Chapter 5
Off-Grid Generators, Gen Sets, and Biomass Systems

5.1 Introduction

As we discussed in the last chapter, there are several energy conversion technologies that can be used to supply electricity to a mini-grid or other off-grid system. Selecting which particular technology or technologies to use is among the most important design decisions, as it largely dictates the system's architecture, reliability, and economics.

This and the next two chapters are concerned with the principles of operation, technical characteristics, and practical considerations of the energy conversion technologies commonly used in small-scale mini-grids. These technologies include:

- Internal combustion engine generator sets (gen sets)
- Biomass systems
- Wind turbines
- Hydroturbine
- Photovoltaic arrays

Our discussion begins with a description of AC generators, gen sets, and biomass systems. We start with generators because, with the exception of PV arrays, all energy conversion technologies used in off-grid electrification rely on generators to produce electricity.

5.2 Electrical Generators

Generators are electrical machines that convert mechanical energy (typically rotational) into electrical energy. Motors, on the other hand, convert electrical energy into mechanical. In principle, there is no physical distinction between a generator

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and a motor; the only difference is the direction of the energy flow. It is for this reason that scavenged motors are sometimes repurposed as generators in improvised off-grid systems.

The device supplying the input mechanical power to a generator is known as the *prime mover*. Examples of prime movers include wind turbines, hydroturbine, and internal combustion engines. The generator must be carefully designed to match the characteristics of the prime mover, in particular its power, speed, and torque characteristics. In this section, we review the basic principles of generators that are especially relevant to off-grid systems, regardless of the prime mover.

5.2.1 Principle of Operation

All electric generators operate on the same basic principle. When the magnetic flux passing through a coiled wire varies over time, Lenz's Law tells us that a voltage will be induced across the terminals of the coil. There are a variety of ways in which to engineer this interaction. A simple way makes use of the magnetic flux produced by a permanent magnet. The magnet is affixed to a shaft, which allows it to rotate. One or more coils are arranged around the shaft. The coils are stationary so that as the magnet rotates there is a relative motion between each coil and the magnet. The flux through each coil will alternate as the north pole and then south pole pass by. The process repeats with every rotation of the shaft. The alternating flux induces a voltage that can be used to power a load connected to the coils. Of course, some mechanical power is required to rotate the shaft. A prime mover is used for this purpose.

Some generators are designed to output AC voltage, and others DC voltage. We will consider only AC generators as these are the most widely used in off-grid systems. Generators for off-grid applications that output DC are often AC generators with an internal solid-state rectifier, rather than true DC generators. There are two general types of AC generators: synchronous and asynchronous. The most common asynchronous generator is the induction generator. Although induction generators are used in some off-grid applications, in particular small-capacity micro hydro power systems, synchronous AC generators are more common and are the focus of our discussion in this section.

5.2.2 Physical Characteristics

Most generators are constructed using a radial flux arrangement, as shown in Fig. 5.1. There is a cylindrical rotor inside a stationary housing—known as the stator—with a small air gap to allow the rotor to rotate freely. The rotor contains the magnet. The rotor and stator are usually made from highly permeable steel, which provides a path of low reluctance for the flux to flow.

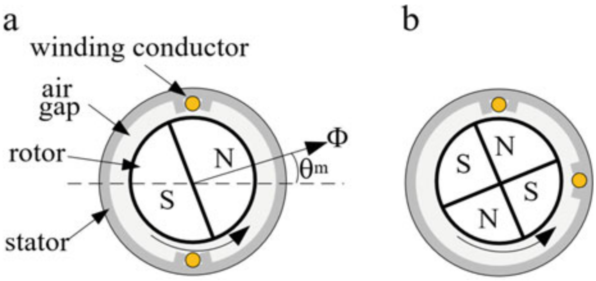


Fig. 5.1 (**a**) Cross-section of a two-pole synchronous generator with a single stator winding shown. (**b**) Cross-section of four-pole synchronous generator

The stator houses coils of wire in which the voltage is induced. Each coil has many turns. The coils are inserted into slots around the stator's interior periphery. These coils are referred to as the "stator" windings, also referred to as "armature" windings. Each winding is wrapped around the length of the stator. The two ends of a single-turn stator winding are shown in Fig. 5.1a.

5.2.3 Electrical Characteristics

Electric generators have three important properties that are important to keep in mind:

1. The electrical load on the generator must be equally matched by the mechanical power provided by prime mover (assuming the generator is electrically and mechanically lossless); otherwise the rotating shaft will speed up or slow down. This is simply a consequence of the law of conservation of energy.
2. The frequency and magnitude of the voltage produced by a generator are proportional to the rotational speed of the rotor and the magnitude of the flux linking the coils. This consequence of Lenz's Law, which we discuss in detail later.
3. The voltage that appears at the generator's terminals depends on the size and power factor of the load. This result also depends on the generator's own internal impedance.

These effects are visualized in Figs. 5.2 and 5.3. Any mismatch in electrical and mechanical power causes the generator's speed to change, as shown in Fig. 5.2. This in turn affects the magnitude and the frequency of the generator voltage. Figure 5.3a shows the effect of rotor speed on frequency. Many loads cannot tolerate large fluctuations in voltage magnitude and frequency. Therefore, it is important to have a control system that balances the mechanical and electrical power. With this control system in place, the generator will operate at a constant speed. However, even if the speed is constant, the terminal voltage will vary with the load, as seen in Fig. 5.3b. We therefore need a second control system to regulate the terminal voltage.

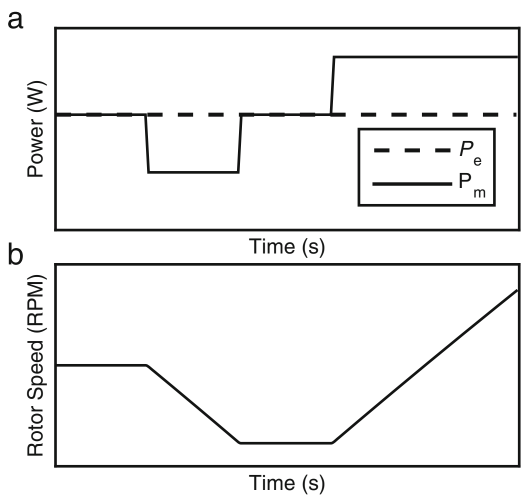


Fig. 5.2 Any mismatch in the electrical power supplied by the generator P_e and the mechanical power input by the prime mover P_m results in a speed and frequency deviation

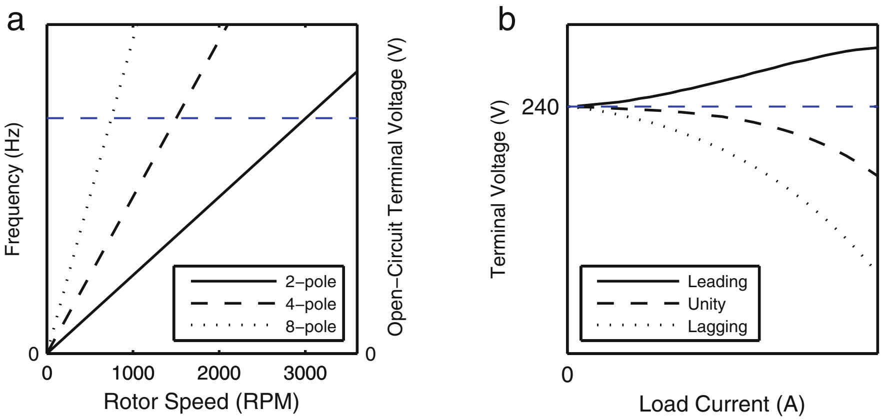


Fig. 5.3 (**a**) The frequency and magnitude of the open-circuit voltage of a generator is proportional to the rotational speed of the rotor. (**b**) The terminal voltage of generator under constant excitation varies with load current and the power factor of the load

The speed and terminal voltage of a generator must be controllable for it to be coupled to the AC bus of a mini-grid. If a generator lacks these capabilities, then it must be coupled to the DC bus through a rectifier. For example, the mechanical power supplied by a wind turbine cannot be increased on demand if it is not windy, and therefore WECS are DC-coupled.[1]

[1] An exception to this is if the WECS utilizes an induction generator. AC coupling is common in large-capacity WECS connected to the national grid where other generators form the AC bus voltage.

5.2.3.1 Induced Voltage

Let us now expand on the qualitative description given in Sect. 5.2.1 of how generators are able to produce voltage. For simplicity, we will consider a single stator winding made of n_{turns} turns of wire. Let the flux produced by the rotor be Φ as shown in Fig. 5.1. As the generator's rotor rotates, the magnitude and polarity of the flux passing through the winding varies. For each complete mechanical rotation, the flux passing through the stator's winding alternates from north to south and back to north in a sinusoidal manner. The flux linking the winding ϕ_{w} at an angular position θ_{m} of the rotor is

$$\phi_{\text{w}} = n_{\text{turns}}\Phi\cos(\theta_{\text{m}}). \tag{5.1}$$

If the rotor spins at an angular velocity of ω_{m} radians per second, then the angular position at any time t is

$$\theta_{\text{m}} = \omega_{\text{m}}t. \tag{5.2}$$

The subscript "m" reminds us that the quantities are referenced to the mechanical speed and position of the rotor. This time-varying flux induces a voltage e in the winding according to Lenz's Law:

$$e(t) = -\frac{\mathrm{d}\phi_{\text{w}}}{\mathrm{d}t} = n_{\text{turns}}\Phi\frac{\mathrm{d}\theta_{\text{m}}}{\mathrm{d}t}\sin(\theta_{\text{m}}) = n_{\text{turns}}\Phi\omega_{\text{m}}\sin(\theta_{\text{m}}) = n_{\text{turns}}\Phi\omega_{\text{m}}\sin(\omega_{\text{m}}t) \tag{5.3}$$

where we have substituted the angular velocity for the derivative of the angular position with respect to time. This description assumes that the generator is open-circuited. When connected to the load, the current through the generator's armature winding also produces flux. This interacts with the flux from the rotor, reducing the total flux linking the coils. This phenomenon is known as "armature reaction" and can be modeled as an inductance as shown later in Sect. 5.2.7.

Sometimes it is advantageous to use several magnets in the rotor. An example of a rotor with two magnets—for a total of four poles, two north and two south—is shown in Fig. 5.1b. With every pair of poles added, the stator windings experience an additional north-to-south and south-to-north flux transition for each mechanical rotation. Therefore, for a given mechanical rotational speed, the flux through the coil varies more rapidly, increasing the magnitude and frequency of the induced voltage. We can rewrite (5.3) to account for the number of poles as:

$$e(t) = n_{\text{turns}}\Phi\omega_{\text{m}}\frac{p}{2}\sin\left(\frac{p}{2}\omega_{\text{m}}t\right) \tag{5.4}$$

where p is the number of poles, which is always an even integer. Since the minimum number of poles that a generator can have is two, the fastest speed that a generator can operate at and produce 50 Hz is 3000 revolutions per minute (RPM) and 3600

RPM for 60 Hz output. The conversion from frequency f in cycles per second (hertz) to revolutions per minute N is simply

$$N = f \times 60. \tag{5.5}$$

The speed that the rotor must operate at to provide a desired electrical frequency f_e can be computed from

$$f_e = \frac{f_m p}{2} = \frac{N_m p}{120} \tag{5.6}$$

where f_m and N_m are the speed of the rotor shaft in hertz and RPM, respectively.

Example 5.1 What must the rotational speed, in RPM, of a conventional internal combustion engine coupled to a four-pole synchronous generator be to provide electricity at 50 Hz?

Solution Rearranging (5.6) shows that the engine shaft must rotate at

$$N_m = \frac{120 f_e}{p} = \frac{120 \times 50}{4} = 1500 \text{ RPM}.$$

Example 5.2 A certain hydroturbine is most efficient when rotating at 750 RPM. How many poles should the synchronous generator coupled to the turbine have if the generator is to supply electricity at 50 Hz?

Solution Rearranging (5.6) shows that for optimal turbine efficiency, the generator should have

$$p = \frac{120 f_e}{N_m} = \frac{120 \times 50}{750} = 8 \text{ poles}.$$

It is possible that the number of poles corresponding to the optimal speed of a prime mover is not an even-numbered integer. In this case, the efficiency curve of the prime mover should be consulted to determine if the number of poles should be rounded up or down to the next even-numbered integer.

In practice, generators have multiple stator windings. If the windings are physically displaced by 120°, then the voltage induced in each winding will be out of phase by 120°, resulting in the familiar balanced three-phase waveform. Smaller capacity generators tend to be single-phase.

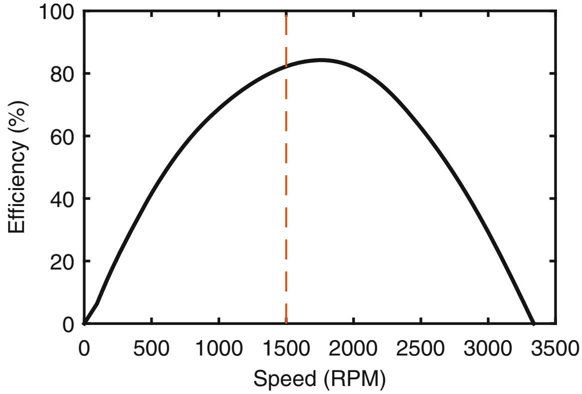


Fig. 5.4 The efficiency of a Pelton hydroturbine depends on its rotational speed

A generator's rotor is usually directly coupled to the shaft of the prime mover—a configuration known as "direct drive." In this case, the rotor and the prime mover's shaft rotate at the same speed. The speed is controlled so that the generator produces the desired frequency. However, the speed required to produce the desired electrical frequency might not overlap with the speed at which the prime mover is most efficient. For example, if a four-pole generator is coupled to a certain Pelton turbine whose efficiency curve is shown in Fig. 5.4, then operating at the 1500 RPM required for 50 Hz voltage output does not maximize the efficiency of the turbine. We could control the turbine so that it operates at its most efficient speed, but the frequency of the voltage would surpass 50 Hz. Gear boxes or pulleys can be used to achieve a desired ratio between rotor shaft and prime mover shaft speeds, but they add complexity and cost and increase maintenance requirements. We should therefore co-design the prime mover and generator so that their shaft speed maximizes the efficiency of the prime mover while producing the required electrical frequency.

5.2.4 Speed, Torque, and Power

As we increase the number of poles of a generator, the speed it must operate at to produce the desired voltage frequency decreases. What are the other implications of this lower-speed operation? Recall from physics that angular speed ω in radians per second, power P in joules, and torque T in newton meters are related by

$$P = T \times \omega. \tag{5.7}$$

This equation tells us that a given amount of power supplied to the rotor shaft can be accomplished at, for example, high torque but low speed, low torque but high speed, or both medium torque and speed. A generator with more poles will experience greater torque to provide the same output power because it rotates slower. A prime mover and generator designed for high-torque, low-speed operation tend to have longer service lives but require more substantial shafts, rotors, and stators to withstand the forces associated with high torque. On the other hand, a prime mover and generator designed for high-speed, low-torque operation require fewer windings and less flux to induce the same voltage per (5.4). This reduces the material, weight, and cost of the generator; however, the higher speed tends to wear components such as bearings more quickly, reducing the service life. In addition, certain losses increase with operational speed. As you can see, design of prime movers and generators requires making several trade-offs.

5.2.5 Rotational Dynamics

We saw in Fig. 5.2 that a mismatch in electrical and mechanical power causes the generator to rotate slower or faster. To understand why, let's briefly review what happens when a net torque T_{net} is applied to a rigid body such as a generator's rotor. The torque causes a change in the rotational speed according to

$$T_{\text{net}} = \alpha_{\text{m}} J = \frac{\mathrm{d}\omega_{\text{m}}}{\mathrm{d}t} J \tag{5.8}$$

where α_{m} is the acceleration and J is the mass moment of inertia, in kilogram meters squared, of the rotor. When the net torque is positive, the rotor accelerates; when it is negative, the rotor decelerates. Only when the net torque is zero is the speed of the rotor shaft constant.

If we ignore losses, then there are two torques acting on the rotor: the mechanical torque provided by the prime mover and the electromagnetic torque caused by the generator. The torques are in opposite directions so that

$$T_{\text{net}} = T_{\text{m}} - T_{\text{e}}. \tag{5.9}$$

The origin of the electromagnetic torque can be explained as follows. Whenever a generator supplies real power to a load, the generator current causes the stator windings to act like electromagnets. Their magnetic fields interact with the magnetic field produced by the rotor. The polarity of each electromagnet is such that it repels a rotor pole rotating toward it and attracts a rotor pole rotating away from it. In other words, the electromagnetic torque is in the opposite direction of the mechanical torque applied to the rotor. The strength of the repulsion and attraction increases with the real power provided by the generator, leading to a similar increase in T_{e}.

Table 5.1 summarizes how the net torque affects the speed of the rotor. Given (5.7), the same net torque conditions that cause the rotor to accelerate or decelerate also apply to the mechanical and electrical power. With this explanation of rotational dynamics in mind, the reader should return to Fig. 5.2 and verify the rotor speed is as expected.

Table 5.1 Effect of net torque on rotor speed

Net torque	Condition	Result
$T_{net} > 0$	$T_m > T_e$, $P_m > P_e$	Rotor accelerates
$T_{net} = 0$	$T_m = T_e$, $P_m = P_e$	Rotor speed constant
$T_{net} < 0$	$T_m < T_e$, $P_m < P_e$	Rotor decelerates

5.2.6 Speed Control Systems

It is clear that to maintain a constant speed, the mechanical power provided by the prime mover must be adjusted to "follow" the changes in electric load. Different prime movers use different systems for speed control, for example, by using valves and throttles to adjust the flow of water to the turbine or air into a combustion chamber. It is also possible to use a ballast load to keep P_e constant even as users turn appliances on and off. This scheme is commonly used in micro hydro power systems.

Even in systems where the prime mover is not required to operate at constant speed, some precautions are necessary to prevent damaging over-speed conditions. Care should be taken to avoid suddenly disconnecting wind turbines and some hydro turbines from their load without also reducing the input mechanical power. Otherwise the rotor might quickly accelerate to a high speed, potentially causing over voltages. The generator and prime mover might also be damaged due to the associated centripetal forces and vibration.

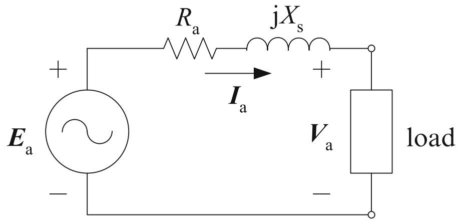
5.2.7 Circuit Model

We saw in Fig. 5.3b that a generator's terminal voltage depends on the generator current and the power factor of the load. To understand why, consider the circuit model for a single-phase generator shown in Fig. 5.5. A similar model applies for an equivalent single phase of a three-phase generator. The model consists of a voltage source in series with a resistance and inductive reactance. The resistor R_a corresponds to the resistance of the armature windings; the inductive reactance X_s—also known as the synchronous reactance—models the self and mutual inductance of the stator windings. Applying Kirchhoff's Voltage Law using phasor quantities yields:

$$\boldsymbol{V}_a = \boldsymbol{E}_a - \boldsymbol{I}_a (R_a + jX_s) \tag{5.10}$$

where $\boldsymbol{E}_a$ is the induced voltage from (5.4) in phasor form, $\boldsymbol{V}_a$ is the terminal voltage, and $\boldsymbol{I}_a$ is the armature current. The terminal voltage therefore depends on the current.

Fig. 5.5 Equivalent circuit model of a single-phase synchronous AC generator armature



Example 5.3 Consider a mini-grid consisting of a load and single-phase generator coupled to an AC bus. The bus voltage is nominally 230 V. The generator's resistance is 0.75 Ω, and synchronous reactance is 7.5 Ω. Compute the terminal voltage if the induced voltage is $\boldsymbol{E}_\mathrm{a} = 230\angle 0°\mathrm{V}$ and $\boldsymbol{I}_\mathrm{a} = 25.0\angle -70°\mathrm{A}$. Compare this to the open-circuit voltage.

Solution The terminal voltage is found by solving for $\boldsymbol{V}_\mathrm{a}$ in 5.10:

$$\begin{aligned}\boldsymbol{V}_\mathrm{a} &= \boldsymbol{E}_\mathrm{a} - \boldsymbol{I}_\mathrm{a}\,(R_\mathrm{a} + \mathrm{j}X_\mathrm{s}) \\ &= 230\angle 0° - 25.0\angle -70°\,(0.75 + \mathrm{j}7.5) = 66.40\angle -44.46°\ \mathrm{V}.\end{aligned}$$

The terminal voltage has dropped significantly. Most loads designed for a 230 V supply will not function properly or at all at such a low voltage.

The open-circuit voltage is always equal to the induced voltage. In this case it is 230 V.

5.2.8 *Excitation Systems*

The circuit model described in the previous section offers a hint at how we can maintain a constant terminal voltage magnitude $|\boldsymbol{V}_\mathrm{a}|$ even as the load changes. We see that from (5.10), the terminal voltage depends on the induced voltage. If we can adjust the induced voltage, we can control the terminal voltage. Recall from (5.4) that the induced voltage is a function of the rotor speed, the number of poles, and flux. Although the speed can be adjusted, constant speed operation is preferred. We cannot realistically change the number of poles of the generator. We can, however, change the rotor flux if electromagnets are used in the rotor instead of permanent magnets. Most generators use electromagnets. Electromagnets can also produce more flux than a similarly sized permanent magnet. This increases the power density of the generator and lowers its cost.

The electromagnets in the generator's rotor require DC current. The system used to provide the DC current to rotor is known as the "excitation" system [5]. The coils of the electromagnet are known as “field” windings because they produce the rotor’s magnetic field. We generically relate the flux produced by the rotor to the field current i_f by a parameter k_f, which itself depends on the physical and magnetic properties of the generator,[2] as

$$\Phi = i_f k_f. \tag{5.11}$$

By controlling the field current, we are able to adjust the flux and thereby control the induced voltage. The flux produced by the electromagnets can magnetize the rotor, so that even with no DC current, there is a small amount of residual magnetism.

There are several excitation systems that are in use today. Generators used in mini-grids tend be “self-excited” in that they use a small portion of their output for excitation.

Example 5.4 Consider the generator in the previous example. Compute the magnitude of the induced voltage required to maintain a terminal voltage of 230 V when the current is $\boldsymbol{I}_a = 25.0\angle -70.0°$ A. Let the angle of the terminal voltage be -44.46°.

Solution The induced voltage $\boldsymbol{E}_a$ is found by rearranging (5.10)

$$\begin{aligned}\boldsymbol{E}_a &= \boldsymbol{V}_a + \boldsymbol{I}_a (R_a + jX_a)\\ &= 230\angle -44.46° + 25.0\angle -70.0° (0.75 + j7.5) = 365.21\angle - 18.29° \text{ V}\end{aligned}$$

The required magnitude of the induced voltage is 365.21 V. To increase the induced voltage to this level requires additional flux. This can be accomplished by increasing the current to the field (rotor) winding.

5.2.8.1 Static Excitation

A static excitation system uses a separate set of windings known as “excitation” windings mounted in the stator, as shown in Fig. 5.6. Static excitation systems are commonly found in the alternators of most automobiles. During start-up, residual magnetism from the rotor provides a small amount of flux that induces a voltage in the excitation winding. The excitation winding is connected to a rectifier that outputs DC current. The rectifier output is connected to carbon brushes. The brushes

[2]The parameter k_f will decrease at high levels of field current as the ferrous material making up the rotor saturates and its permeability drops.

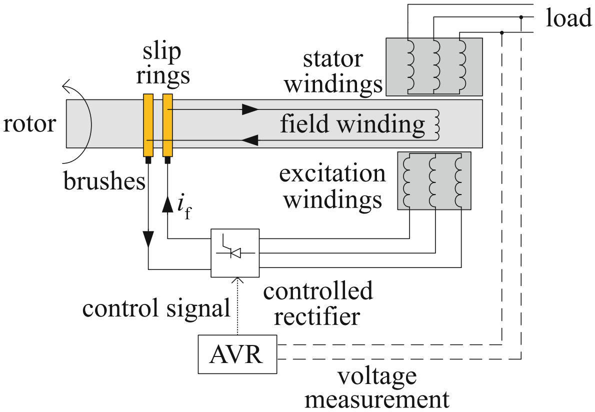


Fig. 5.6 Static excitation system

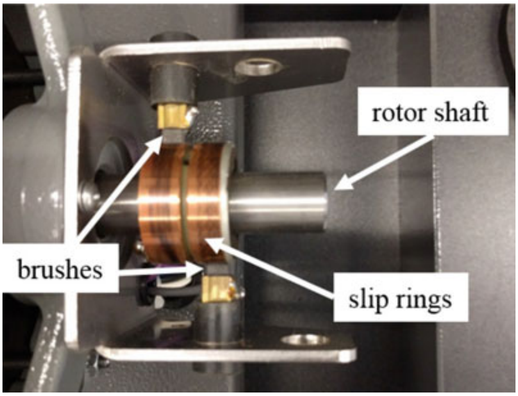


Fig. 5.7 The brushes and slip rings of a synchronous generator supply current to field winding (courtesy of the author)

are pressed against rotating slip rings that are connected to the field winding, as shown in Fig. 5.7. In this way, the stationary rectifier is connected to the rotating field winding.

The field winding current can be controlled using an Automatic Voltage Regulator (AVR) [5]. The AVR senses the generator's terminal voltage (typically the line-to-line voltage between any two phases) and adjusts the field current to achieve the flux needed to keep the terminal voltage constant. The AVR function can be accomplished with an analog or digital circuit. The excitation scheme shown in Fig. 5.6 uses a controlled rectifier whose firing angle is set by the AVR to control i_f. The specifics of controlled rectifiers and AVRs are discussed in more detail in Chap. 9.

Instead of relying on residual magnetism in the rotor to induce voltage in the excitation windings during start-up, some generators rely on an external battery bank that is temporarily connected to the field winding.

A drawback to static excitation systems is that the brushes require maintenance and replacement, and increase losses.

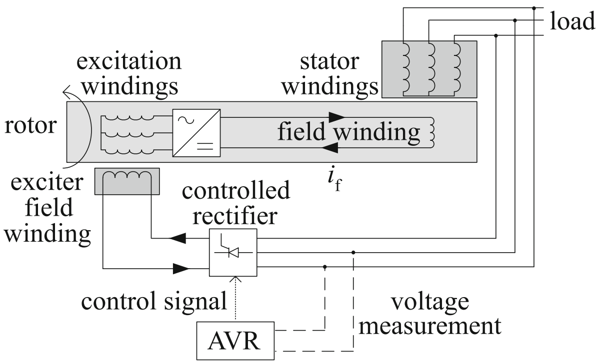


Fig. 5.8 Brushless excitation system

5.2.8.2 Brushless Excitation

To overcome the challenges associated with brushes, brushless excitation systems are sometimes used. In these systems, the excitation winding is on the rotor instead of the stator, as shown in Fig. 5.8. AC voltage is induced in the excitation winding through a stationary electromagnet, which is sometimes called the "exciter field winding." The excitation winding voltage is converted to DC by a rectifier that is attached to, and rotates with, the rotor. The rectifier output is connected to generator's field windings.

The current for the exciter field winding can be supplied by the generator output (using the residual magnetism of rotor during start-up) as shown in Fig. 5.8 or by a pilot exciter. A pilot exciter is a small-capacity permanent magnet generator attached to the end of the main generator shaft. The AC voltage induced in the pilot exciter's stator winding is rectified and supplies DC current to the stationary electromagnet. An AVR adjusts the field current to achieve the desired terminal voltage.

5.2.9 Efficiency

In general, the efficiency of a synchronous generator is high, around 90%, when loaded near rated capacity. The losses that do occur can be categorized as:

- Mechanical: caused by friction of bearings, brushes (if applicable), and windage (aerodynamic drag on the rotor).
- Magnetic: caused by hysteresis and eddy currents associated with the magnetic flux in the rotor and stator.
- Winding (Copper): I^2R losses associated with the armature current, as well as field and excitation windings (if applicable).

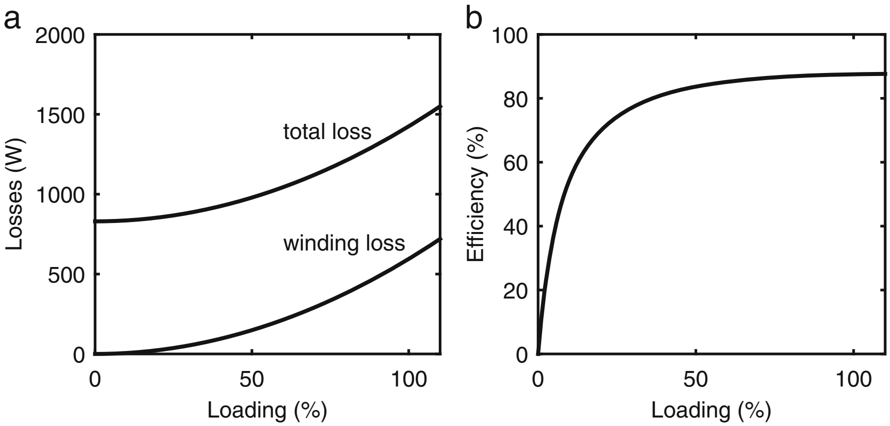


Fig. 5.9 (**a**) Winding losses increase with generator loading. (**b**) The efficiency of a synchronous generator is greatest near rated power

The share of total losses attributed to each category varies with generator loading and speed. Mechanical losses increase with speed but are nearly constant as the load varies. Magnetic losses increase somewhat with speed and load; and copper losses are insensitive to speed but increase rapidly with load as shown in Fig. 5.9a.

The efficiency of a generator is best expressed as a curve rather than a single value. A typical efficiency curve is shown in Fig. 5.9b. The efficiency is low at low loading because the mechanical losses and magnetic losses are high relative to the power produced. The efficiency rapidly rises as the load increases, before plateauing near its rated capacity as the copper losses begin to dominate.

Generators are in fact capable of supplying power in excess of their rating, but this can lead to overheating. High temperatures degrade the generator components, including the winding insulation. An increase in operating temperature over its design value by 10°C can reduce the service life of the generator by as much as 50%. Therefore, generators should only be operated above their rated power for brief episodes—for example, when connected to motors and other devices that require high power during start-up.

5.3 Conventional Internal Combustion Engine Generator Sets

Conventional internal combustion engines (ICE) are commonly used in off-grid systems. In Nigeria alone, there are an estimated 100 million ICE-coupled generators in use. The ICEs used in off-grid systems are most often of the reciprocating type, like those found in automobile engines, rather than turbine type, like those found in large aircraft and power plants. The main components of such a reciprocating ICE generator system are:

Fig. 5.10 Smaller-capacity gen sets are often designed to be portable (courtesy of P. Dauenhauer)

Fig. 5.11 A 660 kW diesel gen set used to power a mini-grid in Haiti (courtesy of Sigora Haiti)

- Fuel tank
- Fuel and air supply system
- Engine
- Cooling and exhaust system
- Generator and excitation system

When these components are packaged together into an integrated unit, it is referred to as a "generator set" or simply a "gen set."

Gen sets range in capacity from a few hundred watts to several hundred kilowatts or even a few megawatts. Gen sets below approximately 10 kW are often constructed to be portable, as shown in Fig. 5.10. Larger gen sets are permanently installed, as shown in Fig. 5.11. Gen sets are usually placed in enclosures that offer protection from the weather and pests, along with acoustic damping.

5.3.1 Principle of Operation

There are two categories of reciprocating ICEs: spark ignition (SI) and compression ignition (CI). Both ignite fuel in a cylindrical combustion chamber, using the resulting expansion to drive a reciprocating piston. The pistons are connected to a crankshaft which rotates and is capable of supplying rotational mechanical power [9].

Spark-ignition engines use a spark plug to ignite a mixture of fuel and air in the combustion chamber. The process consists of:

1. formation of a mixture of air fuel
2. air/fuel mixture intake into the chamber
3. compression (typically by a factor from 8 to 12)
4. spark ignition
5. combustion
6. expansion
7. exhaust

SI engines can be designed to run on gasoline (petrol), natural gas, biogas, syngas, propane, hydrogen (H_2), or alcohols.

Combustion in CI engines occurs by compressing air and a fuel (usually diesel or another oil, including bio-fuels) in the combustion chamber. As the air compresses, its temperature increases, initializing the combustion of the fuel. The process consists of air intake, compression of the air (typically by a factor of 12 to 24), fuel injection, mixture formation, ignition, combustion, expansion, and exhaust.

In SI and CI engines, the crankshaft is directly coupled to the generator's rotor. The designed speed of a gen set is a compromise of several competing factors, including the general speed-versus-torque trade-offs discussed in Sect. 5.2.4 and consideration of the speed-versus-efficiency curve of the engine.

A consequence of these trade-offs is that most small-capacity gen sets—tens of kilowatts or less—use two-pole generators. This means that for 50 Hz systems the engine shaft speed is 3000 RPM. They are often SI engines fueled by petrol, but CI diesel-fueled gen sets in this capacity range are available. Larger capacity gen sets tend to use diesel-fueled CI engines, with four-pole generators operating at 1500 RPM (for 50 Hz systems). The main reasons for this are:

- Higher reliability: CI engines can be operated for 20,000 to 30,000 h before a major overhaul is needed—approximately three times as long as an SI engine. This is due to fewer parts, lower speed operation, and self-lubrication provided by the fuel.
- Decreased fuel consumption: CI engines use higher compression ratios, which allows an improvement in efficiency by about one third over an SI engine; in addition, diesel contains approximately 10% more energy per liter than petrol, so that less fuel is needed.

CI engines are less sensitive to the type and quality of the fuel supplied. This can be relevant in the off-grid context.

5.3.2 Frequency Regulation

Most gen sets are designed to operate at constant speed so that the output frequency is also constant. A speed control device called a "governor" increases the mechanical power to the crankshaft when the crankshaft speed decreases, and decreases the power when the speed increases. The mechanical output power is controlled by throttling (adjusting the amount of the air-gas mixture entering the combustion chamber) in an SI engine or fuel metering (adjusting the amount of fuel injected) in a CI engine. A mechanical governor is typically used in older or lower-quality gen sets; modern and higher-quality gen sets use electronic governors.

5.3.3 Excitation

Larger capacity gen sets use either static or brushless excitation. Voltage regulation can be problematic in lower-quality and less-expensive gen sets. Some portable gen sets do not include an AVR; these gen sets should only be used if there are no sensitive electronic loads and if no other generators or inverters are connected to the AC bus.

Small-capacity gen sets typically rely on the residual magnetism in the rotor at start-up. Generators that have been idle for extended periods will need their residual magnetism to be restored in a process known as "field flashing." Field flashing is the temporary application of DC current from an external source such as a battery to the field winding.

5.3.4 Fuel Consumption and Efficiency

Gen sets are expensive to operate. However, their upfront costs are low, and they are readily available in developing countries, making them popular for off-grid electrification. The bulk of the operating costs are for fuel. Some off-grid systems are so remote that the cost to transport the fuel is more expensive than the fuel itself. As such we are concerned with operating them as efficiently as possible. The main losses associated with the ICE portion of a gen set are:

- Friction: from the pistons, bearings, valve train, pumps, and other moving parts
- Heat transfer: heat from combustion that is rejected to the cooling system
- Exhaust: heat in the gases that are emitted from the engine

A general rule of thumb is that a third of the input energy to an ICE is converted to useful mechanical output, a third is rejected to the coolant, and a third is contained in the heat of the exhaust, yielding a mechanical efficiency of 33% [9]. While an easy

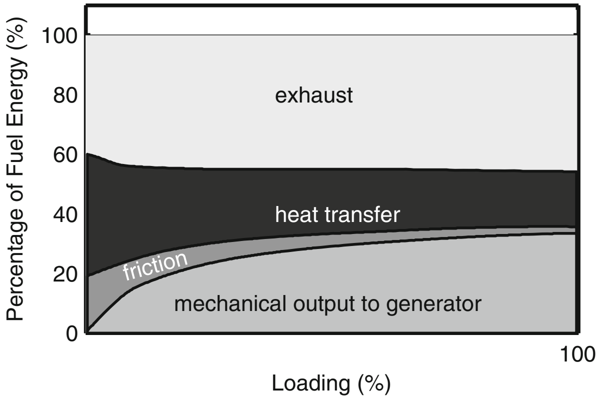


Fig. 5.12 Energy allocation in an ICE

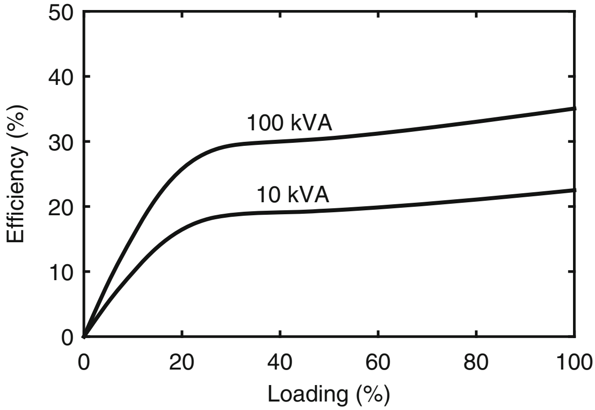


Fig. 5.13 Efficiency curve of gen sets of different rated capacities

rule to remember, it is overly simplistic, as the efficiency of a gen set varies with the load it supplies. Figure 5.12 shows the relative portion of input fuel associated with these losses as load increases [3].

The overall efficiency of a gen set is the product of the ICE and generator efficiencies, both of which depend on the load:

$$\eta_{\text{genset}}(P_{\text{e}}) = \eta_{\text{ICE}}(P_{\text{e}}) \times \eta_{\text{gen}}(P_{\text{e}}) \tag{5.12}$$

with a resulting efficiency curve shown in Fig. 5.13. The maximum efficiency occurs near the rated power and ranges from 20 to 40%.

Table 5.2 shows how diesel fuel consumption, in liters per hour, varies with gen set loading and capacity. The fuel supply and storage aspects should not be overlooked. The fuel requirements of a 50 kW gen set operating at 50% loading continuously for 1 week is nearly 1500 liters.

Table 5.2 Typical gen set fuel consumption

Capacity (kW)	Loading 25% (l/h)	50% (l/h)	75% (l/h)	100% (l/h)
10	1.3	2.5	3.5	4.3
50	4.9	8.7	12.5	16.4
100	8.3	15.9	22.3	27.6
500	39.7	73.8	89.7	118.1

Table 5.3 Typical gen set efficiency

Capacity (kW)	25%	50%	75%	100%
10	19	20	22	23
50	26	29	30	31
100	30	32	34	36

Table 5.3 shows the typical efficiency of gen sets of various capacities. The efficiency increases with loading and with generator capacity. Gen sets that are designed to be portable typically have lower efficiencies, as low weight, not efficiency, is prioritized.

Due to the low efficiency at low loading, a rule of thumb is to avoid operating a gen set below 50% of its rated power. If possible, loads should be scheduled simultaneously to concentrate the gen set's operation into fewer hours of high-load operation, instead of low-load operation spread over more hours. Another reason to avoid low loading is "wet stacking." When diesel gen sets operate at low loading, some of the fuel is not combusted. This can cause an oily material to accumulate in the exhaust system, which needs to be removed. In hybrid systems with batteries, a viable operational strategy is to only operate the gen set to charge the batteries when they are at a low state-of-charge. This control strategy and others are described in Chap. 10.

Example 5.5 Consider a 10 kW gen set supplying power to four 2.5 kW pumps. Each pump must operate for 1 h each day. Compute the fuel savings if the pumps are operated simultaneously for 1 h, compared to if the pumps are operated individually over a 4-h period. The gen set fuel consumption is provided in Table 5.2.

Solution When the gen set supplies the combined load of 10 kW, it is fully loaded (100%). From Table 5.2, it consumes 4.3 liters for the 1 h it is on. When the generator supplies each pump individually, it is loaded at 25% and consumes 1.3 liters per hour for a total of 4 h. A total of $4 \times 1.3 = 5.2$ liters is consumed. By operating the pumps simultaneously, the fuel consumption is reduced by nearly 20%.

Example 5.6 Consider an 800 W petrol generator supplying a mini-grid whose load is a continuous 200 W. Compute the monthly fuel cost assuming: petrol costs US$1.0 per liter, the efficiency at 200 W is 13%, and the energy density of the fuel is 31.5 MJ/l.

Solution The monthly energy consumption is

$$\begin{aligned}\textit{Monthly Energy Consumption} &= 200\ \text{W} \times 24\ \text{h} \times 30\ \text{days/month} \\ &= 144\ \text{kWh/month.}\end{aligned}$$

The input energy is found by dividing the output energy by the efficiency at the loading level:

$$E_{\text{in}} = \frac{144}{0.13} = 1107.7\ \text{kWh} = 1107.7\ \text{kWh} \times 3.6\ \text{MJ/kWh} = 3987.7\ \text{MJ.}$$

The liters of fuel required each month is:

$$\textit{Liters per Month} = \frac{3987.7\ \text{MJ}}{31.5\ \text{MJ/liter}} = 126.59\ \text{liter.}$$

The fuel cost of the generator is therefore US$126.59 per month. Note that an 800 W generator can be purchased for approximately US$200. In less than two months of operation, the fuel costs will have exceeded the capital costs.

5.3.5 *Practical Considerations*

There are several features that make gen sets a common choice for off-grid systems. Gen sets can be purchased in a range of capacities, from a few hundred watts to hundreds of kilowatts. They are widely available and have lower capital costs than most renewable-based energy conversion technologies, at about US$100 to US$300 per kilowatt. Their mechanical nature offers a possibility of repair for minor failures. Gen sets can be operated on-demand with negligible start-up time. When operating as a backup supply for a hybrid renewable system, they can reduce the required battery size. This is done by operating the gen set during occasions with high-demand or low-energy resource availability (e.g., cloudy days for a PV-based system). Portable gen sets are easy to install as they do not require civil works. Most gen sets contain integrated control systems that govern the frequency and magnitude of the voltage they output, making their use convenient.

Gen sets, however, have several disadvantages. Their operating costs are high, primarily due to the fuel expense. They also require a fuel supply chain that must be managed. In remote locations it might be challenging and costly to refuel the generator. Large holding tanks add costs and the potential for leakage and environmental spoilage. The fuel can also only be stored for a certain period of time, perhaps 3 months for petrol to 1 year for diesel.

Gen sets emit air pollution—in the form of carbon dioxide but also particulates and nitric oxides NO_x and sulfur oxide SO_x—as well as noise pollution.

Gen sets have many moving parts which require maintenance, repair, and occasional replacement. Regular oil changes, replacement of air and fuel filters, valve or spark gap adjustment, and other maintenance are regularly required. Trained technicians and replacement parts must be available. The service life of a gen set should be carefully monitored. A typical large-capacity gen set will have a service life of about 3 years of continuous operation, if properly maintained, before a major refurbishment is needed. This is considerably less than a PV array, which might last 15 to 20 years or longer.

5.4 Biomass Systems

Although most gen sets use conventional fossil fuels, they can also be powered from biomass-derived fuel. Biomass systems convert the energy accumulated in organic matter to generate heat and/or electricity. Biomass is distinguished from fossil fuels in that the organic matter in biomass was recently alive. As we discussed in Chap. 2, biomass in the form of fuel wood, charcoal, and crop and animal residue already constitutes a large portion of the energy used by rural off-grid households. This traditional use of biomass is not the subject of this section. Instead, we focus on the biomass systems capable of producing electricity.

Biomass must be processed before it can be efficiently or conveniently used to generate electricity. Depending on the feedstock and process used, different types of biofuels result. Electricity is generated when the biomass-derived fuel is used in an engine to drive a generator as is done in a gen set. The following are biomass-derived fuels used in off-grid electrification:

- Biogas: biomass undergoes a biological process known as anaerobic digestion to produce a gas that is primarily a mixture of methane and carbon dioxide.
- Synthesis gas: biomass is processed through a thermal-chemical reaction to produce a gas consisting of carbon monoxide and hydrogen.
- Solid biomass: biomass is burned as a solid, after being dried and cut.

The input biomass, whatever it may be, is known as the *feedstock*.

5.4.1 Principle of Operation

The energy found in biomass originated as solar radiation (sunlight), which was converted to plant matter[3] through photosynthesis. The energy can be passed up the food chain, albeit inefficiently, from plant to animal and from prey to predator.

In a photosynthetic process, the energy in sunlight combines carbon dioxide and water to form plant matter—sugars, cellulose, and starches, among others. The chemical reaction for glucose, for example, is

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2. \tag{5.13}$$

When plant matter decays, energy is released in the form of heat. The energy can also be released through combustion. In combustion, oxygen reacts with the plant matter to produce carbon dioxide, water, and energy. In the case of glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}. \tag{5.14}$$

We note that this is simply (5.13) run in the opposite direction. Biomass systems ultimately rely on combustion to generate heat and electricity. Although carbon dioxide is released, many consider the combustion of biomass to be carbon neutral, arguing that the carbon released was recently removed from the atmosphere by the feedstock.

5.4.2 Biomass Resource

The amount of energy stored in the earth's biosphere is immense, approximately 1.5×10^{22}J. There are numerous sources of biomass that can be available at the local level, as shown in Table 5.4 [1]. Both plant matter and animal waste can be used in biomass systems.

Table 5.4 Biomass sources

Gasification	Bagasse, bamboo, cashew nut shells, coconut shells, cotton stalks, forest pruning, grass/bushes, maize cobs and stalks, rice husk, saw dust, wheat and millet straw, wood pulp
Biogas	Bread, cattle and pig manure, chicken litter, eggs, human excreta, slaughterhouse waste, stalks, straw, vegetables and grain leaves

[3] We use the term "plant matter" in a broader sense so that it includes all algae, even those species not classified as plants.

Most biomass calculations involve relating the required quantity of input feedstock to produce a certain amount of electrical energy. A critical factor affecting these calculations is the assumed moisture content of the feedstock. The moisture content of fresh cut trees by mass is about 50%. Moisture in manure is higher. Moisture makes up about 75% of the mass of chicken manure and 90% of pig manure. Moisture adds weight and volume, but does not contribute to the energy content of biomass. If the biomass is to be directly burned, then the moisture must be removed beforehand; otherwise the combustion will be inefficient and smoky. Moisture then not only does not contribute to the energy content of biomass, it requires energy to be removed. In applications requiring low-moisture biomass such as gasification and direct combustion, sun drying is an economical option. Sun drying can reduce the moisture of wood to about 10 to 15%. Doing so takes up space and requires oversight.

The energy content of biomass is usually based on the heat produced through combustion. This ranges from about 8 MJ/kg for freshly cut wood to 15 MJ/kg for dried wood [7]. Certain dried crops such as sugarcane and maize may release 18 MJ/kg when combusted. This is low compared to methane, whose specific energy is 56 MJ/kg. The heat released from combustion of dried manure is about 10 MJ/kg, but this varies across different animal species. Daily wet manure production varies from about 0.2 kg for a hen, 3.0 kg for a pig, and about 40 kg for a cow. The biomass yields from crops range from about 5 to 80 dry tonnes per hectare (10,000 m^2) per year, assuming one crop per year. There are many variables that affect the energy content and production rates of biomass, so the values presented in this section should be used for rough estimations only.

The relatively low specific energy of biomass makes its collection, transportation, and preparation burdensome. It is difficult to make a biomass system economically viable unless the biomass has already been concentrated [7]. Biomass is concentrated at agricultural and forest product processing facilities and animal enclosures. To limit transportation costs, the biomass facility should be located close to the feedstock source.

Example 5.7 The electricity requirements of a certain household are 401.5 kWh per year. A biogas system yields 0.3 m^3 of biogas for every 8 kg of input fresh (wet) pig manure. The energy density of the resulting biogas is 23 MJ/m^3. The biogas is used to power a gen set. The efficiency of the gen set is 20%. How many pigs are required if each pig produces 2.3 kg of fresh manure per day?

Solution The average daily electrical energy consumption of the household is

$$E_{\text{daily,elec}} = \frac{401.5\ \text{kWh/yr}}{365\ \text{days/yr}} = 1.1\ \text{kWh/day}.$$

(continued)

Each day the manure from a single pig produces biogas with volume:

$$V_{\text{gas,pig}} = 2.3\ \text{kg} \times \frac{0.3\ \text{m}^3}{8\ \text{kg}} = 0.0863\text{m}^3.$$

The biogas produced from each pig each day is converted to electrical energy according to

$$\begin{aligned} E_{\text{gas,pig}} &= 0.0863\text{m}^3 \times 23\ \text{MJ/m}^3 \times 0.20 \\ &= 0.397\ \text{MJ} = \frac{0.397\ \text{MJ}}{3.6\ \text{MJ/kWh}} = 0.110\ \ \text{kWh/pig/day} \end{aligned}$$

The total number of pigs required is therefore

$$\frac{1.1\ \text{kWh/day}}{0.11\ \text{kWh/day/pig}} = 10\ \text{pigs}.$$

The family must own at least ten pigs for this plan to work.

5.4.3 Biogas

Solid biomass is an inconvenient fuel source. Converting it into gas can increase its energy density and allow it to be efficiently used in gas turbines and gas engines. Biomass is converted to biogas—a mixture composed primarily of methane (CH_4) and carbon dioxide—through anaerobic digestion. The biogas can then be combusted in a gen set to produce electricity. It can also be used in a stove for cooking and for heating and lighting. Anaerobic digestion relies on microorganisms to process the biomass under oxygen-free conditions. Digestion occurs over a period time, usually tens of days. Little energy is consumed, and so the efficiency of converting the biomass to biogas is relatively high. Around 85% of the energy from the input biomass is available in the produced biogas. However, in most small-scale settings, and with shorter digestion times, the efficiency is closer to 60%[7].

Anaerobic digestion is a biological process, relying on various types of bacteria to occur. The general process can be broken down into three parts: (1) in *hydrolysis,* the complex organic polymers are broken down to form sugars, fatty acids, and amino acids; (2) during *acidiogenesis* and *acetogenesis,* the sugars, fatty acids, and amino acids are converted to acetates, single-carbon compounds, hydrogen, and carbon dioxide; and (3) in *methanogenesis,* bacteria produce biogas from the hydrogen, carbon and acetate [7, 8].

The basic reaction inputs are biomass and water, and the result is a mixture of carbon dioxide and methane. The reaction for a general organic polymer with *n*

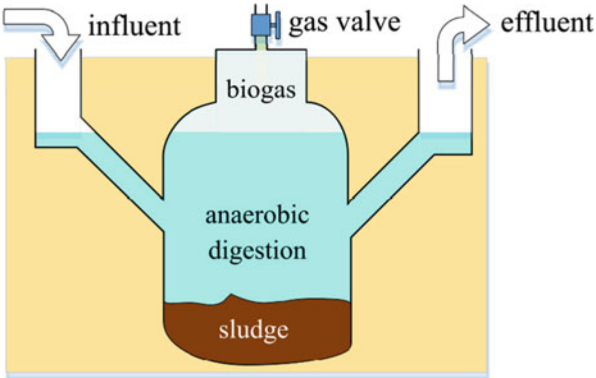


Fig. 5.14 Biogas digester vessel

carbon, *a* hydrogen and *b* oxygen atoms is

$$C_nH_aO_b + (n - a/4 - b/2)H_2O \rightarrow (n/2 - a/8 + b/4)CO_2 + (n/2 + a/8 - b/4)CH_4 \quad (5.15)$$

The resulting gas (biogas) is typically 50–80% methane by volume.

Anaerobic digestion is promoted by wet, dark, and warm—but not hot—conditions. The requirement of water in the reaction means that the input biomass is typically a slurry. The feedstock is often manure or crop waste. Woody biomass is not suitable for digestion due to its high content of lignin, which cannot be broken down by anaerobic bacteria. The high moisture content of manure makes it a convenient feedstock for creating biogas—if it were used to create synthesis gas or directly combusted, it would have to be dried.

Anaerobic digestion occurs in a reactor vessel called a "digester." The basic scheme is shown in Fig. 5.14. Digesters can be simply constructed. They are not exposed to high temperatures or require mixing, although some mixing can improve the yield of biogas. Digesters are commonly made from brick, concrete, and/or steel on or below ground, as seen in Fig. 5.15. Digesters should be gas tight, with a piping system to remove the biogas and a hatch to introduce additional biomass. For digestion to commence, the anaerobic bacteria must be introduced into the digester. This is called inoculation. Conveniently, the bacteria are naturally found in some manure.

The rate at which biogas is produced depends on the temperature in the digester. Increasing temperature promotes methane production—every 10°C increase in temperature approximately doubles the process speed. This reduces the physical size requirements of the digester. However, at around 60°C, the microbial activity quickly drops. Most digesters operate at temperatures between 30 and 40°C. A typical fermentation (digestion) period ranges from 10 to 30 days, depending on the feedstock and digester conditions. Each dry kilogram of biomass input will yield about 0.2 to 0.4 m^3 of biogas. Biogas has an energy content of approximately 20 to 23 MJ/m^3 at atmospheric pressure. This is lower than pure methane (28 MJ/m^3) due to the relatively high carbon dioxide content. A few cubic meters of biogas per

Fig. 5.15 A below-ground biogas digester being constructed in Malawi (courtesy P. Dauenhauer)

day is enough to meet the electricity requirements of a household. The minimum required volume of the digester is found from

$$Digester\ Volume = input\ flow\ (m^3/day) \times fermentation\ period\ (days). \quad (5.16)$$

Biogas can be produced in batches or continuously—with the removal and addition of perhaps 5% of the material per day. Continuous production tends to be more efficient. Biogas often contains of hydrogen sulfide, which should be removed before use in an internal combustion engine. The carbon dioxide can be removed by spraying the biogas with water. The residue from digesters using manure feedstock is a valuable fertilizer. In fact, this is a main motivator for using anaerobic digestion.

Because of their simplicity in construction and management, tens of millions of digesters have been deployed in rural settings. The digesters tend to be small, less than 10 m^3 in volume and cost just several hundred dollars to build. Most use the biogas for cooking and heating, not electricity generation.

5.4.4 Biomass Gasification

Biomass gasification differs from biogas production in that thermal-chemical reactions rather than a biological process are used [2, 4, 6, 7]. The resulting product is a gaseous fuel, known as "synthesis gas" or simply "syngas." The term "bio syngas" is also used to distinguish it from syngas derived from other processes. The exact nature of the syngas depends on the specific process used. The gasification process is complex but fundamentally involves the use of heat, steam, and oxygen

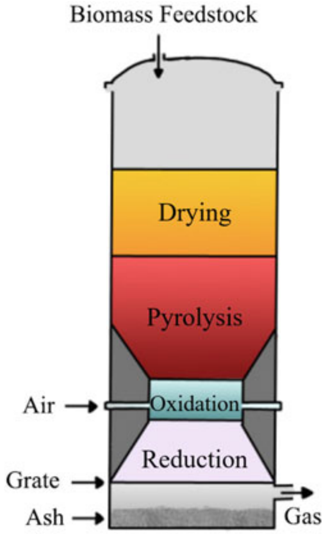


Fig. 5.16 Downdraft biomass gasification process

to convert the biomass to syngas. Syngas is composed primarily of hydrogen and carbon monoxide, with some carbon dioxide, and a small amount of methane.

It is important that the feedstock has low moisture content. Crop residue and woody biomass are often used. The basic gasification reaction using glucose as an example is

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow xCO + yCO_2 + zH_2 + \text{other species}. \tag{5.17}$$

Note that the relative quantities of carbon monoxide, carbon dioxide, and hydrogen vary.

Biomass gasification occurs in a reactor (also known as a “gasifier”), which itself resembles a large metal vessel. Most reactors in rural electrification applications are of the fixed-bed type, of which there are several varieties including updraft, downdraft, and cross-draft. We shall consider the downdraft variety shown in Fig. 5.16. Downdraft gasifiers are best-suited for the small-scale systems used in off-grid electrification. These are typically between 10 and 100 kW of capacity.

Prior to gasification, the biomass must be prepared. This typically involves harvesting, cutting to size, and sun drying. It is then loaded into the top of the reactor. The top of the reactor is at an elevated temperature—100 to 160°C—due to the reactions occurring below. The elevated temperature dries the biomass further. As we proceed down into the reactor, the temperature increases and there is less air (due to the biomass above and below it). As the biomass temperature reaches several hundred degrees Celsius, pyrolysis occurs. Recall from Sect. 2.4.2 that pyrolysis is the thermal-chemical process used to manufacture charcoal. Volatiles and tar are produced, including methane and hydrogen. The remaining biomass is known as “char,” which is primarily carbon.

As we continue down the reactor, we reach a section where air is introduced. Oxidation occurs as the air reacts with the carbon in the char, producing heat and carbon dioxide

$$C + O_2 \rightarrow CO_2. \quad (5.18)$$

The temperature in this section is the highest. Only a portion of char is converted to carbon dioxide. The heat produced by the oxidation in (5.18) supplies energy for the remaining char to react with steam. The steam comes from various sources: residual moisture in the biomass, in the introduced air, and the combination of hydrogen and oxygen gases. The reaction between char and steam forms hydrogen and carbon monoxide in the following reduction reaction

$$C + H_2O \rightarrow H_2 + CO. \quad (5.19)$$

The resulting syngas is at high temperature ($>700°C$). It is removed near the bottom of the reactor. The leftover ash collects at the bottom of the reactor where it is periodically removed. The resulting gas must be filtered to remove ash and tar. The syngas must also be cooled before it can be used in a combustion engine. These processes create waste which must be appropriately managed and also require a reliable source of water.

The energy content of syngas is typically 3 to 6 MJ/m^3; the low end of this range is appropriate for syngas made in smaller-scale settings. This is much lower than natural gas (approx. 30 MJ/m^3) and biogas. The energy content can be increased to 10 to 19 MJ/m^3 by injecting steam or oxygen instead of air during the oxidation stage. But this adds to the cost and complexity and is not typically done in small-scale systems. For each kilogram of dried input biomass, approximately 1.5 m^3 of syngas is produced.

The efficiency of gasification is determined by dividing the energy content of the syngas produced by the energy in the biomass consumed. This is known as the "cold gas efficiency," as it ignores the thermal energy of the syngas. The cold gas efficiency is typically between 20 and 70%. Again, small-scale gasifiers tend to have efficiencies on the low end of the range. This does not include the efficiency losses in the engine and generator.

Biomass gasification units are commercially available. They typically range from tens of kilowatts to a few hundred kilowatts in capacity. Electricity generation from biomass gasification has proven technically and economically successful in certain areas of South Asia. India is reported to have installed over 150 MW of gasification-based power plants, most of which are tens of kilowatts in capacity or less.

Syngas can be directly combusted in a gas turbine or gas engine to drive a generator. Engines designed to run on petrol or diesel can be modified to run on syngas, although their rated power is usually decreased. It is also common to use a mixture of syngas and diesel in an engine. In this "dual fuel" mode, diesel serves as the pilot fuel, and the syngas is mixed with the air prior to combustion. This relatively easy to implement modification can reduce diesel consumption by 80%.

Example 5.8 Consider a biomass gasification system serving 400 houses. Each house consumes 300 Wh of electricity per day. The gasification system is 60% efficient, and the combined efficiency of the engine and generator is 33.3%. The energy content of the dry husk feedstock is 12.6 MJ/kg, which costs US$25 per metric ton. Compute the mass of husk required each day and cost of fuel per kilowatthour of electricity consumption.

Solution The solution process requires several conversions. The daily electrical demand, expressed in megajoules, is

$$(0.300 \times 400)\,\frac{3.6\ \text{MJ}}{1\ \text{kWh}} = 432\ \text{MJ}.$$

The required energy content of the input husks is found by accounting for the efficiency of the gasification and the engine/generator:

$$432 \times \frac{1}{0.6 \times 0.333} = 2162.2\ \text{MJ}.$$

The total mass of husk required each day is therefore

$$2162.2 \times \frac{1\text{kg}}{12.6\text{MJ}} = 171.60\ \text{kg}.$$

The cost of a single kilogram of husk is US$0.025. Therefore, the cost per day is

$$171.60\ \text{kg} \times \text{US\$0.025/kg} = \text{US\$4.29/day}.$$

The cost per kilowatthour is

$$\frac{\text{US\$4.29}}{0.30\ \text{kWh/house/day} \times 400\ \text{houses}} = \text{US\$0.0358/kWh}$$

At a glance, the fuel cost per kilowatthour provided by this system is favorable to grid-provided electricity. However, the fuel cost does not include capital or other operational costs.

5.4.5 Solid Biomass Direct Combustion

Biomass can also simply be combusted to produce heat. The energy released is used to create steam, which drives a steam turbine. The steam turbine is coupled to a generator. This scheme is only practical for larger-capacity systems, typically hundreds of kilowatts to about 20 MW. Solid biomass direct combustion systems are commonly colocated in agricultural and forest product processing facilities. The crop and forest waste serves as a feedstock, eliminating the need for their removal, and a portion of the heat and steam produced can be used in the processing facility. This arrangement is known as "co-generation" or "combined heat and power" (CHP). CHP should be considered whenever possible—it makes use of heat that would otherwise be wasted. Some of the electricity is used to power the facility; any excess can be used to supply a mini-grid.

The biomass used in direct combustion applications must be processed. This typically includes chopping and drying. Like gasification facilities, direct combustion facilities required trained technicians to manage the process.

5.4.6 Practical Considerations

The use of biomass for off-grid electricity generator offers several advantages, depending on the process:

- plant-based biomass can be considered a renewable resource if the rate of use does not exceed the rate of plant growth;
- some biomass processes produce a number of usable by-products, including fertilizer;
- biomass systems can make use of waste products that otherwise would have to be removed from a facility;
- biomass fuels can be stored, allowing generators to produce power on demand;
- in direct combustion systems operating as CHP facilities, the waste heat and steam can be used locally for agricultural or manufacturing processes;
- the collection, transportation and processing of biomass creates employment at the local level and can improve cash flow in rural areas.

The disadvantages include:

- maintaining a consistent supply chain of biomass is problematic; many crop-based agricultural inputs are seasonal and a biomass system might be unable to operate at full capacity during certain times of the year;
- managing digesters, gasifiers, and direct combustion systems requires some training and, in some cases, full-time operators;
- certain biomass processes require waste to be removed;
- certain biomass processes require a reliable source of water;

- the price of the feedstock can be volatile—it should not be assumed that crop residue and other wastes can be obtained for free;
- biomass systems coupled with an agricultural or forest processing facility will likely not continue to be economically viable if that facility shutters.

From a broader perspective, biomass has many uses including as food, to prevent erosion, and as raw material. Replacing food crops or converting forest land to grow biomass crops should generally be avoided.

5.5 Summary

This chapter provided the basic technical principles and characteristics of generators and internal combustion engine-coupled generator sets using conventional and biomass fuels. A generator outputs AC voltage whose magnitude and frequency depend upon the rotational speed of the rotor. Matching the required generator speed with the speed-power or efficiency curve of the prime mover is an important design consideration.

Voltage is induced in a generator's armature windings using a rotating electromagnet. An exciter is used to supply current to the electromagnet. An Automatic Voltage Regulator can be used to control the terminal voltage of the generator. If the load increases without a similar increase in the mechanical power supplied to the generator, then the rotational speed will decrease; similarly, if the load decreases, the speed will increase. The voltage frequency and voltage magnitude are proportional to the generator's rotational speed. It is important for AC-coupled generators to be operated at constant speed, for example, using a governor, and have voltage control. Generators are most efficient when operating at or near their rated power.

Gen sets use internal combustion engines as their prime mover. The engine can either be spark ignition or compression ignition. Gen sets are relatively inexpensive compared to other energy conversion technologies but are more expensive to operate due to high fuel costs. Their fuel consumption can be decreased by operating them at or near full load for shorter periods of time rather than lightly loaded for longer periods of time.

Biomass can be converted to fuels suitable for use in internal combustion engines using anaerobic digestion to produce biogas or gasification to produce syngas. Biogas is primarily methane and carbon dioxide; syngas is primarily hydrogen and carbon monoxide. Biomass can also be directly combusted and used in steam turbines. Biomass systems critically rely on a consistent supply of its feedstock, which can be forest products, crops and crop residue, or animal excrement.

Problems

5.1 Compute the rotational speed in RPM and radians per second, and the torque of a four-pole generator whose developed electrical power is 10 kW at 60 Hz.

5.2 Consider a three-phase 20 kVA gen set whose line-to-neutral induced voltage is $\boldsymbol{E}_\mathrm{a} = 223\angle 0°$ V. The single-phase current supplied is $\boldsymbol{I}_\mathrm{a} = 35\angle -60°$ A. The armature impedance is $0.6 + \mathrm{j}3.6\ \Omega$. Compute the terminal line-to-neutral voltage and the total (three-phase) apparent power provided to the load.

5.3 Repeat Problem 5.2 but with $\boldsymbol{I}_\mathrm{a} = 35\angle 60°$ A.

5.4 A large mini-grid is expected to have a daily load of 980 kWh. Assume the energy is consumed at a constant rate throughout the day. Let the fuel cost be US$1.25/liter. Three options are being considered to serve the mini-grid:

- five equally loaded 10 kW gen sets;
- one 50 kW gen set;
- one 100 kW gen set.

Compute the annual cost associated with each design. Refer to Table 5.2 for the fuel consumption for each gen set. Assume the fuel consumption varies linearly between the loading percentages given in Table 5.2.

5.5 Describe the difference in the processes that convert solid biomass to biogas and to syngas.

5.6 A biogas system is being planned for a community. The system should be sized to provide 12 kWh/day of electricity. The biogas is expected to have a density of 20 $\mathrm{MJ/m^3}$. Determine the volume of biogas that must be supplied each day to a gen set whose efficiency is 19%.

5.7 The feedstock to a gasification system is bagasse (sugarcane crop residue). Each day 1000 kg of the feedstock is available. After drying, the dried sugarcane's specific energy is 16.5 MJ/kg. Compute the energy available for input to the gasification system if the moisture content of bagasse is 40%.

5.8 Consider the gasification system in Problem 5.7. Assume the efficiency of the gasification process is 50% and the gen set efficiency is 24%. Compute the daily electrical energy provided by the system.

5.9 A mini-grid is to be implemented for the community of Ababju. The community has 500 households. Each household is expected to consume 600 Wh per day. Assume the power consumption is constant throughout the day. The mini-grid will be powered using two 10 kW gen sets. Let the price of diesel be US$1.35/liter. Perform the following analyses:

- Compute the annual fuel cost of the gen sets. Assume the gen sets are equally loaded and the fuel consumption is in Table 5.3 (use linear interpolation between the data points). Repeat this calculation if one gen set is fully loaded and other is loaded such that the required power is supplied. Comment on which loading strategy is more fuel efficient.

- The crop resource around Ababju has a specific energy of 15.4 MJ/kg (dry) and costs US$0.02/kg (dry). A gasification system with an efficiency of 57% can be used to convert the biomass to syngas. The syngas will be used in a dual-fuel gen set. The energy supplied to the gen set is 60% from syngas and 40% from diesel. Compute the annual fuel cost (biomass plus diesel) of using this system to power the mini-grid if the gen sets are equally loaded and if one gen set is fully loaded and other is loaded such that the required power is supplied.

References

1. Bhattacharyya, S.C. (ed.): Rural Electrification Through Decentralised Off-Grid Systems in Developing Countries. Springer (2013)
2. Boyle, G. (ed.): Renewable Energy, 2nd edn. Oxford University Press (2004)
3. Caton, J.: An Introduction to Thermodynamic Cycle Simulations for Internal Combustion Engines. Wiley (2016)
4. Goswami, Y. (ed.): Alternative Energy in Agriculture, vol. 2. CRC Press (1983)
5. McLean, G.: Chapter 5 - generators. In: Warne, D. (ed.) Newnes Electrical Power Engineer's Handbook, 2nd edn., pp. 105–133. Newnes, Oxford (2005). doi:https://doi.org/10.1016/B978-075066268-0/50005-6. URL http://www.sciencedirect.com/science/article/pii/B9780750662680500056
6. Sørensen, B.: Renewable Energy, 3rd edn. Elsevier Academic Press (2004)
7. Twidell, J., Weir, A.: Renewable Energy Resources, 2nd edn. Taylor & Francis (2006)
8. Wilkie, A.C.: Biomethane from biomass, biowaste, and biofuels. In: Bioenergy, pp. 195–205. American Society of Microbiology (2008). URL http://www.asmscience.org/content/book/10.1128/9781555815547.ch16
9. Wong, E., Whitall, H., Dailey, P.: Distributed Generation: The Power Paradigm for the New Millennium, chap. 2. CRC Press (2001)