristic. The LFP battery is a popular choice for deep cycle applications. It has good thermal stability, long life, and is safer than other LI batteries. The LFP battery boasts a life up to 10,000 cycles, or 2,000 cycles at high DOD (up to 90 percent). A disadvantage is high self-discharge, and this type must be charged often to maintain a high SOC.

Lithium nickel manganese cobalt oxide (NMC) is popular for medical, EV, and electric bike applications. It has high power and high capacity at the expense of specific energy.

Lithium nickel cobalt aluminum oxide (NCA) is a high-energy and high-power option. Cost is relatively high and safety is low because of thermal runaway possibilities at a high charge rate. This option is under development by Tesla for solar storage applications.

Lithium manganese oxide (LMO) is used for several electric car applications, including the Leaf, Volt, and BMW i3. The LMO option is a moderate design that includes balanced characteristics of safety, specific energy, specific power and cost.

5.1.4 NICKEL METAL HYDRIDE BATTERIES

Nickel metal hydride (NiMh) cells are similar in construction to NiCad cells, except for the metal hydride anode. NiMh batteries are also used for many low-power applications, although they exhibit high self-discharge, and must be charged regularly to maintain capacity. NiMh also has poor peak power capacity and is susceptible to overcharging damage.

5.1.5 OTHER TYPES OF BATTERIES

Other types of batteries being developed are lithium polymer and zinc air. The polymer battery shows good specific energy characteristics, but the solid electrolyte limits the capacity. The zinc air battery also displays good specific energy characteristics, but requires adequate air ventilation for the oxygen to carbon and zinc electrode exchange.

Specific energy (watts-hours/mass) is a measure of performance when weight is a primary concern in the application. *Specific density* (watt-hours/volume) is of primary importance when space is critical. Figure 5.1 shows

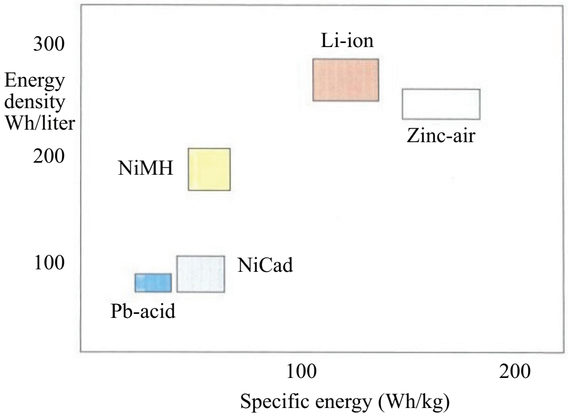

Figure 5.1. Specific energy comparisons.

specific energy and specific density for various types of rechargeable batteries. The lead–acid battery has the lowest energy density and lowest specific energy of all current electro-chemical types. It is also the least costly. Lithium batteries have the highest densities, but also are more expensive.

5.2 CHARGE AND DISCHARGE EFFICIENCY OF BATTERIES

The charge efficiency for lead–acid batteries is high when the battery is at a low SOC. Charge efficiency is low at high SOC. If charging current remains high when the battery approaches full charge, gassing and heat loss occur. Excess hydrogen gas generation is a safety concern, and excessive heat may damage the battery plates. An effective charger reduces charging current to a trickle when approaching full charge.

Two useful relations to remember are about capacity and temperature, which we will discuss in more detail in the following paragraphs. SOC and DOD are complementary: SOC (%) + DOD (%) = 100%. The second relation for lead–acid batteries is a temperature rule of thumb: 10°C drop in cell temperature decreases capacity by 10 percent.

Internal resistance increases significantly at low temperatures, which means lower discharge amperage and lower capacity. Figure 5.2 shows the effect of temperature on the capacity of a lead–acid battery. Below zero temperatures significantly decrease the capacity, which explains why a cold auto battery delivers low current and poor starting ability.

Any battery typically requires more ampere-hours (Ah) of charge to restore to full SOC after a specified Ah discharge. The charge-to-discharge

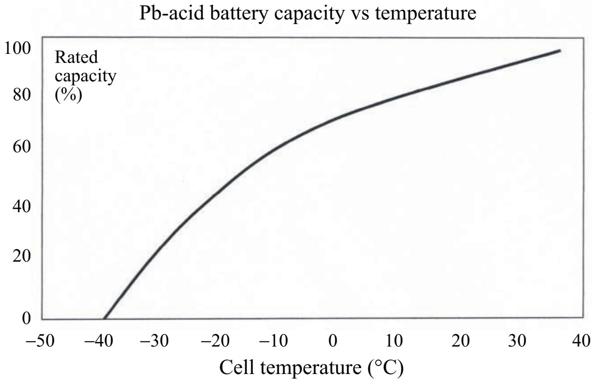

Figure 5.2. Battery capacity and temperature.

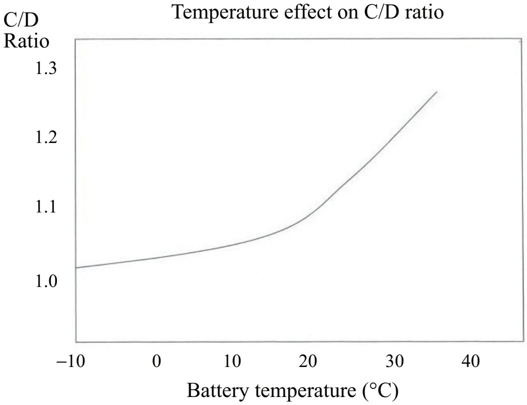

Figure 5.3. Temperature and C/D ratio.

ratio (C/D) is the amp-hour input over Ah output for zero net change in SOC. If C/D is 1.1, it means the battery needs 10 percent more Ah charge than what was discharged to restore to the fully charged state. Battery specifications should provide the C/D ratio for a range of temperatures, as shown in Figure 5.3.

DOD and the number of cycles determine the life of a battery. The lifecycle of a NiCad battery is shown in Figure 5.4 for a range of temperatures. Higher temperature decreases the life of a battery. If the battery is discharged to 50 percent of its capacity, it will fail quicker than if the DOD is limited to 30 percent of the capacity.

A common specification for the capacity of batteries is the amp-hour rating (C) at a given charge/discharge rate. C/n represents the charge or discharge rate in amperes (A) and charge/discharge time (n) in hours.

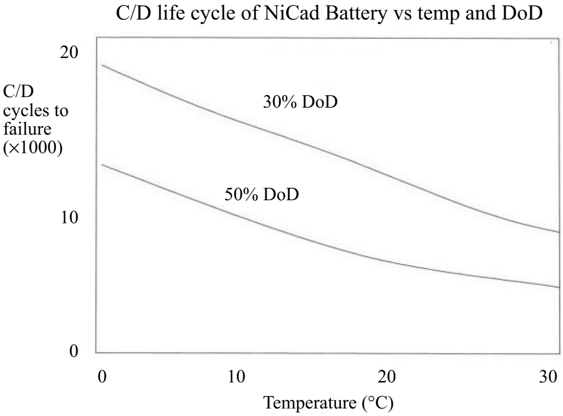

Figure 5.4. Lifecycle and DOD.

C/20 is a common rating for deep cycle batteries. For example, a 100-Ah C/20 battery will provide 100 Ah of energy at a 5-amp rate for 20 hours. If the 100-Ah battery is discharged at a higher rate (e.g., 10 amps), it will probably provide less than 100 Ah of energy in 20 hours. Likewise, the 100-Ah battery will deliver more than 100 Ah if discharged at a lower current (e.g., 2 amps). A C/10-rated 100-Ah battery will deliver 100 Ah if discharged at 10 amps, but will probably fall short of the rated capacity when discharged at 20 amps. It is important to check the capacity specifications and select a battery that meets the requirements of the load. Also, the charge controller must match the C/n specification for optimum performance and to protect the battery from over- or under-charging.

Battery failure occurs if a series cell opens, shorts, or experiences capacity loss. If a parallel cell fails and creates an open circuit, it is difficult to notice. Also, a weak series-connected cell is difficult to detect. The best method to detect cell failure is to measure the SG. If cells can be isolated from the bank, a charge/discharge test may be used. Battery voltage measurement is helpful to measure cell condition, but not as reliable as SG measurement or the discharge test. Frequent battery bank replacement is a good remedy to prevent loss of capacity.

5.3 OTHER STORAGE MEDIUMS

There are many methods to store potential energy for future electrical generation. A ubiquitous example is water storage. There are countless dams and reservoirs constructed to store elevated water that is converted into electrical power through turbines and generators. This section will introduce a few new promising concepts for practical mass storage of energy, including flywheels, superconducting magnets, and compressed air.

5.3.1 FLYWHEELS

The flywheel has been used in a few applications to store energy, but limited by bearing and windage losses. It has been proven an effective method of storing kinetic energy in a rotating inertia with innovative designs that reduce losses. The rotor is constructed of fiber epoxy composite that can withstand high centrifugal forces. Bearings are magnetic, which have very small frictional losses. High-vacuum installations reduce windage losses. The results of these designs have demonstrated flywheel round-trip efficiency of 90 percent. An advantage of the flywheel is the high discharge lifecycle (i.e., greater than 10,000), and a high DOD without the lifecycle losses associated with other storage systems. It is easy to couple with a motor or generator to convert mechanical energy into electrical energy. The only problem left with the development of effective flywheel applications is scaling to meet the storage capacity requirements of electric utility applications.

5.3.2 SUPERCONDUCTING MAGNETS

Energy storage in magnetic fields is a developing technology that has been proven at a small scale (8 kW). Resistance decreases as temperature decreases, and approaches zero (superconducting state) as absolute temperatures are approached. This critical temperature is around 9°K for niobium-titanium, which has been extensively used as the conducting element in the superconducting coil. Recently, more types of material have been found that exhibit superconducting properties at much higher temperatures, around 100°K. This development makes this method of storage much more feasible, as liquid nitrogen cooling may be used instead of helium, and significantly less refrigeration power is required. The charge/discharge efficiency of the superconducting magnet is around 95 percent. An advantage over the flywheel is no moving parts, and minimal maintenance for a 30-year life.

The basic elements of the superconducting storage system are a cryostat with the superconducting coil, voltage regulator and shorting switch, inverter, transformer, capacitor, and refrigeration system. The working principle is that the energy is stored in the magnetic field of a coil. Energy stored in the coil is related to the current and inductance:

$$E = \tfrac{1}{2} I^2 L \text{ (joules)} \tag{5.1}$$

where
L is the inductance of the coil
I is the coil current

The relation between the voltage and current is given by:

$$V = R\,I + L\,(di/dt) \tag{5.2}$$

When the resistance (R) of the coil approaches zero, the circuit does not require a voltage to maintain current in the coil and the magnetic field. The coil terminals may be shorted and the energy in the coil *freezes*. The current continues to flow in the coil indefinitely. When power is required by the load, the switch opens momentarily to charge a capacitor. The capacitor is connected to the load through an inverter. A small amount of periodic power is required by the charging circuit to overcome losses in the nonsuperconducting elements of the circuit. Charge and discharge cycles may be very short, making superconducting magnets an attractive alternative for supplying large amounts of power in a short time.

5.3.3 COMPRESSED AIR

Energy storage using compressed air is effective if a large volume is available. Underground cavern storage is preferred to aboveground tanks for safety and economic reasons. Air may be under constant pressure—as below an aquifer or a variable volume tank—or constant volume—as in a storage tank, cavern, depleted oil or gas fields, or abandoned mines. The advantage of constant pressure is that the capacity remains constant as the volume is depleted. Generators may continue to run at rated capacity to maximum DOD. A disadvantage of compressed air systems is the increase in the temperature of the air when compressed. As the gas temperature cools down after compression, some of the energy is lost, with a corresponding loss in stored energy. Many compressed air plants have been built around the world with capacities up to 300 MW. The round-trip efficiency is estimated at 50 percent. Approximately 100 MWh of energy can be stored with 1 million cubic feet of storage at 600 psi. Studies show the lead–acid battery and pumped water storage are less-expensive alternatives.

5.3.4 SUPER CAPACITORS

Super capacitors or ultra-capacitors are showing increased potential as storage devices with advances in nano-material technology. A key factor in capacitor efficiency is the separation of surface charges. With separation now in the range of 0.3 to 0.8 nano-meters, super capacitors are able to store more energy in a given volume. Graphene is being used in new capacitor construction to obtain higher energy density, although the cost of material is still high.

There are many advantages that super capacitors have over conventional batteries. The charge and discharge rate is much faster. They can operate for many more cycles without degradation, much longer life than batteries. Internal resistance is low, which increases efficiency, and there are no toxic materials. Super capacitors are ideally suited for high bursts of power. Specific energy is much higher than batteries, in the range of 0.5 to 15 wh/kg. By comparison, lithium ion batteries have a specific energy of 100 to 265 wh/kg.

Super capacitors also have disadvantages. The volumetric energy density is very low: 5 to 8 wh/liter. The space requirements are about 10 times greater than conventional batteries. For these reasons, super capacitors are more suited as a complimentary technology that can provide high bursts of power or regenerative braking. Conventional batteries are better suited to provide long-term low power.

5.4 STANDALONE SYSTEM DESIGN

Standalone renewable energy systems can be simple lighting systems, hybrid residential energy systems, or remote village designs. Solar cars are also examples of standalone systems. The common feature of a standalone system is that they are not interconnected with a utility system. It may be a direct current (DC) or alternating current (AC) system. Another common feature is some type of storage system, usually electro-chemical batteries. The economics of standalone systems are based on the unavailability of a utility connection. A remote location with the expense of extending utility service may justify a renewable source and storage system. The added cost of batteries and related maintenance usually prohibits installing a standalone system if the utility service is readily available. This section will explain the design of wind energy generation and lead–acid battery storage, which may be scaled and applied to other types of storage. Standalone designs are significantly more complex than grid-connected systems.

Storage of electric energy is the key element of a standalone system. The renewable source by nature is intermittent, and energy must be stored with deep cycle batteries. The capacity of the battery bank maintains the load for a reasonable duration when the renewable source is not available. Otherwise, a fossil fuel backup generation system is added to extend the storage capacity. A small diesel or gas-fueled generator may be used to charge the batteries if the designed duration is exceeded and the load is critical. Backup generation adds significantly to the cost of the system, including fuel costs, maintenance, and inefficient operation if not fully loaded. The alternative to backup generation is shutdown of the electrical system. Several hours of blackout may also be a reasonable alternative.

5.4.1 LOAD ANALYSIS

The first step in the design of a standalone system is load analysis. Determine the power required by each load and the estimated duration or run time for each appliance connected to the electrical system. We will assume the system will include a DC to AC inverter for typical household loads. A table should be constructed that shows power and energy requirements for each load at different times of the year.

Table 5.2 shows how to determine the power and energy requirements for a standalone home. Two critical factors are derived from Table 5.2: peak demand and average daily load. The total peak power (demand) in watts is 2,060, and the highest daily load is 6,240 watt-hours (Whrs). We can assume all loads will not be on simultaneously, and should estimate a load factor to account for coincident loading.

Load factor is the ratio of highest expected load to the total connected load. A load factor of 40 percent gives us an average peak load of 824 watts. Peak load determines the capacity of the inverter. An inverter rated for 1,000 continuous watts and 2,000 maximum watts would be a good choice for the load in Table 5.2. The average daily load determines the capacity of the battery.

Autonomy is the number of days without PV generation that the system will support the expected load. Three days of storage is considered normal backup for a residential system with a standby generator to charge the batteries if the renewable source is not available. Winter months are usually the highest usage if air conditioning is not included in the load. The table gives us 6,240 watt-hours (Wh) per day load, which equals 18.7 kWh for the three-day backup.

The AC voltage for this example is 120 V single-phase. The inverter DC input voltage is determined by the wire length, battery capacity, and

Table 5.2. Load analysis

Load description	Power (watts)	Dec–Feb		Mar–May and Sep–Nov		Jun–Jul	
		Hrs per day	Whrs per day	Hrs per day	Whrs per day	Hrs per day	Whrs per day
Kitchen lights	200	4	800	3	600	2	400
Living room lights	150	2	300	1	150	1	150
Bedroom lights	80	1	80	1	80	1	80
Refrigerator	150	7	1,050	7	1,050	8	1,200
Microwave oven	600	0.5	300	0.5	300	0.5	300
TV, stereo	180	2	360	2	360	1	180
Furnace fan	400	8	3,200	5	2,000	0	0
Washer	300	0.5	150	0.5	150	0.5	150
TOTAL	2,060		6,240		4,690		2,460

the renewable source voltage. The most common systems are 12, 24, or 48 volts. A 12-volt system is usually the best fit for a small PV system, because 36 cell modules are readily available. 12-volt batteries are also common. A larger capacity system might use 48 volts DC to reduce DC current and wire size. If we chose 24 volts DC for the load in Table 5.2, the required amp-hours is 780 Ah (18,720 wh/24 volts). The next step is choosing a battery that provides the voltage and Ah rating required by this load.

Batteries may be purchased as individual two-volt cells, three-cell six-volt units, or six-cell 12-volt units. Batteries must be wired in series to obtain the system DC voltage and parallel to obtain the Ah requirement. Two 12-volt batteries in series equal the 24-volt system voltage. If we choose 200-Ah deep cycle lead–acid batteries, four parallel batteries will provide 800 Ah of capacity. The bank will consist of four parallel strings of two 12-volt batteries without correction for temperature or DOD limits. If the battery bank is stored in a heated area, no temperature correction is needed. For outdoor storage or minimal heating, a temperature correction factor must be included, which will increase the bank size, or reduce the three-day backup period in the winter. A DOD limit should also be applied to increase the life of the battery. If we limit DOD to 20 percent times capacity, the capacity must be increased. The derated capacity is 975 Ah (780 Ah/0.8), and two more batteries must be added, for a total of 1,000 Ah capacity. The three-day backup will draw the 10-battery bank down to a SOC of 200 Ah, which will decrease battery life if allowed to occur often.

The renewable system is sized to recharge the battery bank each day with an estimated output for any time of the year. We must check the charge capacity of the battery to insure it will absorb the renewable generator output. If the bank is not heated, the charge capacity may be limited to 50 to 60 percent for temperatures below 0°F.

5.4.2 STANDALONE SYSTEMS WITH WIND ENERGY GENERATION

A wind turbine generator may be used as the renewable source for a standalone system similar to a PV application. An inverter will be used to change battery DC voltage to 120-volt AC load voltage. The battery bank is designed, as in the preceding example, for the load capacity and voltage determined by the wind generator output. As wind generators are typically installed a long distance from the load, and up a 100- to 200-foot tower, the wire size and voltage drop are critical factors. Long wire causes high voltage drop. For this reason, the battery bank voltage should be 48 volts or higher. Instead of a charge controller, the wind generator may be an alternator with field winding control. A regulator controls the field current and increases or decreases the charging current depending on the SOC and voltage of the battery. Similar to an auto regulator, the wind turbine regulator reduces current to the battery as the SOC increases by decreasing field current to the alternator. Voltage is limited to about 2.3 volts per cell for lead–acid flooded batteries for a normal charge rate.

Sizing the wind turbine depends on the wind resource, load demand, and average daily load. Given the connected load of 2,060 watts, a load factor of 40 percent, and an average peak load of 824 watts, the maximum generator capacity should be about 2,000 watts. However, we must determine the energy produced by the wind turbine for the average wind speed at the site to properly size the wind turbine. Several methods may be used to select a wind turbine that will generate the energy that meets the load. If the wind turbine generator (WTG) manufacturer supplies a power curve, we can estimate the average power produced for the site wind speed. Another method is to use Equation 3.3 (see Chapter 3) to determine the rotor diameter and select a WTG with appropriate capacity.

To apply the power Equation 3.3, we must calculate air density for the elevation. Equation 3.6 is used to calculate air density (ρ) for an elevation of 2,000 meters.

$$\begin{aligned}\rho &= 1.225\ \text{kg/m}^3 - (1.194\ \text{x}\ 10^{-4}) \times 2{,}000\text{m} \\ &= 0.986\ \text{kg/m}^3 \end{aligned} \tag{5.4}$$

The power coefficient may be provided by the WTG manufacturer or estimated at 40 percent for a two- or three-blade turbine. The best method to determine the average wind speed is to install a monitoring system at hub height and collect two or three years of data. If actual measurements are not available, data from a local airport may be used. However, we must extrapolate the average wind speed from the airport anemometer height to the WTG hub height using Equation 3.17. Let us assume the average wind speed for the proposed site is 6 m/s. The average power required to recharge the battery each day is 260 watts (6,240 wh/24 hours) from the load in Table 5.1. The generator, field regulator (i.e., charge controller), battery efficiency, and wire loss may be approximated in a derating factor. If the derating factor is estimated to be 20 percent, the average load is 260 / 0.8 = 325 watts. Substituting this information in Equation 3.3 gives us the following relation:

$$P = 325 \text{ watts} = \tfrac{1}{2}\,(0.986 \text{ kg/m}^3)\, A\, (6 \text{ m/s})^3 \times 0.4 \tag{5.5}$$

$$A = 2 \times 325 / [(0.986)\,(6)^3\,(0.4)] \tag{5.6}$$

$$A = 7.63 \text{ m}^2 \tag{5.7}$$

The diameter is 3.12 meters (10.3 feet) from the calculated area ($A = \pi D^2/4$). A wind turbine with a rotor diameter of about three meters will provide the energy needed to recharge the battery each day. Of course the wind turbine output is dependent on the intermittent wind. High wind and excess energy will be lost, and low wind conditions will rely on the battery capacity to provide load for three days. Oversizing the WTG by 20 percent is a good practice.

A search for wind turbines for home use will provide several wind turbines of rotor diameter of about 10 feet. We can check the predicted annual energy output for these machines to match the load requirements of 6.24 kWh per day. A typical 200-watt WTG has a nine-foot diameter rotor and predicts 3,005 kWh per year energy output for a 14-mph (6.26 m/s) average wind speed.[1] This equals 8.2 kWh per day, and exceeds our load estimate by about 30 percent. A Kestrel e300i turbine with a 10-foot diameter rotor predicts an annual energy output of 3,356 kWh per year, and also exceeds our battery recharging needs. If our average wind speed is 12 mph, these wind turbines predict annual outputs of 2,254 and 2,551 kWh per year, which are close to our load requirement. Both of these machines are designed to charge a battery bank of 12, 24, or 48 volts.

5.4.3 HYBRID STANDALONE SYSTEMS

Hybrid systems integrate several types of renewable energy sources. The most common system combines a gas or diesel generator with photovoltaics, a wind turbine, and a battery. The advantage of a hybrid system is an increase in the certainty of meeting the demand load at all times. Wind and solar irradiation is intermittent, but the likelihood of having one or the other source for the three-day backup period is much higher than with one source. The conventional gas or diesel backup system can be minimized or eliminated.

Hybrid systems are more complex to design than simple standalone systems with single sources because the voltage and power must match the battery capacity and load. If a conventional generator provides AC to the load, the renewable systems must be synchronized, requiring special

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[1] Buyer's Guide. June and July 2010. *Home power* 137, p. 48.

monitoring and control equipment. If all sources are available, the battery charge controller must be sized to limit power to the battery charging capacity. Also, excess energy is wasted and reduces the overall efficiency of the system. Power control systems are available that integrate the battery, renewable energy systems, and conventional systems using transfer switches and protection devices.

5.4.4 FUEL CELLS AND HYDROGEN

The fuel cell has potential as a standalone and hybrid component. The fuel cell has many advantages over conventional power generation that uses fossil fuels. The most favorable attribute is zero emissions. A hydrogen-powered fuel cell produces water and no airborne pollutants. Fuel cell plants are replacing the diesel generator and battery UPS (uninterruptible power supply) systems. They also are being used to meet peak demands of utility systems. Fuel cells have several disadvantages that limit their application. They are more expensive than conventional power systems. Hydrogen fuel is also expensive and difficult to store and transport. Hydrogen may be generated with renewable systems using electrolysis, a very energy-intensive process.

Several countries and energy companies are working to replace fossil fuels with hydrogen as a primary fuel. Italy constructed the Enel power plant, which is the first industrial-scale facility with a capacity of 20 MW. Enel receives hydrogen as a byproduct from a petrochemical plant and plans to use RDF (refuse-derived fuel) from solid waste. On a large scale, the city of Reykjavik, Iceland, is planning on becoming the first city powered totally with hydrogen by 2050. The country is converting transportation means to hydrogen and building hydrogen fuel centers.

The fuel cell is an electromechanical device that generates electricity by a chemical reaction that does not change the electrodes or electrolyte materials. The electrodes do not wear out, as in batteries, and there are no moving parts, which give the fuel cell a long, maintenance-free life. The energy-producing process is the reverse of electrolysis. Hydrogen and water combine in an isothermal operation to produce electricity and water. If natural gas, ethanol, or methanol are used to produce hydrogen, carbon dioxide and some traces of carbon monoxide, hydrocarbons, and nitrous oxides are byproducts, although less than 1 percent of that produced by the internal combustion engine.[2]

There are several types of fuel cells with various energy densities and costs. Power density ranges from 0.1 to 0.6 watts/cm^3. The phosphoric

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[2] Patel, M.R. 2006. *Wind and Solar Power Systems*, 242. 2nd ed. CRC Press.

acid fuel cell (PAFC) is the most common in relatively small applications. The alkaline fuel cell (AFC) is used by aerospace systems and is the most expensive type. The AFC uses potassium hydroxide (KOH) as the electrolyte with porous anodes and cathodes. The proton-exchange membrane is also known as the solid-polymer fuel cell (SPFC) and is the most promising type for small-scale applications, such as home power systems. The molten carbonate fuel cell (MCFC) works at higher temperatures (600°C to 700°C) and may be the choice for utility-scale applications in the future. The higher-temperature cells are the most efficient. Solid-oxide (SOFC) fuel cells are another high-temperature design that may be used in large utility or wind farm applications. Costs range from 200 to 1,500 U.S. dollars per kW, which is 2 to 15 times the cost of diesel engines.

Hydrogen storage is a problem for fuel cells, vehicles, and all hydrogen fuel systems. Compressed H_2 gas is notorious for developing leaks, and liquid hydrogen requires high compression and expensive storage tanks. Liquid H_2 is best for long-term and large quantity storage. On the bright side, hydrogen has a much higher energy density than storage in an electro-chemical battery. Gaseous hydrogen can store about 47,000 BTU/ft^3, compared to 2,000 BTU/ft^3 for a conventional battery. Liquid hydrogen will store up to 240,000 BTU/ft^3. Gasoline is still the most convenient energy storage medium with an energy density of 1,047,000 BTU/ft^3.

Hydrogen is the simplest and most abundant element. It is composed of a single proton and electron. Electrolysis is a simple method to obtain hydrogen from water. Hydrogen and oxygen gas are produced by passing electrical current through a salt water solution. A fuel cell is the reverse of this process, as electrical current is generated when a fuel and water combine in a cell with an anode, cathode, and electrolyte. Figure 5.5 shows a basic fuel cell.

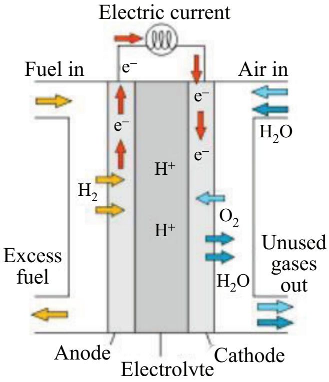

Figure 5.5. Basic fuel cell.

5.5 PROBLEMS

Problem 5.1

Design a battery array that will maintain 4 days of autonomy in a cabin with the following loads and appliances: refrigerator, gas furnace (fan), 200 watts of lighting and miscellaneous loads of 300 watts. The load factor is 30 percent. Use 12 volt batteries and a 48 volt DC to 120 volt AC inverter. Battery SOC should not drop below 40 percent.

Problem 5.2

Design a small wind turbine charging system that will accommodate the battery and loads in problem 5.1. Assume the location is in Wyoming where the average yearly wind speed is 16 mph, and elevation is 2,000 meters. What will be the necessary swept area and blade length of the wind turbine?

CHAPTER 6

ECONOMICS

Any capital investment should be analyzed for economic feasibility. Environmental security is not the only reason for investing in a renewable energy system. There are many tangible and intangible benefits associated with renewables; therefore, we must look at the big picture and include externalities, in addition to the revenue from energy production. Chapter 1 addressed some of the externalities associated with conventional electric energy generation, but did not attempt to place a cost for pollution, global warming, and other societal effects of fossil fuel combustion. As we study the basic economics of renewable energy investment and returns, a dollar amount will not be assigned to externality costs because it is controversial and arbitrary. Our economic analysis will include a basic payback analysis, return on investment, and methodology to determine the levelized cost of energy for a renewable system. We will use a few basic economic tools, such as present value, to determine the return on investment.

6.1 SIMPLE PAYBACK

Payback or breakeven (BE) analysis is the most common method used to compare capital investment. Initial investment (I) is recouped by reoccurring revenue (R) over the lifetime of the equipment. Inflation, depreciation, and the time value of money are ignored. The initial investment is the cost of equipment and installation, less incentives, rebates, and tax credits. Although the timing of the tax credits and incentives is not the same as the initial payment, a lumped sum at time zero simplifies the payback calculation. Revenue is also lumped into annual payments instead of the actual monthly utility savings and revenue. The revenue for small systems is usually an estimate of the annual energy production at a fixed utility rate.

Table 6.1. WTG system costs

Components	Cost (in U.S. dollars)
Generator, blades, and inverter	15,666
Tower and foundation	8,309
Installation	1,727
Miscellaneous	139
Total installed cost	25,841
ITC (25% federal tax credit)	(6,460)
Net cost	19,381

An example of a simple payback calculation is shown in Table 6.1 for the purchase of a 10-kW interconnected wind generator system. The initial cost of equipment and installation is 25,841 U.S. dollars. The net cost (I) after the federal investment tax credit is 19,381 U.S. dollars. The annual revenue (R) is estimated as 1,760 U.S. dollars, based on 22,000 kWh annual generation at 8 cents/kWh.

Assuming all generation is used at the site with net metering, breakeven in years is calculated as the ratio of the investment cost to annual return:

$$\mathrm{BE} = \mathrm{I} / \mathrm{R} = \$19{,}381 / \$1{,}760 = 11 \text{ years} \tag{6.1}$$

The simple payback analysis ignores many significant factors, such as depreciation, inflation, rate increases, maintenance, and possible equipment failures. However, it provides a very useful comparison to similar installations at various locations. Weather and average wind speed variations affect the annual revenue. Each utility jurisdiction has different avoided-costs rates for renewable energy. Tax exemptions vary from state to state. Incentives vary widely among utilities and change with policy.

6.2 ADVANCED BREAKEVEN ANALYSIS

With the help of a spreadsheet, the breakeven analysis can be improved by adding rate increases, inflation, depreciation, and maintenance factors. Table 6.2 shows the breakeven calculation with a 2% increase in utility rates each year after installation. Breakeven with rate increases is about nine years for the WTG system described earlier. The analysis is based on production of 22,000 kWh/year and expected life of 20 years.

Table 6.2. Payback with annual 2% electric rate increases

Year	Energy Rate $/kWh	Revenue	Accumulated revenue
1	$0.080	$1,760	$1,760
2	$0.082	$1,795	$3,555
3	$0.083	$1,831	$5,386
4	$0.085	$1,868	$7,254
5	$0.087	$1,905	$9,159
6	$0.088	$1,943	$11,102
7	$0.090	$1,982	$13,084
8	$0.092	$2,022	$15,106
9	$0.094	$2,062	$17,168
10	$0.096	$2,103	$19,272
11	$0.098	$2,145	$21,417
12	$0.099	$2,188	$23,605
13	$0.101	$2,232	$25,837
14	$0.103	$2,277	$28,114
15	$0.106	$2,322	$30,436
16	$0.108	$2,369	$32,805
17	$0.110	$2,416	$35,221
18	$0.112	$2,464	$37,686
19	$0.114	$2,514	$40,199
20	$0.117	$2,564	$42,763

The spreadsheet analysis allows other factors to be included in the evaluation. Table 6.3 adds a discount factor of 6.0% per year. The discount rate is arbitrary, as it is related to inflation and the economy. The value chosen was used by the Electric Power Research Institute (EPRI)[1] for electrical generation facilities when this WTG was installed.

The discount factor changes the payback significantly. With the 6% discount, investment recovery occurs in year 12. We should keep in mind the energy rate increase is a conservative 2%, and could increase to lower the recovery time.

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[1] Discount Rate for Electrical Generation Facilities, EPRI, Economic Methodology, Economics of Solar Energy Technologies, 1992, p. 39.

Table 6.3. Payback with discounted revenue

Year	Energy rate	Revenue	Accumulated	Revenue	Accumulated
	$/kWh		revenue	6% discount	revenue
1	$0.080	$1,760	$1,760	$1,760	$1,760
2	$0.082	$1,795	$3,555	$1,694	$3,454
3	$0.083	$1,831	$5,386	$1,630	$5,083
4	$0.085	$1,868	$7,254	$1,568	$6,651
5	$0.087	$1,905	$9,159	$1,509	$8,160
6	$0.088	$1,943	$11,102	$1,452	$9,613
7	$0.090	$1,982	$13,084	$1,397	$11,010
8	$0.092	$2,022	$15,106	$1,345	$12,354
9	$0.094	$2,062	$17,168	$1,294	$13,648
10	$0.096	$2,103	$19,272	$1,245	$14,893
11	$0.098	$2,145	$21,417	$1,198	$16,091
12	$0.099	$2,188	$23,605	$1,153	$17,244
13	$0.101	$2,232	$25,837	$1,109	$18,353
14	$0.103	$2,277	$28,114	$1,067	$19,421
15	$0.106	$2,322	$30,436	$1,027	$20,448
16	$0.108	$2,369	$32,805	$988	$21,436
17	$0.110	$2,416	$35,221	$951	$22,387
18	$0.112	$2,464	$37,686	$915	$23,302
19	$0.114	$2,514	$40,199	$881	$24,183
20	$0.117	$2,564	$42,763	$847	$25,031

The discounted revenue for any time period is calculated using equation 6.2. Table 6.3 applies this formula to each row using revenue (R) for that year and n = 1.

$$\text{PV revenue} = \sum_{n=1}^{10} R_1 / (1+d)^n \qquad (6.2)$$

where R_1 = first year revenue = $1,760
n = year in the 10-year period
d = discount rate = 6%

Other factors that will improve the breakeven analysis are maintenance costs and depreciation. Maintenance costs include gearbox

Table 6.4. Net cash flow

Year	Discounted	State	Depreciation	O&M	Cash	Investment	Investment
	revenue	Incentive			flow	cost	balance
1	$1,760			$0	$1,760	($19,380)	($17,620)
2	$1,694	$969	$775	($180)	$3,258		($14,362)
3	$1,630	$969	$775	($180)	$3,194		($11,169)
4	$1,568	$969	$775	($180)	$3,132		($8,037)
5	$1,509		$775	($180)	$2,104		($5,933)
6	$1,452		$775	($180)	$2,047		($3,885)
7	$1,397			($180)	$1,217		($2,668)
8	$1,345			($180)	$1,165		($1,504)
9	$1,294			($180)	$1,114		($390)
10	$1,245			($1,200)	$45		($345)
11	$1,198			($180)	$1,018		$673
12	$1,153			($180)	$973		$1,646
13	$1,109			($180)	$929		$2,575
14	$1,067			($180)	$887		$3,463
15	$1,027			($180)	$847		$4,310
16	$988			($180)	$808		$5,118
17	$951			($180)	$771		$5,889
18	$915			($180)	$735		$6,624
19	$881			($180)	$701		$7,325
20	$847			($180)	$667		$7,993

oil changes, blade replacement, and inverter replacement. In this case, an O&M (operation and maintenance) cost is included in year 10. The O&M includes blade repair, inverter replacement, and miscellaneous inspection and repairs. A business can include depreciation, with a basis equal to installed cost less the federal incentive. Five-year straight line is used with an investor tax rate of 20%. State incentives (three year, 5% tax credit) are also included. With these additions, the return of investment is in year 11, when the investment balance turns positive (see Table 6.4).

6.3 RETURN ON INVESTMENT

Another method of economic analysis is the return on investment (ROI). ROI determines the rate at which the investment is recovered, and therefore must have a definite investment period. We can choose a period of 10, 20, or 25 years, depending on the investor's preference. If two or more investment opportunities are being evaluated, the investment periods must be equal. Let us choose a 20-year period and assume the asset is fully depleted, so the salvage value is zero. Again, let us start with simple ROI that does not include inflation, derating factors, or rate increases. For the aforementioned PV system, the initial investment cost is 19,380 U.S. dollars and the annual revenue is 1,760 U.S. dollars. The simple ROI is:

$$\text{ROI} = \$1{,}760 / \$19{,}380 = 9.1\% \tag{6.3}$$

Now, we can compare the 9% ROI for the solar investment with another energy investment of the same expected life or period (20 years). A spreadsheet may be created to include inflation, derating, factors, equipment replacement, and so on, to the analysis, similar to the breakeven analysis. However, more complex rate formulas must be used when the annual revenue is not constant. ROI is also not well suited to short investment periods.

6.4 LEVELIZED COST OF ENERGY

Levelized cost of energy (LCOE) is a common metric used for economic analysis of commercial and utility-scale renewable energy systems. The metric is useful when comparing RE sources to fossil fuel costs or the utility-avoided cost rates. LCOE takes into account all capital and operating costs over the life of a project. The basic definition of LCOE is the lifetime cost of a RE installation divided by the amount of energy the installation generates.

$$\text{LCOE} = \text{lifecycle cost (\$)} \\ / \text{ lifetime energy production (kWh)} \tag{6.4}$$

Lifecycle cost (C) includes the initial capital cost investment (I), investment tax credits (ITC), operating and maintenance (O&M), loan payments (LP), and production-based incentives (PBI).

$$C = I - ITC + O\&M + LP - PBI \tag{6.5}$$

Initial capital cost investment, O&M, and loan payments increase the LCOE. ITC and PBI decrease the LCOE. These formulas are used to determine incentives (e.g., federal and state ITC) that have stimulated the RE industry by driving down the initial cost investment and ROI.

Although equations 6.4 and 6.5 appear to be simple calculations, the cost terms require some careful analysis. All costs and incentives must occur at the same time to accurately reflect their value. Present value analysis is used to adjust future costs and revenue for inflation. All future costs and incentives are adjusted by the assumed inflation rate so they represent the same value of the dollar as the initial capital investment (I). For example, the ITC may not be realized up to one year after the initial investment is made, because it is a tax credit realized only at tax time. The state ITC is realized as tax credits over the three years of the project. Loan payments may occur for 15 or 20 years. O&M costs may be an inverter replacement after 10 years of operation. To account for these timing discrepancies, we must assume a discount rate for the project lifecycle that reflects inflation and the time value of money.

Discounted costs are calculated using the following equation, which is analogous to equation 6.2.

$$\text{PV Cost} = \sum_{n=1}^{10} C_1/(1+d)^n \tag{6.6}$$

where C_1 = first year revenue = \$1,760

n = year in the 10-year period

d = discount rate = 6%

The present value of the annual O&M expenses of 180 \$/year, are determined using equation 6.6:

$$\text{PV (O\&M1)} = \sum_{n=1}^{10} \$180 / (1+.06)^n = \$1,325 \tag{6.7}$$

The present value of the year 10 O&M cost is 1,200 U.S. dollars, because the cost was estimated in a year one dollar. If the O&M cost were in year 10 dollars, the present value (PV) would be calculated by:

$$\text{PV (O\&M2)} = \text{O\&M} / (1 + .05)^{10} \tag{6.8}$$

The state investment tax credit (S-ITC) is realized in years 2, 3, and 4. Therefore, we must discount these amounts to year 1 using an arbitrary discount rate of 5%.

$$\begin{aligned}\text{S-ITC} &= \$969 / (1+.05)^1 + \$969 / (1+.05)^2 + \$969 / (1+.05)^3 \\ &= \$923 + \$879 + \$837 = \$2,639\end{aligned} \tag{6.9}$$

If we assume the federal credit (FITC) is received in the same year as initial investment (I) of 25,841 U.S. dollars is made, we do not need to discount the FITC. We also assume there is no loan (LP = 0). The cost of the project in year one dollars is determined by equation 6.10.

$$C = I - FITC - SITC + O\&M1 + O\&M2 \tag{6.10}$$

$$C = \$25{,}841 - \$6{,}460 - \$2{,}639 + \$1{,}325 + \$1{,}200$$

$$= \$19{,}267$$

Now, we may calculate the 10-year LCOE with the predicted 10-year generated energy (E):

$$LCOE = C / E = \$19{,}267 / 220{,}000\ \text{kWh}$$

$$= \$0.088 / \text{kWh} \tag{6.11}$$

A PV system will typically operate for 20 years without any additional O&M costs. Energy generated in 20 years of operation is estimated at 440,000 kWh. If we include the 20-year energy production into the LCOE formula, we obtain a much better LCOE:

$$LCOE = \$19{,}267 / 440{,}000\ \text{kWh} = \$0.044 / \text{kWh} \tag{6.12}$$

Another method of calculating LCOE discounts energy production, because it is the source of revenue and should be treated as inflated payments not equal in value to year one costs.

$$\text{PV Energy} = \sum_{n=1}^{10} 22{,}000 / (1+.06)^n = 161{,}922\ \text{kWh} \tag{6.13}$$

$$LCOE = \$19{,}267 / 161{,}922 = \$0.12 / \text{kWh}$$

The LCOE method, discount rates, and years of service are critical factors that may make or break the viability of the project. The three methods we have used provide a range of the LCOE of 0.044 to $0.12 $/kWh. This is competitive with most electric utility rates. As equipment costs continue to decrease, installation costs decrease, and efficiency increases, solar will soon be the energy of choice without any incentives.

The LCOE is most useful when sizing a system that will be interconnected to a utility with variable electric rates. For example, a utility might have a two-tier rate system that charges 0.09 $/kWh for monthly energy usage below 800 kWh and $0.13 for energy consumption over 800 kWh/month. This rate structure is sometimes called "inverted block." Total electric charges are based on "volumetric" usage, which means the more electricity used increases cost. For this example, an LCOE of 0.12 $/kWh is a good investment when the system is sized to generate the energy to displace all usage over 800 kWh. If the system is sized larger to displace all energy usage, the return on the lower tier rate of 0.09 $/kWh is not feasible. Utilities that have more complicated rate structures, such as time-of-use (TOU) rates, the LCOE analysis becomes more useful to the investor.

Xcel Energy has proposed a of time-of-use rate structure for on-peak, off-peak, and shoulder times. On-peak is 2 to 6 pm, weekdays and non-holidays. Off-peak is 9 pm to 9 am. Shoulder times are all other hours of the day. An additional energy cost adjustment (ECA) of 2 to 3 cents/kWh is not included in this table because it is a variable cost dependent on the supply and demand.

Time of day	Summer cost/kWh	Winter cost/kWh
On-peak	\$0.13814	\$0.0888
Shoulder	\$0.0842	\$0.05413
Off-peak	\$0.0444	\$0.0444

If these TOU rates are implemented, the economic evaluation for renewable generation becomes more complex. It also impacts design and installation, as energy becomes more valuable during peak hours. It would be advantageous to install PV modules with west-facing orientations. Although not as much solar energy is available in the afternoon hours, energy generated from 2 to 6 pm may generate more revenue or offset more expensive usage than during the shoulder times. Wind energy systems in this utility area would be more profitable during the summer months and during peak times.

6.5 OTHER ECONOMIC EVALUATION METHODS

Economic evaluations become very complex quickly when the timing of revenue does not occur at the end of a period, as we assume in the earlier examples. It is always a good policy to draw a timeline showing all costs and revenues before calculating breakeven or ROI. Economic formulas, such as present worth, future value, and periodic payments, can be found in engineering economics textbooks. A course on economic analysis and investment is highly recommended for all engineering students.

6.6 PROBLEMS

Problem 6.1

Calculate the economics for a 20-kW WTG-interconnected system. The installed cost is 6 U.S. dollars per watt. The utility retail rate is 12 cents/kWh. The homeowner also is eligible for the 30% ITC after the first year of operation.

- What is the net system cost after incentives?
- What is the annual estimated energy production? (use wind power calculations for a sea-level site and wind speed of 14 mph). The overall system efficiency is 70% and Cp is 0.4.
- What is the payback or breakeven in years?

Problem 6.2

What is the ROI for the previous problem system if the investment period is 20 years?

Problem 6.3

What is the breakeven of the previous problem system if the utility rate increases 3% each year?

Problem 6.4

Using a spreadsheet analysis, determine the LCOE for the following system design:

WTG Size = 20.0 kW
Installation cost = 6.00 \$/watt
ITC = 30% received the first year of operation
O&M = \$300 / year
Discount rate = 3%

CHAPTER 7

SOLAR THERMAL SYSTEMS

Solar thermal systems have been around for many years to provide hot water for domestic, commercial, and industrial use. Solar irradiation heats a collector and transfer fluid, which transfers the thermal energy to storage or direct use. The collector may be flat-plate, evacuated tube, parabolic trough, or concentrator with reflecting mirrors (heliostats). Flat-plate collectors are generally used for domestic hot water because the temperatures are limited to about 180°F. The evacuated tube is more efficient, and can reach 300°F to 400°F at the header. The concentrator systems (parabolic trough, heliostat, etc.) heat the collector fluid to very high temperatures that can drive generators for electric power or preheat water for the boiler of a conventional fuel plant. Some type of storage system captures thermal energy for use when solar energy is not available. Domestic storage is usually a well-insulated 200- to 1,500-gallon water tank. Industrial systems may use salt brine that stores energy by changing state (i.e., solid to liquid). All thermal systems require a heat transfer and control system, which may be a simple pump and temperature differential controller. This chapter will describe the basic domestic solar hot water systems and high-temperature applications used to supplement energy systems or generate electricity.

7.1 DOMESTIC HOT WATER

Solar water heating is arguably the best application of solar energy. Domestic solar thermal systems can be very basic, requiring a collector, storage, and method of heat transfer. Small systems installed on residential rooftops can provide all hot water needs for a home, if sized properly. Simple systems for domestic hot water are efficient and inexpensive. In areas where freezing is not a problem, a simple solar collector may consist of a shallow collector box with black absorber plates. These *direct* systems (passive) do not require pumps or controllers, and rely upon water pressure to move domestic water from the source through the collector to the faucet. *Indirect* systems (active) use pumps to move the transfer fluid through the collector to a storage tank. Domestic water flows through copper coils in the storage tank using domestic water pressure. Domestic water in an indirect system is always isolated from the solar collector loop. A differential temperature controller turns the collector pump on when the collector temperature exceeds the storage tank temperature by a set difference (e.g., 5°F to 10°F). The differential controller also switches the pump off when the collector temperature drops to the storage temperature. There are two basic designs for indirect hot water systems: the open-loop (drain-back) system and the closed-loop pressurized system. Each design has specific requirements for piping and control systems. The open-loop system is simpler and does not require periodic maintenance as closed-loop systems do.

7.1.1 OPEN-LOOP SYSTEMS

The simplest design for the solar collector loop is the open loop, sometimes called the drain-back system as shown in Figure 7.1. The collector loop is open to the atmosphere, and relies on gravity to drain the collector loop. The collector pump moves water from the storage tank to the collector on the roof (i.e., elevated above the storage tank). When the collector

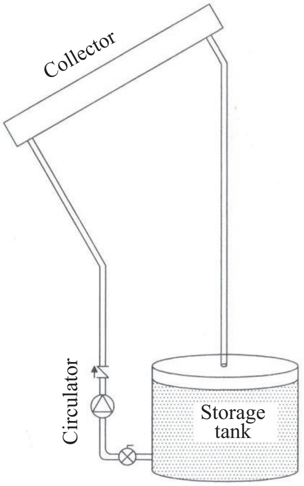

Figure 7.1. Open loop (drain-back) system.

fills with water, it falls back to the storage tank through a vertical or sloped pipe. When the pump shuts off, all collector water flows back to the storage tank. A temperature sensor in the collector prevents operation when collector temperature is below freezing. This design eliminates the need for antifreeze in the collector loop. It is intrinsically safe from contamination of domestic water, because the collector and storage tank use domestic water instead of a glycol mix or oil. A copper coil is installed in the tank to heat the domestic cold water for the hot water system. Domestic water pressure forces water through the storage tank coil directly to the faucet, or to a (backup) conventional hot water heater that uses gas or electricity.

7.1.2 CLOSED-LOOP SYSTEMS

The collector loop for a closed-loop system is pressurized and contains a 50 percent glycol–water mix or an oil-transfer liquid. Figure 7.2 shows a closed loop system. Propylene glycol is usually used because it is not as toxic as other antifreeze coolants. An oil-transfer liquid is used if very high temperatures are expected, because the boiling point is much higher than a glycol mix. The specific heat capacity for oil is about 0.5, lower than water or glycol. The closed-loop system is necessary if the collector cannot be located directly above the storage tank. It also eliminates the possibility of frozen pipes if a freeze switch fails or if the pipes move and no longer drain with gravity. The specific heat capacity for the glycol mix

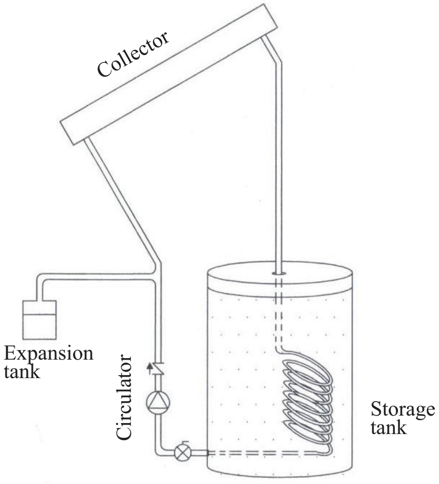

Figure 7.2. Closed-loop system.

is 0.85, slightly less efficient than the open-loop design, but this difference is negligible for small systems. A copper pipe is generally used instead of cross-linked polyethylene pipe (XLPE) in the collector loop. XLPE may be used in domestic water systems and some radiant loops if the fluid temperature is less than 150°F. XLPE is limited to 80 psi and 150°F. The heat exchanger in the storage tank is generally 100 feet of ¾-inch soft copper coiled inside a large (> 1,000 gallons) storage tank.

7.1.3 COLLECTORS

Flat-plate collectors are commonly used for domestic hot water systems. Figure 7.3 shows a typical flat plate collector. The flat-plate collector is a very durable, proven product that has some advantages over the vacuum tube technology. It can be stagnated (no fluid flow) in full sun without damage. It also sheds snow better than a vacuum tube, because the glass cover will warm from convection within the collector frame. The glass envelope of a vacuum tube remains at ambient temperatures due to the excellent insulation and does not melt snow or ice. Therefore, vacuum tubes should be installed at a more vertical angle than a flat-plate collector (>50º tilt). The vacuum tube collector generates much higher fluid temperatures and is more efficient because the vacuum insulates the glass from the atmosphere and minimizes heat loss from the collector plate. Figure 7.4 shows a typical vacuum tube installation.

The *vacuum tube* collector takes up slightly more space than a flat plate because of the separation between tubes. If a single tube in a 30-tube collector fails, it may be replaced individually. Stagnation may damage vacuum tube collector plates, as extreme heat build-up will cause plate emissions that collect on the inside glass and reflect radiation from the

Figure 7.3. Flat-plate collector.

Figure 7.4. Vacuum tube collector.

tube. Vacuum tube systems usually include dual-collector pumps with an uninterruptable power supply (UPS) backup to insure coolant flow whenever the differential controller is "on." The flat-plate collector has header pipes at the top and bottom, and the vacuum tube array has one header pipe at the top where each tube delivers heat from a single transmitter tube.

7.2 SOLAR THERMAL SPACE-HEATING SYSTEMS

Many domestic solar thermal systems have expanded to include capacity for household space heating in addition to hot water systems. A typical home might have a 200 square foot of collector and a storage tank of 1,500 gallons. The collector loop is similar to the domestic hot water system using the vacuum tube technology and a closed-loop pressurized system. A heat reject pump and radiator is added to dissipate excess energy in summer months when the tank is approaching the maximum safe temperature (< 190°F).

A relatively sophisticated hydraulic system is used to distribute the thermal energy from storage to various space-heating systems, such as radiant floor heating, furnace fan coils, and energy recovery ventilator (ERV) equipment. A series primary/secondary loop is shown in Figure 7.5. This design is also called an injector loop system. The primary loop is central to the system with circulator pump P3, which runs whenever a secondary loop needs energy from storage or the collectors. Closely spaced T-fittings connect the secondary loops into the primary loop. Figure 7.5 also shows a bypass loop (P7 and HX2), which brings the collector energy

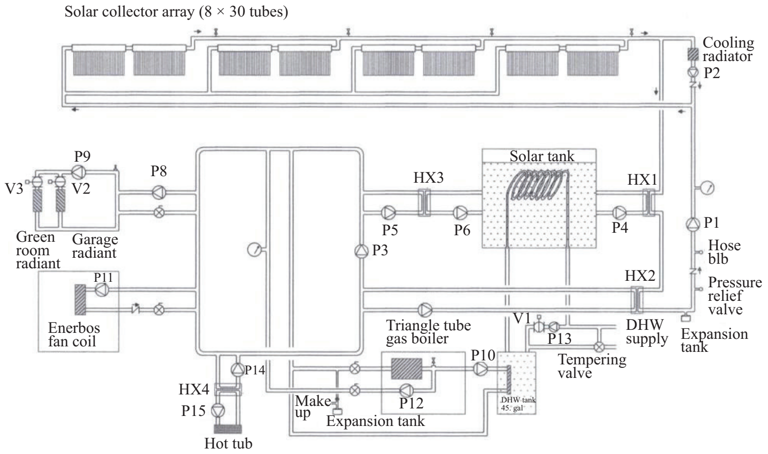

Figure 7.5. Injector loop system.

directly to the primary loop when solar energy is available and there is a call for heat energy by one of the secondary systems. Heat exchangers HX1 and HX2 isolate the glycol loops from the primary loop and storage tank. As the storage tank is open to atmospheric pressure, heat exchanger HX1 isolates the pressurized collector loop from the storage tank, and HX3 isolates the primary loop from the storage tank. A gas boiler provides stage-2 backup heating. Whenever solar energy cannot keep up with the demands of the house, the gas boiler is started and pump P12 delivers 180º F water to the main loop. The gas boiler also provides backup for domestic hot water (DHW) with pump P10. Pump P13 provides hot water for the DWH tank when the solar tank is above 120°F.

The primary/secondary loop design prevents flow in one circuit from interfering with flow in another circuit. This is called *hydraulic separation* and can be designed with series or parallel loops, or with a hydraulic separator tank. Figure 7.5 is an example of the series primary/secondary type. Critical in this design is the distance between secondary Tees located in the primary loop. The distance between the injector Tees cannot be greater than four times the pipe diameter for proper fluid flow and separation.

Figure 7.6 is an example of a parallel primary/secondary system with a boiler as the primary energy source. The boiler tank may be heated with solar or fossil fuels. The secondary circuits are connected into the primary loop, with parallel pipes between headers. This design is more complicated than the series system, but may adapt better to the physical layout of the system. It is equally as efficient for separation as the series design.

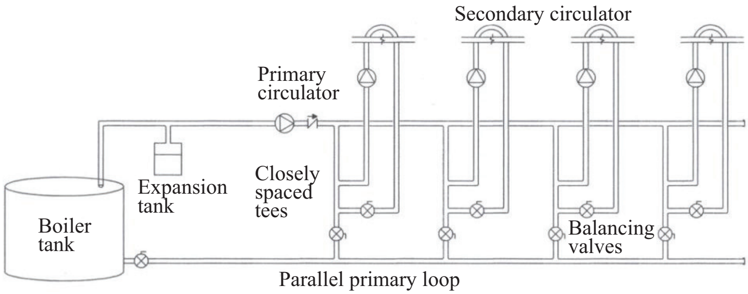

Figure 7.6. Parallel primary/secondary loop design.

The parallel loop system is usually filled with water, but a glycol mix may be used if any part of the system is exposed to freezing conditions. Heat exchangers may also be inserted in secondary circuits that are exposed to freezing conditions, but an additional circulator pump is then required to circulate glycol in the isolated loop.

7.3 ELECTRIC GENERATION USING SOLAR THERMAL SYSTEMS

Utility-scale solar thermal systems require direct sunlight, and the U.S. Southwest locations are ideal for this technology. Indirect or diffuse irradiation will not generate enough heat for efficient operation. Parabolic trough collectors are used when very high temperatures are needed to drive a turbine and electric generator. A 64-MW solar plant (Nevada One) uses parabolic collectors to generate steam for the turbine generator. The parabolic collector has replaced the heliostat mirror system formerly used by Solar One and Solar Two installed near Barstow, California. Solar One operated from 1981 to 1995 and consisted of 1,818 heliostats focused on a 10-MW thermal electric generator. Solar Two operated from 1995 to 2009 and used 1,926 heliostats. It also incorporated a molten-salt storage system for round-the-clock generation. The salt used for change-of-state storage is 60 percent sodium nitrate and 40 percent potassium nitrate.

A recent solar thermal plant installation shown in Figure 7.7 is located near Tonopah, Nevada. The plant uses concentrating solar power (CSP) technology and molten-salt thermal energy storage. The plant incorporates over 10,000 heliostats on a 1,500 acre field. The heliostats focus sunlight on a central receiver atop a 640-feet tower. Receiver tubes are made of nickel-based alloy steel that heat up molten salt to 566°C. The salt is a mixture of sodium nitrate and potassium nitrate and flows through the

Figure 7.7. Solar thermal plant.

receiver at 5,800 gallons per minute. The molten salt passes through a heat exchanger that creates superheated steam and drives a steam turbine generator. The electrical generator's capacity is 110 MW and can generate 500 GWH annually. The system is enhanced by thermal storage tanks that maintain operation throughout the night and during cloudy days. The reported efficiency is 24 to 30 percent. Critical to the CSP operation is the control function to focus the heliostats on the receiver tubes. Each heliostat has a computer controller that insures the proper orientation given the sun altitude and azimuth. A recent failure of a few controllers caused solar energy to focus on an electrical wiring compartment below the receivers, and the intensive heat damage caused an extended shutdown. Solar reflection has also caused some problems for pilots of aircraft at the Los Vegas airport.

Xcel Energy installed a solar thermal system at the coal-fired Cameo plant near Palisade, Colorado, to preheat feed water to the boilers used for electric generation in 2010. The solar system is integrated with Unit #2, a 49-MW steam turbine. The thermal system covers 6.4 acres with right rows of 500-feet parabolic concentrator collectors. The total collector area is 70,400 square feet. The trough is made of curved, pure glass mirrors that focus sunlight on the receiver tube. The transfer fluid is a food-grade mineral oil that is pumped through the tube to a heat exchanger. The operating temperature of the collector is 350°F to 575°F. The heat exchanger heats condenser water from 360°F to 407°F for the boiler feed-water input. A 3 to 5 percent increase in heat rate efficiency is expected. The solar system will reduce coal use by 900 tons and CO_2 production by 2,000 tons.

7.4 GROUND SOURCE HEAT PUMPS

Ground source heat pump (GSHP) systems use the relatively constant temperature below the ground as a heat-exchange medium. The technology is analogous to a refrigerator that uses ambient air as the heat-exchange medium. However, the GSHP is used to heat in the winter and cool in summer by reversing the thermodynamic process. The capital investment and drilling costs limit system size for residential systems. A typical residential system can reduce heating and cooling energy costs by 40 to 60 percent. The peak demand for heating and cooling is provided by a backup gas or electric system.

Many utilities are offering incentives to install GSHP systems in domestic and commercial applications. A homeowner can benefit by eliminating the need of a gas or oil furnace and rely totally on an electric backup furnace with the GSHP. The GSHP can maintain indoor temperatures using the ground thermal reservoir as a source for most of the year. The GSHP electric load is a pump that circulates water or glycol in the ground collector and a fan to distribute the heat in a forced-air-handling system. The electric furnace is needed for the coldest days of the year, and an evaporative cooler may be needed for a few hot summer days. The utility also benefits with a slight increase in electric use and reduction of gas demand. A typical domestic application requires a pipe grid installed 20 feet below the surface or vertical pipe(s) drilled to 100 or 200 feet.

7.5 PROBLEMS

Problem 7.1

How many British thermal units (BTUs) are required to heat a 40-gallon water thermal storage tank from 40°F to 120°F?

Problem 7.2

If the collector flow rate is two GPM, how long must the pump run to generate the BTUs calculated in problem 7.1? (Assume the collector increases the water temperature by 20º.)

Problem 7.3

If a vacuum tube collector increases water temperature of a 1,000-gallon storage tank by 40°F degrees. About how long did the pump run if the flow rate was 4 GPM?

APPENDIX A

GLOSSARY

Absorbed glass matt (AGM): A fibrous silica glass mat to suspend the electrolyte in batteries. This matt provides pockets that assist in the recombination of gasses generated during charging back into water.

AC-coupled system: Renewable energy system that connects directly to a utility grid with a GC inverter.

Alternating current (AC): Electric current in which the direction of flow is reversed at frequent intervals, usually 100 or 120 times per second (50 or 60 cycles per second or 50/60 Hz).

Ampere (A) or amp: The unit for the electric current; the flow of electrons. One amp is one coulomb passing in one second. One amp is produced by an electric force of one volt acting across a resistance of one ohm. Sometimes, this is abbreviated as I for intensity.

Ampere-hour (Ah): The quantity of electrical energy equal to the flow of one ampere of current for one hour. Typically used to quantify the battery bank capacity.

Autonomous system: A standalone system that has no backup-generating source. May or may not include storage batteries.

Avoided cost: The minimum amount an electric utility is required to pay an independent power producer, under the PURPA regulations of 1978, equal to the costs the utility calculates it avoids in not having to produce that power using conventional base generation.

Balance of system (BOS): All system components and costs other than the major components. It includes design costs, land, site preparation, system installation, support structures, power conditioning, operation and maintenance costs, indirect storage, and related costs.

Base power: Power generated by a utility unit that operates at a very high capacity factor.

Battery: Electro-chemical energy storage device.

Battery capacity: The total number of ampere-hours that can be withdrawn from a fully charged cell or battery.

Battery cell: A galvanic cell for storage of electrical energy. This cell, after being discharged, may be restored to a fully charged condition by an electric current.

Battery cycle life: The number of cycles, to a specified depth of discharge, that a cell or battery can undergo before failing to meet its specified capacity or efficiency performance criteria.

Battery self-discharge: The rate at which a battery, without a load, will lose its charge.

Battery state of charge: Percentage of full charge or 100 percent minus the depth of discharge.

British thermal unit (BTU): The amount of heat energy required to raise the temperature of one pound of water from 60°F to 61°F at one atmosphere pressure.

Cadmium (Cd): A chemical element, atomic number 48, used in making certain types of solar cells and batteries.

Capacity factor: The amount of energy that the system produces at a particular site as a percentage of the total amount that it would produce if it operated at rated capacity during the entire year. For example, the capacity factor for a wind farm ranges from 20 to 35 percent.

Cathodic protection: A method of preventing oxidation (rusting) of exposed metal structures, such as bridges and pipelines, by imposing between the structure and ground a small electrical voltage that opposes the flow of electrons and that is greater than the voltage present during oxidation.

Central power: The generation of electricity in large power plants with distribution through a network of transmission lines (grid) for sale to a number of users. Opposite of distributed power.

Charge controller: A device that controls the charging rate and state of charge for batteries.

Charge rate: The current applied to a cell or battery to restore its available capacity.

Current: The flow of electric charge in a conductor between two points having a difference in potential (voltage).

Cycle life: Number of discharge–charge cycles that a battery can tolerate under specified conditions before it fails to meet specified criteria as to performance (e.g., capacity decreases to 80 percent of the nominal capacity).

Days of autonomy: The number of consecutive days a standalone system battery bank will meet a defined load without a solar energy input.

DC-coupled system: A renewable energy system that charges a battery using a charge controller. The battery may be connected to the utility grid with a GC inverter. The battery is usually connected to a dedicated load panel with a standalone inverter or bidirectional inverter.

Deep cycle battery: A type of battery that can be discharged to a large fraction of capacity many times without damaging the battery.

Deep discharge: Discharging a battery to 50 percent or less of its full charge.

Depth of discharge (DOD): The amount of ampere-hours removed from a fully charged cell or battery, expressed as a percentage of rated capacity.

Direct current (DC): Electric current in which electrons flow in one direction only.

Discharge rate: The rate, usually expressed in amperes over time, at which the electrical current is taken from the battery.

Disconnect: A switch gear used to connect or disconnect components of a PV system for safety or service.

Distributed power: Generic term for any power supply located near the point where the power is used.

Duty cycle: The ratio of active time to total time; it is used to describe the operating regime of appliances or loads.

Efficiency: The ratio of output power to input power. Expressed as a percentage.

Electric circuit: Path followed by electrons from a power source (generator or battery) through an external line (including devices that use the electricity) and returning through another line to the source.

Electric current: A flow of electrons; electricity.

Electrical grid: An integrated system of electricity distribution, usually covering a large area.

Electrolyte: A liquid conductor of electricity in which the flow of current takes place by migration of ions. The electrolyte for a lead–acid storage cell is an aqueous solution of sulfuric acid.

Energy: The ability to do work. Stored energy becomes working energy when we use it.

Energy audit: A survey that shows how much energy you use in your house, apartment, or business. It can indicate your most intensive energy-consuming appliances and identify heating and cooling leaks that will help you find ways to use less energy.

Energy density: The ratio of energy available from a battery to its volume (Wh/1) or mass (Wh/kg).

Energy payback time: The time required for any energy-producing system or device to produce as much energy as was required in its manufacturing.

Equalization: The process of mixing the electrolyte in batteries by periodically overcharging the batteries for a short period to refresh cell capacity. Equalization removes sulfate build-up on the electrodes.

Float charge: Float charge is the voltage required to counteract the self-discharge of the battery at a certain temperature.

Float life: Number of years that a battery can keep its stated capacity when it is kept at float charge.

Gassing current: A portion of charge current that goes into electrolytical production of hydrogen and oxygen from the electrolytic liquid in the battery. This current increases with increasing voltage and temperature.

Gel-type battery: A lead–acid battery in which the electrolyte is composed of a silica gel matrix.

Generation mix: The makeup of an electric utility's energy sources providing energy to the grid. Typical sources may be coal, natural gas, oil, nuclear, hydro, wind, or PV.

Gigawatt (GW): One billion watts; one million kilowatts; one thousand megawatts.

Grid-connected: A generator that is electrically connected to the utility grid, also called grid-interactive.

Hybrid system: A renewable energy system that includes more than one source of electricity generation, such as PV, wind, or fossil fuel generators.

Inverter: A device that converts DC electricity into AC electricity (single or multiphase), either for standalone systems (not connected to the grid) or for utility-interactive systems.

Junction box: An electrical box designed to be a safe enclosure in which to make proper electrical connections.

Kilowatt (kW): 1,000 watts.

Kilowatt-hour (kWh): One thousand watt hours. The kWh is a unit of energy. 1 kWh = 3,600 kilo-joules (kJ).

Lifecycle cost: An estimate of the cost of owning and operating a system for the period of its useful life; usually expressed in terms of the present value of all lifetime costs.

Line-commutated inverter: An inverter that is tied to a power grid or line. The commutation of power (conversion from DC to AC) is controlled by the power line so that, if there is a failure in the power grid, the PV system cannot feed power into the line. Also called a grid-connected (GC) inverter.

Load: Anything in an electrical circuit that, when the circuit is turned on, draws power from that circuit.

Megawatt (MW): One million watts; 1,000 kilowatts.

NEC: An abbreviation for the National Electrical Code, which contains safety guidelines and required practices for all types of electrical installations. Articles 690 and 694 pertain to solar photovoltaic systems and small wind generator systems.

Nominal voltage: A reference voltage used to describe batteries, modules, or systems (e.g., a 12-, 24-, or 48-volt battery, module, or system).

Ohm: The unit of resistance to the flow of an electric current.

Peak load; peak demand: The maximum load, or usage, of electrical power occurring in a given period of time, typically a day.

Peak power: Power generated by a utility unit that operates at a very low capacity factor; generally used to meet short-lived and variable high-demand periods.

Photovoltaic (PV): Pertaining to the direct conversion of photons of sunlight into electricity.

PV panel: Often used interchangeably with a *PV module* (especially in one-module systems), but more accurately used to refer to a physically connected collection of modules (i.e., a laminate string of modules used to achieve a required voltage and current).

PV peak watt: Maximum rated output of a cell, module, or system. Typical rating conditions are 1,000 watts per square meter of sunlight, 68°F (20°C) ambient air temperature and one m/s wind speed.

PV system: A complete set of components for converting sunlight into electricity by the PV process, including the array and balance of system components.

Power factor: The ratio of the average power and the apparent volt-amperes.

Quad: A measure of energy equal to one trillion BTUs; an energy equivalent to approximately 172 million barrels of oil.

Remote site: A site that is not located near the utility grid.

Resistance (R): The property of a conductor that opposes the flow of an electric current, resulting in the generation of heat in the conducting material. The unit of resistance is an *ohm*.

Satellite power system (SPS): A concept for providing large amounts of electricity for use on the earth from one or more satellites in geosynchronous earth orbit. A very large array of solar cells on each satellite would provide electricity, which would be converted into microwave energy and beamed to a receiving antenna on the ground. There, it would be reconverted into electricity and distributed the same as any other centrally generated power, through a grid.

Shelf life of batteries: The length of time, under specified conditions, that a battery can be stored so that it keeps its guaranteed capacity.

Square wave inverter: The inverter consists of a DC source, four switches, and the load. The switches are power semiconductors that can carry a large current and withstand a high voltage rating. The switches are turned on and off at a correct sequence, at a certain frequency. The square wave inverter is the simplest and the least expensive to purchase, but it produces the lowest quality of power.

Standalone: An autonomous or hybrid PV system not connected to a grid. Standalone systems usually require batteries or some other form of storage.

State of charge (SOC): The available capacity remaining in a cell or battery, expressed as a percentage of the rated capacity. For example, if

25 amp-hours have been removed from a fully charged 100 amp-hour cell, the state of charge is 75 percent.

Sulfation: A condition that afflicts unused and discharged batteries; large crystals of lead sulfate grow on the plate, instead of the usual tiny crystals, making the battery extremely difficult to recharge.

Superconductivity: The pairing of electrons in certain materials that, when cooled below a critical temperature, causes the material to lose all resistance to electricity flow. Superconductors can carry electric current without any energy losses.

Surge: The momentary start-up condition of a motor requiring a large amount of electrical current.

Surge capacity: The ability of an inverter or generator to deliver high currents momentarily required when starting a motor.

Temperature compensation: An allowance made in charge controller set points for changing battery temperatures.

Thermal electric: Electric energy derived from heat energy, usually by heating a working fluid, which drives a turbo generator.

Thermal mass: Materials, typically masonry, that store heat in a passive solar home.

Total harmonic distortion (THD): The measure of closeness in shape between a waveform and its fundamental component.

Transformer: An electromagnetic device used to convert AC electricity, either to increase or decrease the voltage.

Transmission lines: Conductors and structures used to transmit high-voltage electricity from the source to the electric distribution system.

Trickle charge: A charge at a low rate, balancing through self-discharge losses, to maintain a cell or battery in a fully charged condition.

Uninterruptible power supply (UPS): The designation of a power supply providing continuous uninterruptible service when a main power source is lost.

Utility-interactive inverter: An inverter that can function only when tied to the utility grid and uses the prevailing line-voltage frequency on the utility line as a control parameter to ensure that the PV system's output is fully synchronized with the utility power.

Volt (V): A unit of measure of the electrical force or potential on the electrons in an electric circuit. One volt produces one ampere of current when acting against a resistance of one ohm.

Watt (W): The unit of electric power, or amount of work. One ampere of current flowing at a potential of one volt produces one watt of power.

Watt-hour (Wh): A quantity of electrical energy when one watt is used for one hour.

Waveform: The shape of the curve graphically representing the change in the AC signal voltage and current amplitude, with respect to time.

APPENDIX B

COLORADO NET METERING RULES

SUMMARY

Senate Bill 51 of April 2009 made several changes, effective from September 01, 2009, to the net metering rules for investor-owned utilities as they apply to solar electric systems. These changes include shifting the maximum system size for solar electric systems from 2 MW to 120% of the annual consumption of the site; redefining a site to include all contiguous property owned by the consumer; and allowing system owners to make a one-time election in writing to have their annual net excess generation carried forward as a credit from month to month indefinitely, rather than being paid annually at the average hourly incremental cost for that year. The Colorado Public Utilities Commission (PUC) incorporated these changes in the final rules they adopted in September 2009. While SB 51 dealt explicitly with solar electric systems, the final rules pertain to all eligible energy resources listed earlier.

Systems sized up to 120% of the customer's annual average consumption that generate electricity using qualifying renewable energy resources are eligible for net metering in investor-owned utility (IOU) service territories. Municipal and cooperative utilities are subject to lesser capacity-based maximums as described next. Electricity generated at a customer's site can be applied toward meeting a utility's renewable-generation requirement under Colorado's renewable portfolio standard (RPS), though the renewable electricity certificates remain with the net metering customer unless purchased by the utility. The RPS mandates that 4 percent of the renewables requirement be met with solar energy; half of this percentage must come from solar electricity generated at customer's facilities.

Any customer's net excess generation (NEG) in a given month is applied as a kilowatt-hour (kWh) credit to the customer's next bill. If, in *a calendar year, a customer's generation exceeds consumption, the utility must reimburse the customer for the excess generation at the utility's average hourly incremental cost for the prior 12-month period. Net metering customers of an IOU may make a one-time election in writing on or before the end of the calendar year to have their NEG carried forward from month to month indefinitely. If the customer chooses this option, they will surrender all their kWh credits if and when they terminate service with their utility.*

If a customer-generator does not own a single bi-directional meter, then the utility must provide one free of charge. Systems over 10 kilowatts (kW) in capacity require a second meter to measure the output for the counting of renewable energy credits (RECs). Customers accepting IOU incentive payments must surrender all RECs for the next 20 years. Cooperative and municipal utilities are free to develop their own incentive programs at their discretion, but they are not subject to the solar-specific requirements of the RPS.

House Bill 08-1160, enacted in March 2008, requires municipal utilities with more than 5,000 customers and all cooperative utilities to offer net metering. The new law allows residential systems up to 10 kW in capacity, and commercial and industrial systems up to 25 kW, to be credited monthly at the retail rate for any net excess generation their systems produce. Co-ops and municipal utilities are authorized to exceed these minimum size standards. The statute also requires the utilities to pay for any remaining NEG at the end of an annual period, but does not define what the annual period is, nor the rate at which it will be paid. The law says the utilities will make a payment based on a "rate deemed appropriate by the utility." The new law also required the PUC to open a new rulemaking to determine whether the existing interconnection standards adopted in 4 CCR 723-3, Rule 3665 should be modified for co-ops. Municipal utilities are required to adopt rules "functionally similar" to the existing PUC rules, but may reduce or waive any of the insurance requirements.

BACKGROUND

In December 2005, the Colorado Public Utilities Commission first adopted standards for net metering and interconnection, as required by Amendment 37, a renewable energy ballot initiative approved by Colorado voters in November 2004.

APPENDIX C

ACRONYMS AND ABBREVIATIONS

AC	Alternating current
Ah	Amp hours
AMI	Air mass index
ASES	American Solar Energy Society
AWEA	American Wind Energy Association
BTU	British thermal unit
Cp	Rotor energy conversion efficiency
DC	Direct current
DOD	Depth of discharge
DOE	Department of energy
EIA	Energy Information Agency
EPRI	Electric Power Research Institute
GC	Grid-connected
GHG	Greenhouse gas
GSHP	Ground source heat pump
GWh	Giga watt hours
GW	Giga watts
HVDC	High-voltage direct current
IEEE	Institute of Electrical and Electronics Engineers
ISES	International Solar Energy Society
IOU	Investor Owned Utility
ITC	Investment tax credit
kW	Kilowatt
kWh	Kilowatt hours
LC	Line-commutated (inverter)
LCOE	Levelized cost of energy

MPP	Maximum power point
MPPT	Maximum power point tracking
MW	Megawatt
MWh	Mega-watt hours
NEC	National Electric Code
NEG	Net Excess Generation
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NRTL	Nationally recognized test laboratory (e.g., UL)
NWTC	National Wind Test Center
PBI	Production-based incentive
PPA	Purchased power agreement
PTC	Production tax credit
PV	Photovoltaic
PWM	Pulse width modulation
QF	Qualifying facility
RE	Renewable energy
REC	Renewable Energy Credit
REC	Renewable energy credit
RPS	Renewable energy portfolio standard
SOC	State of charge
SRC	Specific rated capacity (kW/m^2)
STC	Standard test conditions
THD	Total harmonic distortion
THM	Total head mass (nacelle + rotor)
TSR	Tip speed ratio (rotor)
UL	Underwriter Laboratories
VOC	Open circuit voltage

APPENDIX D

TABLE OF CONVERSIONS

1 kWh	3,412 BTUs
1 BTU	0.293 wh
1 Quad	293 billion kWh
1 meter	3.28 ft
1 foot	0.305 meters
1 m/s	2.237 mph
1 mph	0.45 m/s
1 mph	1.61 km/hr
1 km/hr	0.621 mph
1 rpm	2π or 6.28 radians/min
1 rpm	0.1047 radians/sec
1 rad/s	9.55 rev/min (rpm)
1 gal	4.405 liter
1 liter	0.227 gal
1 cm	0.394 in
1 in	2.54 cm
1 sq ft	0.093 sq m
1 sq m	10.76 sq ft
Tc (°C)	(5/9)(Tf-32)
Tf (°F)	(9/5)Tc + 32
1 gal H_20	8.337 lbs
1 ft^3	6.43 gal (dry)

ABOUT THE AUTHOR

Gary D. Price is an Affiliate Professor at the Metro State University of Denver. He teaches a renewable energy course for the Electrical Engineering Technology (EET) Department. Gary also owns Sunnyside Solar, a renewable energy company that designs and installs solar electric systems for residential and commercial customers. Gary holds a BS degree in Electrical Engineering from North Dakota State University, an MS degree in Electrical Power Engineering from the University of Colorado, and an MBA degree in Finance from the University of Denver. He is currently registered as a Professional Engineer in the State of Colorado and is certified as a Professional Solar Installer by the North American Board of Certified Energy Practitioners. Gary lives and works in Louisville, Colorado.

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Renewable Power and Energy

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Gary D. Price is an affiliate professor at the Metro State University of Denver. He teaches a renewable energy course for the electrical engineering technology (EET) department. Gary also owns Sunnyside Solar, a renewable energy company that designs and installs solar electric systems for residential and commercial customers. Gary holds a BS degree in electrical engineering from North Dakota State University, an MS degree in electrical power engineering from the University of Colorado, and an MBA degree in finance from the University of Denver. He also is currently registered as a professional engineer in Colorado and is certified as a professional solar installer by the North American Board of Certified Energy Practitioners. Gary lives and works in Louisville, Colorado.

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