

# Chapter 4

## Off-Grid System Architectures



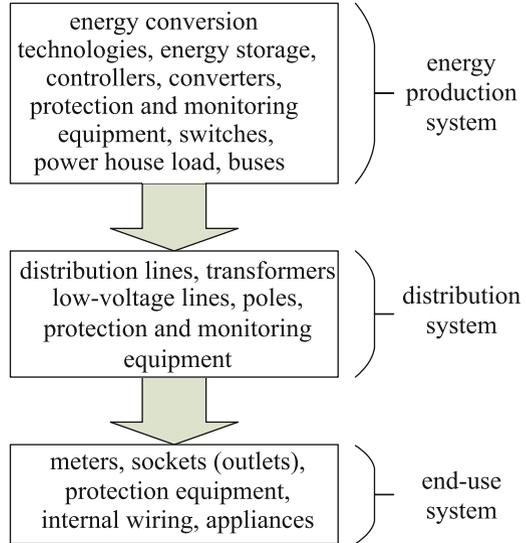
### 4.1 Introduction

As discussed in Chap. 3, the most obvious and direct way to provide electricity to an unserved area is through a connection to the national grid. This may be impractical though, if the community in need of service is too far from the existing grid and/or the load is too little to justify the infrastructure investment. In cases such as these, off-grid systems should be considered. This chapter is concerned with mini-grid systems for off-grid electrification. Solar home systems and solar lanterns are discussed in Chap. 13. By some estimates, as many as 140 million people in Africa alone could be served by mini-grids by 2040 [1]. Scaling to this level will require between 100,000 and 200,000 systems.

The basic function of a mini-grid is to produce and distribute electricity to users in a limited geographic area. The mini-grid is designed to meet the desired electricity access tier. Recall that electricity access tiers are a way of describing the overall quality of the electricity service, as discussed in Sect. 2.7. At a minimum, a mini-grid contains at least one energy source and one load. More complex systems may include multiple sources, energy storage, converters, and controllers and are able to supply AC and DC loads. Other components such as protection devices and monitoring equipment may be present but are not discussed here for the sake of brevity.

Mini-grids can be separated into three systems: energy production, distribution, and end use, as seen in Fig. 4.1. Each system is associated with a separate set of components. Most of the energy production components are located inside a “power house.” This may be a dedicated stand-alone structure, or a room inside a building such as school or hospital. Repurposed shipping containers have also been used. The distribution system components connect the energy production system to the end users by way of overhead or underground lines. Larger-capacity mini-grids might

**Fig. 4.1** The three systems of a mini-grid



use medium-voltage distribution lines and transformers; however, most mini-grids use low-voltage distribution. Much of this book, including this chapter, is concerned with the energy production system.

The architecture of a mini-grid refers to how its various components are connected together to form a complete system. There are a variety different mini-grid architectures. For the moment, we are not concerned with the technical details of how the individual components function. Rather, we are interested in how they function at a macro-level and how they can be used as building blocks to form a mini-grid.

## 4.2 Terminology

There is yet to be a universally accepted set of terminology when describing off-grid systems. For example, there is no precise boundary between mini-grids and micro-grids, and any exact definition would be somewhat arbitrary.

However, the use of consistent terminology reduces confusion. The following terms are commonly used in academic literature [2].

- Centralized system (national grid): a large power system that is often a state-owned, vertically integrated and regulated monopoly with centralized control and coordination of generation, transmission, and distribution. Such systems typically serve a large geographic area.
- Decentralized system: composed of autonomous units where generation and distribution have no centrally coordinated interaction with other units.
- Off-grid: an electrical system which is detached from the national grid.

**Fig. 4.2** A small-scale, decentralized, hybrid mini-grid using wind and solar power in Muhuru Bay, Kenya (courtesy E. Patten)



- Small-scale: a system whose power production rating does not exceed 5 MW (a mini-grid of this size is actually quite large—it could likely serve several thousand rural households).
- Hybrid: an off-grid system using two or more types of energy conversion technologies to produce electricity.
- Conventional generation: generators that run solely on fossil fuels (usually diesel or gasoline).
- Stand-alone: a system that serves a single user such as a solar home system or solar lantern, typically rated at less than 1 kW.
- Mini-grid: an off-grid system that serves multiple users, typically rated at less than 100 kW and often less than 10 kW.

The mini-grids used in rural electrification tend to be off-grid and small-scale. Many are decentralized. Hybrid mini-grids are common, but not universal. Many of the architectures discussed also apply to stand-alone systems. An example of a small-scale, decentralized, hybrid mini-grid using both wind and solar power is shown in Fig. 4.2.

### 4.3 Mini-Grid Building Blocks

The basic building blocks of a mini-grid are:

- Energy conversion technology
- Load
- Energy storage
- Converter
- Controller

A basic description of these components is provided in the following sections.

**Table 4.1** Common energy conversion technologies for off-grid systems

Energy source	Conversion technology
Biomass	Internal combustion engine, steam turbine
Hydro	Hydroturbine
Natural Gas/LPG	Internal combustion engine
Petroleum/Diesel	Internal combustion engine
Solar	Photovoltaic (PV) module
Wind	Wind turbine

### 4.3.1 Energy Conversion Technologies

Electric generators of all sorts convert other forms of energy into electricity. Diesel generators, wind turbines, and solar panels all do this. We broadly and generically refer to these types of devices as *energy conversion technologies*. For example, a wind energy conversion system converts the kinetic energy in a mass of moving air to electrical energy, and a diesel generator converts the chemical energy in hydrocarbons to electrical energy. The energy sources and associated conversion technologies typically encountered in mini-grids are listed in Table 4.1. There are other sources and conversion technologies such as geothermal and solar–thermal that might be practical for large-scale electricity generation, but not for small-scale mini-grids. Other technologies such as tidal and wave are not mature or require very particular local conditions to be viable.

Other components such as gear boxes, generators, and controllers are needed to produce electricity. To highlight this, we use the terms “gen sets,” “wind energy conversion systems” (WECS), and “micro hydro power” (MHP) instead of “internal combustion engines,” “wind turbines,” and “hydroturbines.” The selection of the energy conversion technology—or technologies in a hybrid system—largely depends on the availability of the energy source, its capital and operation costs, and the reliability and availability requirements of the load.

### 4.3.2 Loads

The term “load” has multiple meanings in electrical engineering. It commonly refers to the power or energy required by a component or the physical component itself. The context often makes it obvious which meaning is being used. The following description uses the latter meaning.

A load is an end-use device that consumes electrical energy. Lights, mobile phone chargers, and appliances such as refrigerators, computers, televisions, pumps, heaters, and motors are examples of loads. Components whose primary function is to distribute, store, or convert electricity are generally not considered loads. A rectifier, which converts AC to DC, would be an example of such a component. Power absorbed by components such as these is not consumed by the end user, and so it is separately categorized as a loss within the system.

Loads can be classified as being AC or DC. Some mini-grid architectures can only supply AC loads, some only DC, and some can supply both. AC loads must be supplied by an AC source whose voltage magnitude and frequency are within certain ranges to operate properly; similarly, DC loads must be supplied by a DC source of appropriate magnitude and polarity for proper function.

### ***4.3.3 Energy Storage***

Mini-grids incorporate energy storage to improve their availability and reliability. Energy storage allows the load to exceed the generation for some period of time. Energy storage is optional in some mini-grid architectures but is especially important in those powered by solar and wind energy. The most common form of energy storage in mini-grid systems is an electrochemical battery. Most often, lead-acid batteries are used, but lithium-ion batteries are now becoming popular.

### ***4.3.4 Controllers***

Controllers affect how components of mini-grids operate and interact with each other. Controllers are used to:

- manage the charging and discharging of batteries by regulating their terminal voltage so that the battery lifespan is prolonged;
- regulate the frequency of the system voltage and mechanical revolution speed of the generators;
- regulate the magnitude of the AC voltage;
- maximize the power production from photovoltaic arrays and wind turbines;
- synchronize and manage how power is allocated from generators and inverters connected in parallel;
- coordinate the interaction of different components.

Controllers increase the capital cost and complexity of a mini-grid. These initial the costs are often justified, particularly as system size increases. Controllers increase the lifespan of components and quality of the electricity service. Off-grid system control is further discussed in Chap. 10.

### ***4.3.5 Converters***

Most modern controllers use electronic devices to function. Often, they use a converter to achieve the desired control action. Examples of converters include rectifiers, which convert AC to DC; inverters, which convert DC to AC; and DC-

DC converters, which change the magnitude of a DC voltage source. These devices are power electronic-based converters. The converters used in off-grid systems are described in detail in Chap. 9. Transformers are sometimes used in mini-grids serving large geographic regions where voltage drop and losses are a concern.

## 4.4 System Coupling

The various mini-grid building blocks can be connected in several ways. One common way of categorizing mini-grid architectures is based on how the components are coupled. There are three types of coupling: AC, DC, and AC–DC. The type of coupling depends on how the *energy sources* are connected, independent of whether the load is AC or DC.

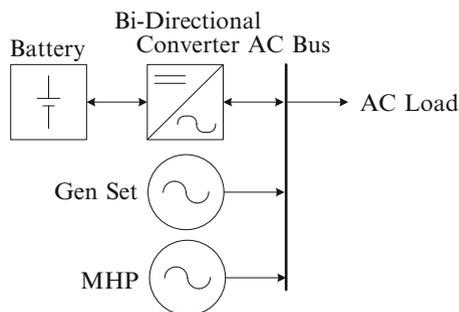
### 4.4.1 AC Coupling

The central feature of an AC-coupled mini-grid is the AC bus, as shown in Fig. 4.3. Note that the schematics shown in this chapter are intended to be illustrative only—it is possible, for example, for an AC-coupled system to have somewhat different components. The schematics show the high-level connection of the components, with the arrows indicating the possible flow of power. For clarity, the distribution and end-use systems are not shown. Do not confuse the schematics with circuit models, even though at times the same symbols are used in both.

In electrical terms, a *bus* is simply a node in the system where various components are connected. National grids can have thousands of buses; mini-grids often have just one. The AC Bus is often just a copper bar inside the circuit breaker box with several cables and switches or circuit breakers attached.

All the components connected to the AC bus are in parallel, and so they operate at the same voltage frequency and magnitude. This means that the voltage output by the generators must be synchronized. Synchronization is discussed in Chap. 10.

**Fig. 4.3** Example of an AC-coupled mini-grid



DC components cannot be used unless they are connected to the AC bus through a rectifier or an inverter. The voltage frequency and magnitude at the AC bus should be approximately constant. Certain sensitive loads cannot tolerate deviations beyond a few percent without damage or malfunction. Other loads such as heaters and incandescent lights are more robust and can tolerate variation in the voltage and frequency.

Control of the AC bus voltage frequency and magnitude is an important aspect and consideration of AC-coupled systems. Normally, one component is controlled so that it resembles a voltage source. This component is said to be “forming” the AC bus. The other sources must be able to synchronize to the AC bus voltage and are controlled as current sources to inject power into the bus.

For reasons discussed in the next chapter, only energy conversion technologies capable of adjusting their power output on demand and that have a voltage control system can be used to form the AC bus. This functionality is usually found in conventional- and biomass-fueled internal combustion engines and certain MHP systems. Inverters are also capable of forming the AC bus. One reason why WECSS and PV modules cannot be used to form the AC bus is that they are only capable of producing power when there is sufficient wind speed or sunlight. However, they can be integrated into the system as long as some other source forms the AC bus voltage. AC-coupled systems can be easily expanded by connecting additional load and generation to the AC bus.

### ***4.4.2 DC Coupling***

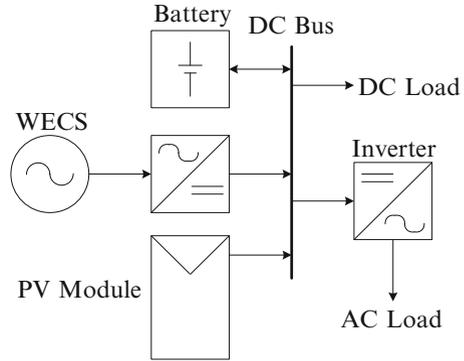
In DC-coupled systems, the energy sources are connected in parallel at a DC bus. In most off-grid systems, there is a single DC bus, as shown in Fig. 4.4. DC-coupled systems almost always include a battery. AC components must include an inverter or rectifier to be integrated into a DC-coupled system. The battery sets the DC bus voltage. Although the problem with forming and maintaining the frequency of the AC bus is eliminated (unless multiple inverters are connected in parallel), the battery must be protected from being over- or undercharged.

For this reason, a system with a DC bus should have charge controllers or diversion loads and diversion load controllers. A charge controller limits the current supplied by a source; a diversion load provides a parallel path for the current, reducing the current into the battery. The DC-coupled architecture is used in smaller-capacity mini-grids and in solar lanterns and solar home systems. Expanding a DC-coupled grid to serve additional AC load is problematic because it might require a larger-capacity inverter.

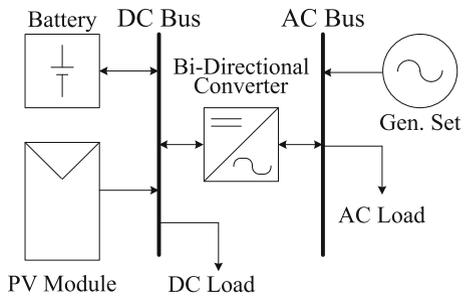
### ***4.4.3 AC–DC Coupling***

An AC–DC-coupled architecture includes at least one AC-coupled source and at least one DC-coupled source, as shown in Fig. 4.5. It offers the most operational

**Fig. 4.4** Example of a DC-coupled mini-grid



**Fig. 4.5** Example of an AC-DC-coupled mini-grid



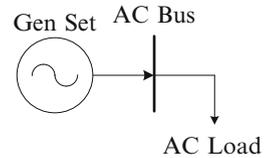
flexibility. In this architecture there are at least two buses: one AC and one DC. The buses are coupled through converters. The flow can be one directional, DC to AC or AC to DC, or bi-directional. The AC-DC-coupled architecture is used in many hybrid mini-grids.

The decision to use a particular architecture is dictated by the choice of energy conversion technology and load. Most often we select the architecture that (1) minimizes AC/DC and DC/AC conversion so as to reduce losses and (2) has the fewest overall components to reduce the cost and complexity. This naturally suggests that systems with AC sources and loads use AC-coupled architecture and those with DC sources and loads use DC-coupled architectures. Hereafter we describe some of the more common AC-, DC-, and AC-DC-coupled architectures.

### 4.5 Conventional or Biomass Internal Combustion Engine Generator Systems

In this common and simple AC-coupled architecture, a gen set supplies an AC load, as shown in Fig. 4.6. The generator forms the AC bus. The power output is adjusted to regulate the AC bus frequency by controlling the flow of fuel or air to the engine. The power supplied by the gen set flows to the AC bus—which in practice is an

**Fig. 4.6** Architecture of an internal combustion engine generator system



outlet or perhaps a distribution box similar to that found in homes—and then to the connected loads. There is usually no need for a transformer or other conversion equipment between the generator and load. The architecture is the same whether the gen set is fueled by a conventional fuel or a biomass-derived fuel.

Gen sets can be readily obtained in most areas and have low up-front capital cost but high fuel costs. This architecture is suitable in applications where reliable or on-demand power is needed, but total energy use is low. For example, an off-grid system for a community center that only requires electricity for special occasions is well-served by this architecture. The architecture is more common in areas with low fuel costs, perhaps through government subsidy.

## 4.6 Photovoltaic Systems with DC Load

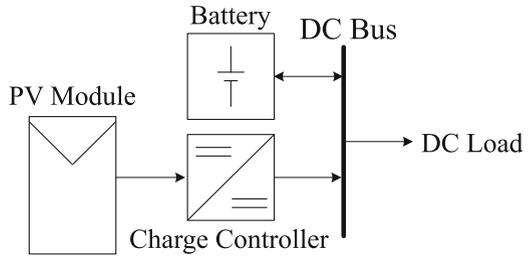
This DC-coupled architecture consists of photovoltaic (PV) modules and a battery. In its most basic configuration, it only supplies DC loads. The architecture is used in solar home systems and solar lanterns. It is conceptually simple and its components are readily available. PV modules naturally output DC current. The battery provides a stable DC voltage, which many electronic loads require, and allows the system to provide electricity in the evening and in periods of low irradiance (sunlight). The battery is charged when the current from the PV module is in excess of the load current and is discharged when the load current exceeds that of the PV module.

In engineered systems, a charge controller, as shown in Fig. 4.7, is included. The role of the charge controller is to prevent the battery from being overcharged. Some charge controllers also prevent the battery from being discharged. In some PV systems, a component known as a “maximum power point tracker” is connected between the charge controller and the PV module. This electronic device adjusts the operating voltage of the PV module to improve its power production.

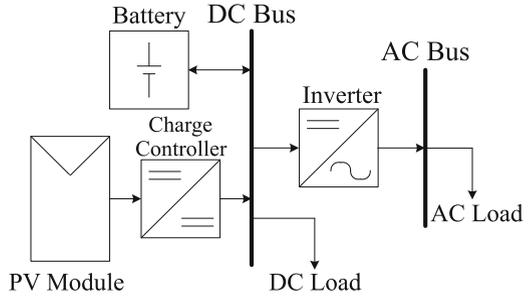
## 4.7 Photovoltaic Systems with AC Load

An inverter is required to serve an AC load from a PV system. This is shown in Fig. 4.8. In this architecture, the inverter forms the AC bus. The inverter converts DC to AC at a specific frequency and voltage, typically 50 Hz and 230 V, depending on national standards. The inverter mimics the AC voltage in the national grid

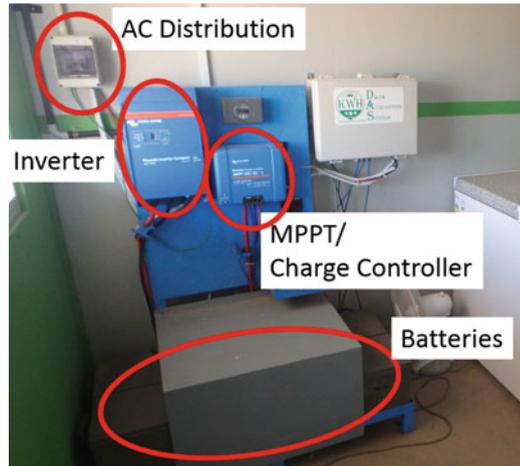
**Fig. 4.7** Architecture of a photovoltaic system with DC load



**Fig. 4.8** Architecture of a photovoltaic system with AC and DC load



**Fig. 4.9** Storage, control and converter components of a 2.25 kW PV system with AC load (courtesy of KiloWatts for Humanity)



so that appliances mass manufactured for the grid-connected market can be used. These are usually less expensive and more widely available than DC appliances. The components of a 2.25 kW mini-grid, excluding the PV array, are shown in Fig. 4.9. This system does not have DC load.

## 4.8 Wind Energy Conversion Systems

As discussed previously, a WECS cannot form the AC bus. Instead, they are often used in DC-coupled systems, as shown in Fig. 4.10. Most WECSs output AC, and so a rectifier is required to couple them to the DC bus. The battery provides voltage stability and allows for on-demand electricity when the wind speed is insufficient to power the load.

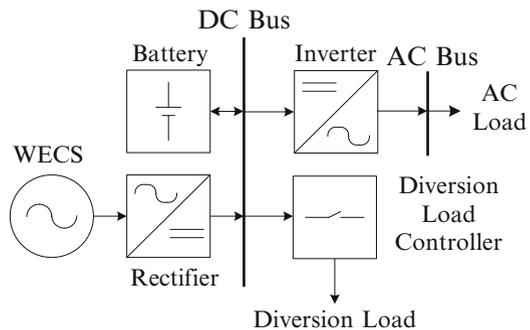
For reasons discussed in Chap. 10, systems with DC-coupled WECSs incorporate a diversion load and a dedicated diversion load controller to prevent overcharging the battery. The controller connects a diversion load—a resistor with a high power rating—in parallel with the battery so that the current from the WECS divides between the battery and diversion load.

## 4.9 Micro-Hydropower Systems

MHP systems can be AC-coupled and DC-coupled or used in AC–DC-coupled architectures. For systems with capacity less than approximately 5 kW or with irregular water flow, DC-coupled architectures are often used. The architecture mimics that of the wind turbine system in Fig. 4.10, with the hydroturbine replacing the wind turbine. The power house of an AC-coupled MHP system is shown in Fig. 4.11.

In larger-capacity systems with consistent flow, the AC-coupled architecture is common. The AC bus voltage is formed by controlling the excitation system of the MHP system, and the frequency is maintained by using either a mechanical governor, which adjusts the water input to the turbine, or an electronic load controller (ELC) and ballast load. The ELC and ballast load are conceptually similar to a diversion load controller, and diversion load, but are coupled to the AC bus. Unlike a governor, which controls the power output of the MHP system to maintain the AC bus frequency, the ELC controls the power to a load. A system using an ELC and ballast load is shown in Fig. 4.12. If a governor is used, then the system is as in Fig. 4.6, with the MHP system replacing the gen set.

**Fig. 4.10** Architecture of a wind turbine system



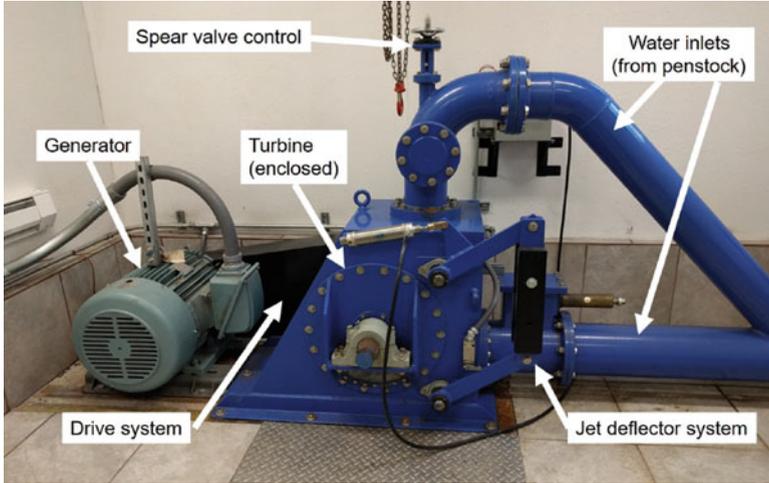
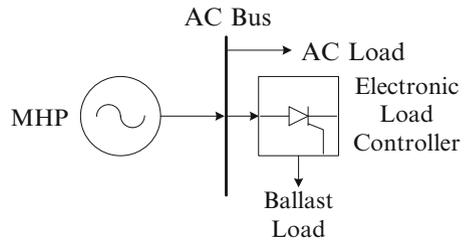


Fig. 4.11 A 25 kW AC-coupled MHP system using a two-jet Pelton turbine (courtesy of author)

Fig. 4.12 Architecture of an AC-coupled MHP system



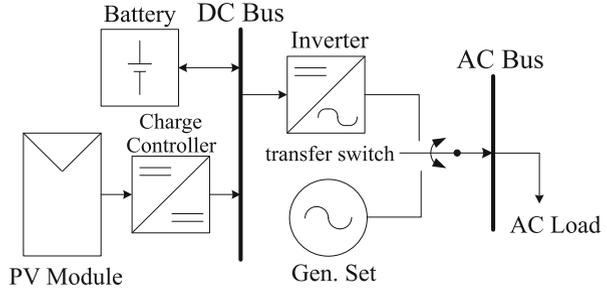
### 4.10 Hybrid Systems

Hybrid systems use two or more different energy conversion technologies for electricity production. Although the term “hybrid” is general, it is most often applied to systems in which one of the sources is a conventional gen set and another is a renewable source. Hybrid systems diversify the energy sources, which can improve reliability and lower operating and capital costs. However, they are more complex to design and operate.

#### 4.10.1 Hybrid Conventional Gen Set/PV Systems

In this AC–DC-coupled architecture, a conventional gen set is coupled with a PV module to serve an AC load. In some systems, the gen set is always or almost always running, in which case the energy produced by the PV array reduces the

**Fig. 4.13** Architecture of a switched hybrid system utilizing a gen set as a backup supply



fuel consumption. In others, the gen set is only operated as a backup, recharging the batteries or to supplying power if the load becomes especially large. There are several possible sub-architectures that can be used, as discussed next.

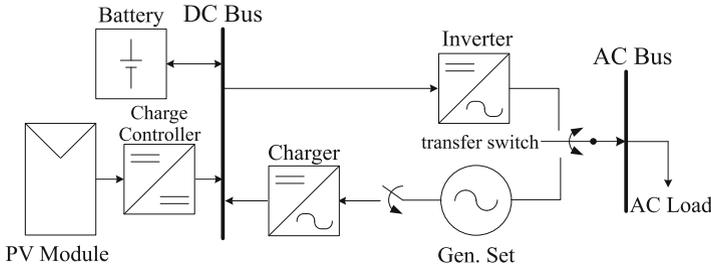
#### 4.10.1.1 Switched Architecture: Gen Set Backup

Figure 4.13 shows the simplest hybrid gen set/PV architecture. It mimics the architecture of a PV system with AC load. However, there is a transfer switch that connects the gen set to the load while disconnecting the inverter. In other words, the load is served by either the generator or the inverter, not both. There is no need to synchronize the inverter and gen set. The transfer switch can be manually operated or automatic.

#### 4.10.1.2 Switched Architecture: Gen Set Backup with Battery Charging

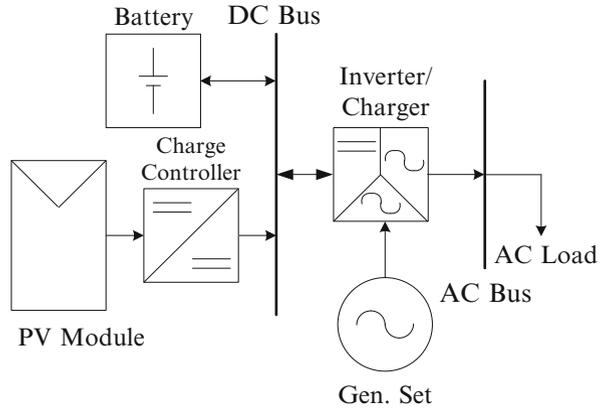
The switched architecture can be modified as shown in Fig. 4.14 to allow the gen set to charge the battery, even as it is serving the load. This prevents the battery from being undercharged. A rectifier and charge controller, perhaps integrated into the same unit, are needed. Simultaneously supplying the load and recharging the battery can improve the efficiency of the gen set, saving fuel. As with the previous architecture, either the gen set or the inverter supplies the load.

Some systems will use the gen set only for battery charging, eliminating the transfer switch altogether. In this architecture, the inverter exclusively serves the load. Because the AC load is never directly supplied by the gen set, a smaller-capacity gen set can be used. A drawback is that all of the energy provided by the gen set is converted from AC to DC—and potentially stored by the battery—and back to AC. These extra conversion steps are inefficient.



**Fig. 4.14** Architecture of a switched hybrid gen set/photovoltaic system where the gen set can be used to charge the battery or supply power directly to the load

**Fig. 4.15** Architecture of a hybrid gen set/photovoltaic system where the gen set can simultaneously charge the battery and supply power to the load



**4.10.1.3 Architecture with Battery Charging**

The hybrid architectures discussed so far do not allow the AC load to be simultaneously supplied by the gen set and inverter. This functionality is useful when the load occasionally exceeds the power output capability of either the gen set or inverter alone.

Simultaneous supply is possible using the architecture in Fig. 4.15. It requires an inverter that can synchronize its output to that of the gen set. The gen set can charge the battery through a rectifier and charge controller similar to that of Fig. 4.14. However, rather than using a separate rectifier and charge controller, a bi-directional inverter is used, as shown in Fig. 4.15. A bi-directional inverter facilitates power flow to and from the DC bus, allowing the gen set to charge the battery. A charge controller, which is often integrated into the same unit as the bi-directional inverter, is used to manage the charging of the battery from the gen set. Alternatively, the gen set can be directly connected to the AC bus, with the bi-directional inverter facilitating power flow to the DC bus.

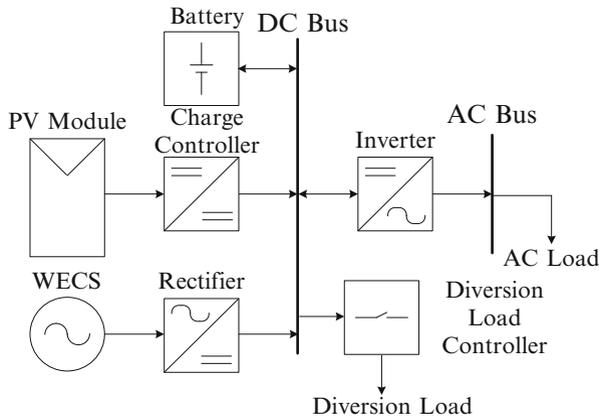


Fig. 4.16 Architecture of a hybrid PV/WECS renewable energy system

### 4.10.2 Hybrid Renewable Systems

A subset of hybrid systems are those that combine two or more renewable energy sources, such as PV panels and wind turbines. The sources used dictate the type of coupling.

Hybrid renewable systems should be selected when the renewable resources have complementary characteristics, for example, using a WECS with a PV module at a location where it is windy in the evening when there is no sunlight. If such a complementarity does not exist, then in general it is preferred to use a single resource, as it makes the system less complicated. The architecture of a DC-coupled hybrid PV/WECS is shown in Fig. 4.16. Separate controllers are needed for the PV module and the diversion load.

## 4.11 Improvised Systems

Many households in off-grid communities rely on “improvised” or “non-engineered” systems as shown in Fig. 4.17. These systems often use low-cost scavenged or repurposed equipment. In some cases, cleverly constructed wind and hydroturbines have been made, as seen in Figs. 4.18 and 4.19. Improvised systems generally have low reliability and voltage quality but nonetheless can provide beneficial electricity access when nothing else is available.

**Fig. 4.17** An improvised system consisting of a PV module (not shown), repurposed lead–acid battery, modified sinewave inverter, and AC load (courtesy of author)



**Fig. 4.18** An improvised wind turbine used for battery charging in Zambia (courtesy of author)



### 4.12 Summary

Mini-grids are electrical systems, isolated from the national grid, that serve multiple users. Mini-grids use energy conversion technologies to convert the energy available in fossil fuels, biomass, moving air and water, sunlight, and other sources to electricity. Various converters, controllers, and energy storage devices are used to facilitate the supply of electricity to the users. A number of architectures are possible, many of which were discussed in this chapter. The architectures vary in their complexity, reliability, flexibility, and relative cost. The architecture is defined by where the energy sources are connected. If all the energy sources are connected to the AC bus, then the system is AC-coupled; if there are only energy sources coupled to the DC bus, then it is DC-coupled; systems with energy sources connected to both AC and DC buses are AC–DC-coupled mini-grids. The voltage magnitude and frequency of the AC bus must be formed by a single source, with the rest synchronizing to it. This adds complexity to the control of the sources. The DC bus avoids this complexity, but instead care must be taken to not overcharge or over discharge the batteries.

**Fig. 4.19** An improvised battery charging scheme (courtesy of P. Dauenhauer)



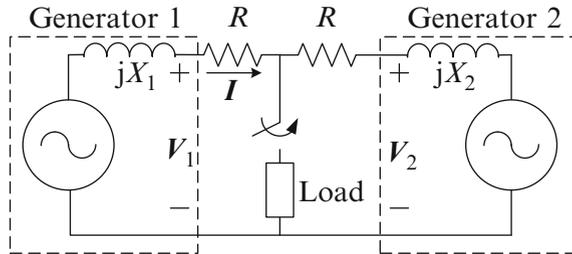
## Problems

- 4.1** Describe the basic function of an inverter, rectifier, and charge controller.
- 4.2** Draw a schematic of a mini-grid consisting of a conventional gen set, PV array, and WECS. The PV panel and WECS are coupled to the DC bus. The gen set forms the AC bus. Include any required controllers.
- 4.3** Consider a mini-grid with two single-phase, AC-coupled generators. The generators are modeled as a voltage in series with an inductive reactance. The circuit is shown Fig. 4.20. The load is not connected. The generators are controlled so that their terminal voltages  $V_1$  and  $V_2$  are held at:

$$V_1 = 233\angle 0^\circ V$$

$$V_2 = 227\angle 10^\circ V$$

**Fig. 4.20** Two generators in parallel



Let the resistance in the conductors connecting the generators each be  $R = 0.20 \Omega$ . Compute the resulting current  $I$ . What does this result suggest about the importance of synchronizing generators connected to the AC bus.

**4.4** An off-grid system will provide overnight lighting to a hospital using LED lights. The system will use PV modules to supply the power. Draw a schematic of the system; assume the LED lights can be connected to a DC bus or AC bus. Justify why you selected the LEDs to be connected to the DC bus or AC bus.

**4.5** Draw a schematic of a hybrid off-grid system that is supplied by a PV module, a WECS, and a gen set. Assume there are both AC and DC loads and that the inverter and gen set can be synchronized. Your design should allow for the gen set to charge batteries connected to the DC bus.

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