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Microgrid Modeling and Simulations

A. Aneesh Chand

School of Engineering and Physics, The University of the South Pacific, Suva, Fiji; aneeshamitesh@gmail.com; kushalaniketp@gmail.com; kabir.mamun@usp.ac.fj

A. Kushal Prasad

School of Engineering and Physics, The University of the South Pacific, Suva, Fiji; aneeshamitesh@gmail.com; kushalaniketp@gmail.com; kabir.mamun@usp.ac.fj

A. Kabir Mamun

School of Engineering and Physics, The University of the South Pacific, Suva, Fiji; aneeshamitesh@gmail.com; kushalaniketp@gmail.com; kabir.mamun@usp.ac.fj

F.R. Islam

School of Science and Engineering, University of Sunshine Coast, Queensland4556, Australia; fislam@usc.edu.au

Nallapaneni Kumar Manoj

School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong

P. Rajput

Department of Physics, Indian Institute of Technology Jodhpur, NH-65 Nagaur Road, Karwar, 342037, Jodhpur, Rajasthan, India; pramodraj.rajput3@gmail.com

and P. Sanjeevikumar

Department of Physics, Indian Institute of Technology Jodhpur, NH-65 Nagaur Road, Karwar, 342037, Jodhpur, Rajasthan, India; pramodraj.rajput3@ gmail.com

1 Introduction

An increase in the production of electricity plays a vital role in the increase of global warming. The increase in the distributed generation, such as wind, solar, fuel cells (FCs), and biomass, will create a significant impact on future power generation. Compared to conventional energy sources, the distributed energy sources are more environmentally friendly and provide a high level of flexibility and scalability. In the microgrid, the distributed generator and its loads are a single block of the control system. Microgrids can operate as island mode or grid-connected mode. The microgrid can introduce the reduction of the reversal of power in an alternating current (AC) or a direct current (DC) grid. Microgrids are needed to meet challenges such as increased reliability locally, fewer losses in the feeder, high efficiency, and better voltage profile. Unique control mechanisms have been developed for the coordination of microgrid operations. This section discusses different types of components that are associated with a hybrid AC/DC microgrid and its simulation modeling.

2 Loads

Generally, loads are the central part of any grid network. The types of possible loads that feed to a hybrid microgrid are shown in Table 4.1. The loads are classified into two main groups:

- Electrical loads
- Thermal loads

Usually, in residential appliances, there are combinations of electrical and thermal loads. These loads consume energy according to their impedance, current, and power rating according to Equations 1–3.

TABLE 4.1

Standard AC and DC loads

Common Loads	
AC-Powered Loads	**DC-Powered Loads**
Microwave oven	Laptop
Dishwater	Cell phone
Toaster	Home theatre system
Refrigerator	Variable speed drives for washers, dryers, or air-conditioning
Washing machine	
Electric clothes drier	

$$Power = P_{spsc} + jQ_{spsc} \tag{1}$$

$$Current = \frac{P_{spsc} + jQ_{spsc}}{|V|} \tag{2}$$

$$Impedance = \frac{P_{spsc} + jQ_{spsc}}{|V|^2} \tag{3}$$

## 2.1 Renewable Energy Resources (RERs)

Many researchers and power engineers are currently studying the dynamic state of hybrid AC/DC microgrids. RERs are dominating microgrid architecture and the current market, due to their integrality ease. These resources have a promising future due to their environment-friendly nature and full availability. Thus, it is vital to understand the components in implementing a hybrid AC/DC microgrid.

3 Modeling of Photovoltaic Cell

Electricity can be produced by photovoltaic (PV) cells from sunlight. The amount of power produced by the PV cells depends on the availability of the light and other performance parameters, as shown in Figure 4.1. The converted efficiency of the PV cells mainly depends on the percentage of the solar light inclination toward the PV cells. Much research is underway to improve the conversion efficiency, bringing the price down in order to make solar power more affordable. Most of the energy from light received by PV cells is lost before its conversion into real useful power.
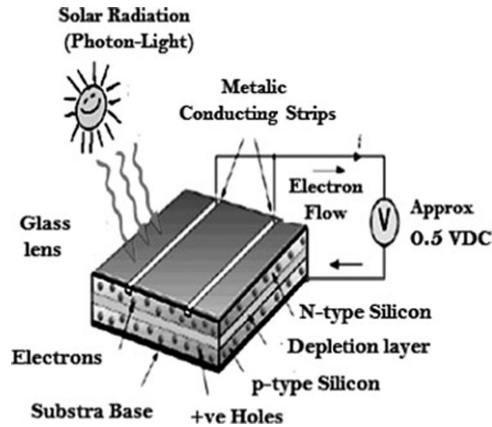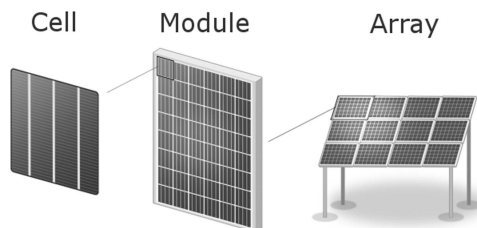
FIGURE 4.1
Basic structure of a photovoltaic cell

3.1 PV System

The French scientist Edmund Bequerel discovered the photoelectric effect in the 18th century. He found out that there are a few materials that are able to generate current in a small amount when it exposed to sunlight. In the 19th century, Albert Einstein found a fundamental principle of the PV effect, which became the basis for this technology. Bell Lab developed the first PV module. A PV system consists of one or more panels to produce electricity. The PV setup consists of several modules, including mechanical and electrical connections, various mountings, and electrical output regulators.

The core material of the a PV cell is semiconductor materials made of silicon. The semiconductor wafer creates a positive electric field on one side and a negative electric field on the other side. The light energy hitting the cells makes the electrons charged, and they can become detached from the atoms of the semiconductor material. The electrical conductors are connected on both sides to form a closed electrical circuit that produces current across the electrical load. Usually, the PV cells are circular or rectangular in construction.

3.2 PV Module

The PV cells are connected in series to create high current and connected in parallel to create high voltage of around a few milliamps and 0.5 V respectively. At nighttime and during any permanent or temporary shading, there is a possibility of reverser current. Separate diodes can protect this problem. The monocrystalline cells have better reverse current characteristics, and the diodes are not necessary for that type of panel. The shaded cells produce a large reverse current, which leads to overheating of the
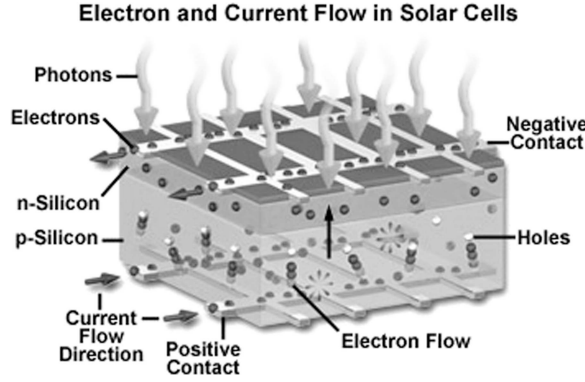
FIGURE 4.2
Photovoltaic array

panels. More temperature reduces the efficiency of the panels. So, panels need to be installed properly. In a single module, usually, there are 36 or 72 cells. The transparent front side, PV cell, and backside form the PV modules. The front end of the panel is usually made of tempered glass. Usually, the efficiency of the PV module is less than a PV cell, because radiation is reflected by the glass cover and shadowing effect.

3.3 PV Array

An interconnection of many PV cells in parallel or series forms a PV array, as shown in Figure 4.2. A single module is useful to manage any commercial electrical load. For this reason, modules are connected to form an array to meet the real-time load requirements. For getting desired voltage as well high current load requirements, usually the PV arrays are connected in parallel and each individual modules also connected in parallel to produce sufficient current required. In city or town areas, the PV arrays are placed on the rooftops of greenhouses or buildings, and for village areas the output of the panel is fed to a DC motor for pumping water for agriculture purpose.

3.4 Working of PV Cell

The photoelectric effort is the main reason behind the operations of each PV cell. The absorption of light in a particular wavelength allows for the release of electrons of a specific material. Due to this effect, when the sunlight hits the solar surface, a portion of the solar energy is accepted by the semiconductors. The valance band electrons will move to conduction band when receives energy which crosses the energy of bandgap. This effect makes the hole–electron pairs in the semiconductor material, and the process is clearly depicted in Figure 4.3. The conduction band electrons will move freely in one direction due to the electric field in the solar cells. This electron movement creates a current flow that can be tapped by connecting metals in both sides of the solar cells. The current and the voltage produces the required energy from solar power.

Electron and Current Flow in Solar Cells

FIGURE 4.3
Working of a photovoltaic cell
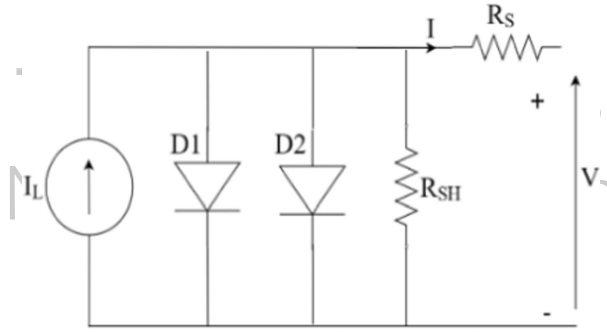
FIGURE 4.4
Ideal photovoltaic cell

The principal process involved in generating energy from a PV system is to convert light energy in to electrical energy; this process is based on the doping process of P-N junction of the semiconductors. Nowadays, there is an increase in PV-based power plants for grid-connected or off grid as they produce DC output power, DC/AC converter used in case of connecting in the AC system. The output voltage of each cell is given by Equation 6.

The output power of a PV system depends on the geographical location (ir-radiation data) and the size of the plant and materials of the PV; Equation 7 shows the mathematical modeling of the PV array, which was obtained using Equations 4–6. The schematic design of the PV model is illustrated in Figure 4.5.

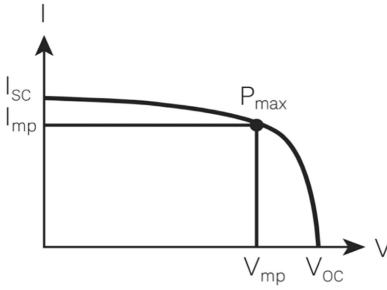$$I_{pv} = I_{ph} - I_o \left(e^{\frac{qV_{pv}}{mkT}} - 1 \right) \tag{4}$$

FIGURE 4.5
Photovoltaic array

$$V_{pv} = V_{oc} = \frac{mkT}{q} ln\left(1 + \frac{I_{sc}}{I_o}\right) \tag{5}$$

$$P_{pv} = V_{pv}I_{pv} = V_{pv}\left(I_{sc} - I_0\left(e^{\frac{qV_{pv}}{mkT}} - 1\right)\right) \tag{6}$$

3.4.1 Implementation Benefits and Drawbacks

Less environmental pollution, inexhaustibility, useful for load balancing, and flexible plant scale are the significant advantages of the use of solar energy. However, certain drawbacks are also involved, such as the high cost of installation of PV plants, suitable for high irradiation geographical, power losses in converters, switching mechanisms. Researchers are continually addressing these problems to overcome them. Probability distribution functions and mathematical models are sources to predict the PV behavior and their penetration into the smart grid due to variability in their behavior.

4 Maximum Power Point Tracking

An electronic system called maximum power point tracking (MPPT) is used to make solar panels produce their maximum possible power. The MPPT is not a mechanical tracking system that moves the panels towards sunlight all the time. The electronic MPPT system can vary the operating point continuously for each solar module, which allows the panel to deliver its maximum power. In typical situations, a PV array's output power mainly depends on the temperature, irradiation, and the load characteristics, and its dynamic characteristics make the maximum output not possible always.

For this reason, MPPT needs to be implemented in the solar power system to get the maximum power for output voltage.

4.1 The Necessity of MPPT

In the voltage versus power graph of a PV array, the maximum power operating point can be identified for a specific voltage and load current. Usually, the efficiency of the solar cells module is about 13%, which is very low. Since the efficiency for a PV array is very low, it is very much required to operate the solar panels at the maximum power operating point with the help of MPPT under variable temperature and irradiance conditions. The maximized power operating conditions will improve solar power efficiency by up to 27%. The role of MPPT ensures maximum power to the load. For effective extraction of maximum power from the solar panels, it needs to interconnect with DC/DC converters. These converters can change the duty cycle to match the load impedance to ensure maximum power transfer to the load.

4.2 Algorithms for Tracking of Maximum Power Point

There are many standard classical algorithms available for MPPT.

1. Perturb and observe
2. Incremental conductance
3. Parasitic capacitance
4. Voltage-based peak power tracking
5. Current-based peak power tracking

The MATLAB®/SIMULINK simulation model of the solar PV system with a PV array, MPPT, and boost converter for a sample system is shown in Figure 4.6.

5 Wind Power Productions

A large amount of air is moving on the surface of the earth due to kinetic energy, called wind energy. Wind turbines can extract energy from wind energy. The kinetic energy is converted into its other form by moving the giant blades of the wind turbine. The wind turbine, in turn, rotates the generator in the same direction through the gearbox. Through this action, the generator produces electricity in a large quantity. In this process, the kinetic energy is converted into rotational mechanical energy and finally converted into electrical power.
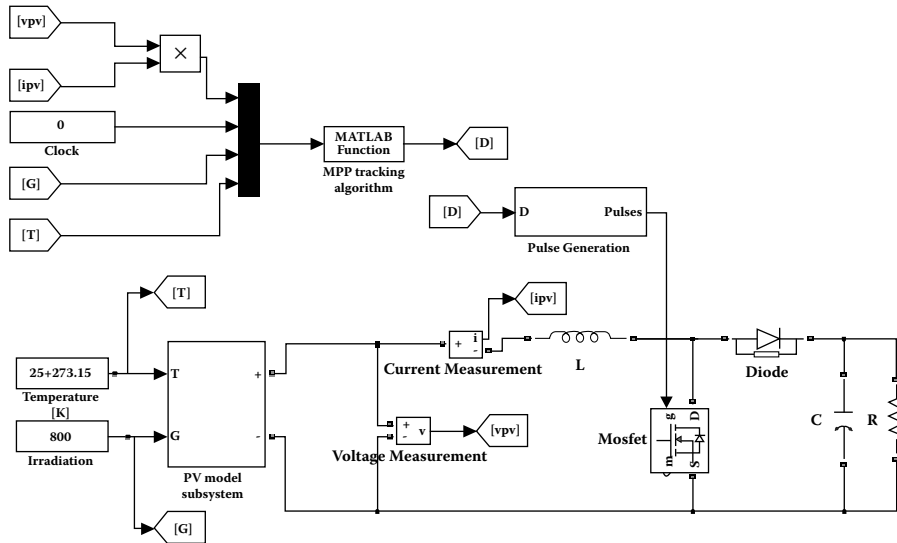
FIGURE 4.6
Photovoltaic, maximum power point tracking, and boost converter model

5.1 Wind Energy Conversion System

Based on the advanced technology, wind energy production becomes cheaper day by day. Therefore, various types of configurations have been analyzed and formed different systems. The turbines are specified and classified in different ways based on several factors as follows:

- Rotor axis orientation: horizontal and vertical
- Rotor position: upwind or downwind of the tower
- Rotational speed: constant or variable

Apart from the above classification, the wind turbines are also classified based on the blades, hub, and yaw. Since the input for the wind power is continuous, variable wind from speed ranges gives variable voltage and frequency. To achieve stable voltage and frequency as output for the wind energy conversion systems, the unique converter system is very much required. Three types of wind turbine–based wind energy systems are available based on their control of power.

5.2 Types of Wind Power Generator

5.2.1 Constant Speed

In this model, the wind turbine speed is maintained at constant speed irrespective of the wind speed, and it is decided by the required frequency of
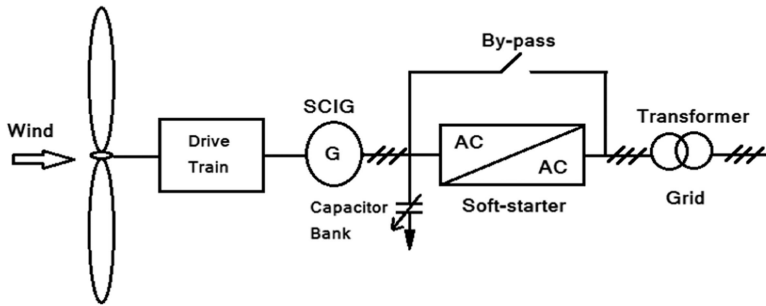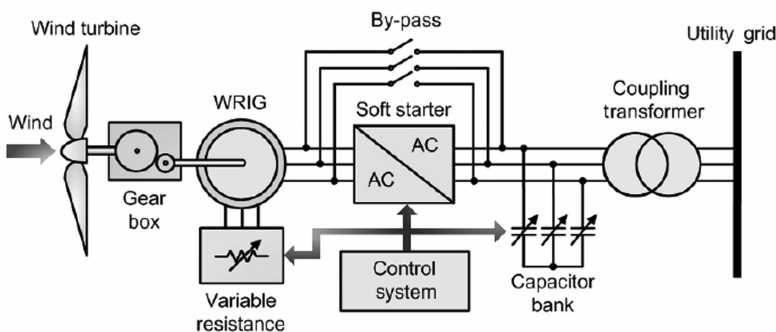
FIGURE 4.7
Constant speed wind system configurations

the grid, ratio of the gear, and the design of the generator. In this model, the conversion system has a wind turbine coupled with a squirrel cage induction generator via a gearbox, as shown in Figure 4.7. The soft starter and the bank of capacitance are also available for better grid connection and will act as a compensator device.

Among all configurations, this model is simple, highly robust, offers better reliability, and is well established. Nevertheless, this model has its disadvantages too, that is, no control of reactive power consumption, high stress, and limited power quality.

5.2.2 Variable Speed

This model is the same as the constant speed model except the wound rotor induction generator and the variable resistance are installed, as shown in Figure 4.8. Here the speed is not constant, and by using the variable resistance, the synchronous generator speed is varied from 0% to 10% through an optically controlled converter mounted on the shaft of the generator.

FIGURE 4.8
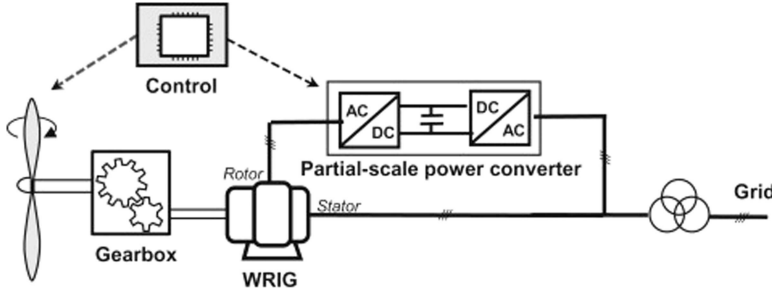Variable speed wind system configurations

FIGURE 4.9
Frequency converter wind system configurations

This model provides better flexibility with the control of the generator with variable resistance, but the range of control is limited.

5.2.3 Variable Speed with Partial-Scale Frequency Converter

This model is the better evaluation of the variable speed model with some modifications in the control and structure. The generator and the output stator windings are interfaced with the constant frequency power grid, and the rotor of the generator interfaces with a voltage source converter. Hence, this model is called a variable speed with partial frequency converter, as shown in Figure 4.9.

Apart from the better speed control, this model has a reliable grid connection and better compensation of reactive power. This model provides a much more extensive range of speed control of 30% of the rated speed of the generator.

As concern increases for RE-based energy generation that is environmentally friendly and low cost, wind-powered energy is considered to be one of the most effective potential alternative energy resources, because it is renewable and clean. A wind turbine uses the kinetic energy of wind to rotate the turbine, which is connected to a generator. The power derived from the wind turbine at a specific location generally depends on the wind velocity at tower height and turbine speed characteristics as:

$$V_h = V_i \left[\frac{h}{h_i} \right]^x \tag{7}$$

where V_h and V_i, speed of the wind at hub height h and h_i respectively, x, power-law exponent.

The real power is obtained using Equation 8, where R is wind turbine radius and C_P is turbine power conversion coefficient. Equation 6 can be further derived, as shown in Equation 9, where, η_o is the collective efficiency of the turbine and generator.
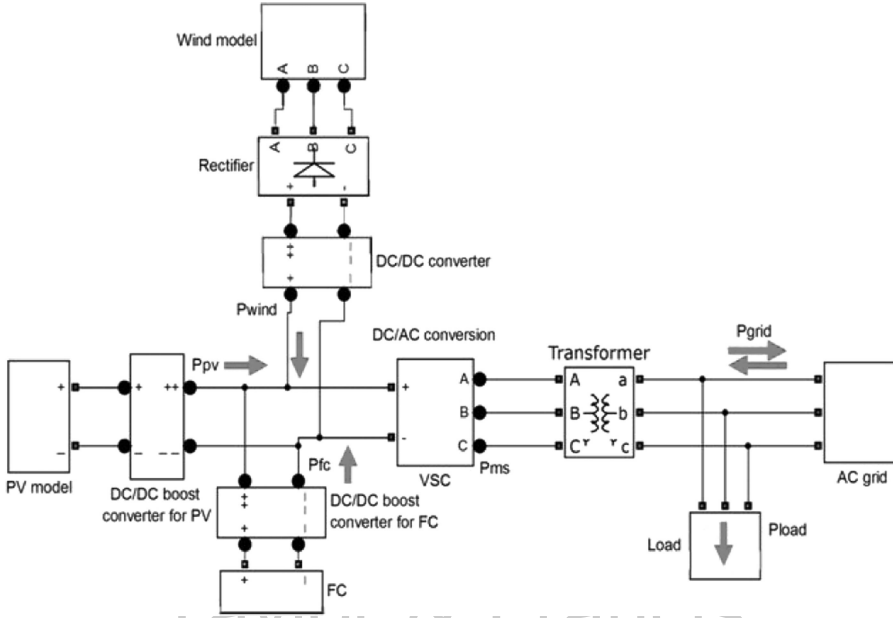
FIGURE 4.10
WES with DC/DC converter and maximum power point tracking

$$P_{in} = 0.5\rho\pi R^2 V^3 C_p \tag{8}$$

$$P_e = \eta_o P_m \tag{9}$$

5.2.4 Implementation Benefits and Drawbacks

Although wind energy has no harmful effects and power production is affordable, there are also certain drawbacks such as uncertain availability, independent power output, etc. Due to its randomness and stochastic behavior, probability-based modeling techniques are required, and its optimum allocation can be sought out by the use of evolutionary algorithms. Figure 4.10 indicates the DC/DC converter-based wind energy conversion systems of a sample system implemented in MATLAB®/SIMULINK, as shown in Figure 4.10.

6 Energy Storage System

A summary of the different energy storage system (ESS) categories is illustrated in Figure 4.11.
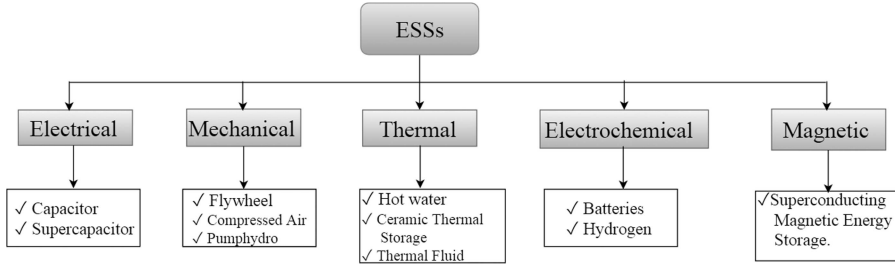
FIGURE 4.11
Different types of energy storage system

6.1 Batteries

Rechargeable batteries are the most significant and extensively used ESS technologies in the electric system. The common application of batteries is in vehicles, home energy systems, and microgrids (improves power quality and energy management). They are used widely in most cases to improve system performance, reliability, and efficiency. Batteries are used mostly in all topologies of microgrids. Such a device produces DC output power and can directly connect to DC bus (DC microgrid) as well as deploy in an AC microgrid through an inverter.

Battery storage technology can be categorized as follows:

- Lead acid
- Lithium iron
- Zinc-bromine
- Aqueous hybrid ion
- Tesla powerwall battery

The state of charge (*SoC*) and depth of discharge (*DoD*) indicates the amount of energy left in a battery, and the percentage can be expressed as.

$$SoC(t + 1) = SoC(t) + \frac{n_{crg} \times \rho_{b,t} \times \Delta t}{BattCap_{KWh}} \tag{10}$$

6.1.1 Implementation Benefits and Drawbacks

Some benefits of batteries are as follows: available in all sizes; withstand slow, fast and overhanging conditions for power delivery; and best in terms of reliability and working capabilities. There are also some common drawbacks; batteries are not suitable for large power storage, and disposal is an issue.

6.2 Microturbine

A microturbine (MT) generation system (MGS) is considered another common power-generating system that is early integrated with micro turbine. Microturbines include a permanent magnet synchronous machine, gas turbine, a rectifier, and an inverter.

6.2.1 Implementation Benefits and Drawbacks

MTs are environmentally friendly, highly reliable, and efficient. Because they have few moving parts, less maintenance is required and they produce low carbon emissions. Then again, the high cost is the main factor.

6.3 Flywheel

A flywheel is also considered as a mechanical battery, purely a mass rotating about an axis. A flywheel energy storage system (FESS) mainly consists of spinning, bearing, rotor, housing, a power electronics interface, and MG, as shown in Figure 4.12. The flywheel can be used as ESS and a generator for the desired purpose.
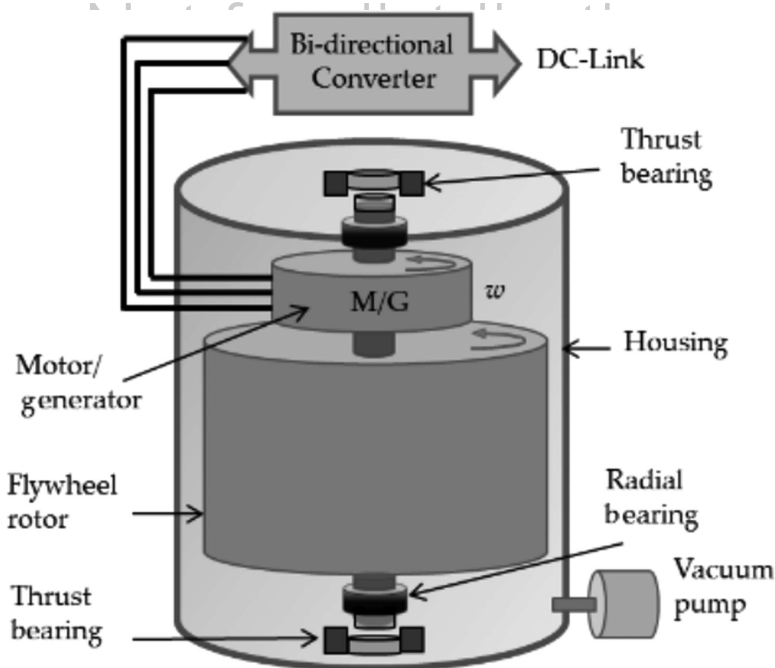

FIGURE 4.12
A typical structure of a flywheel

As said initially, a flywheel uses a mechanical storage form of kinetic energy. The efficiency of the flywheel is determined with rotor shape and materials. Equation 11 clarifies that it is linearly proportional to the moment of inertia and the square of its angular velocity, where E signifies stored energy, I the moment of inertia, and ω is the angler velocity. The useable energy that is generated from the flywheel is ranged with a minimum speed (ω_{min}) and maximum speed (ω_{max}), expressed as in Equation 12.

$$E = \frac{1}{2}I\omega^2 \tag{11}$$

$$E = \frac{1}{2}(\omega_{max}^2 - \omega_{min}^2) \tag{12}$$

Logically, the process of storing the energy of a flywheel is made by accelerating the rotor to a very high speed (ω_{max}), while it releases energy by decelerating the rotor to slow down until eventually coming to a complete stop (ω_{min}).

6.3.1 *Implementation Benefits and Drawbacks*

A flywheel has no harmful effects on the environment, is low maintenance so offers long operational life, requires no fuel and water, can integrate with RERs, and is more efficient with large scale microgrids.

An FESS offers many benefits along with some drawbacks like high cost due to evolving technology and flywheel consist of rotating mechanism; it can pose a danger if it is not constructed well.

6.4 Fuel cell

An FC is a chemical-based reaction that produces electricity from hydrogen and oxygen and emits only water vapor, as shown in Figure 4.13. An FC consists of four key elements: airflow system, hydrogen flow system, cooling, and humidification. Essentially, there are five common FCs types, and they are shown below:

- Alkaline fuel cell
- Proton exchange membrane fuel cell
- Phosphoric acid fuel cell
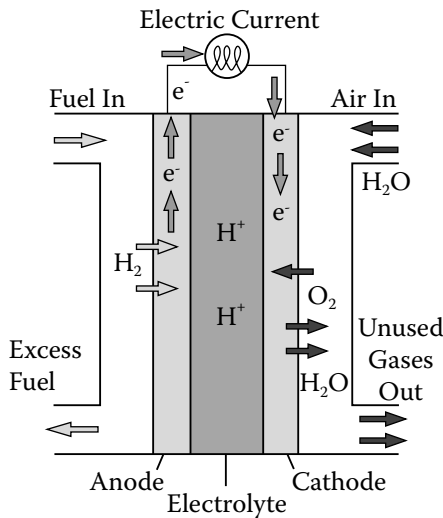- Solid oxide fuel cell
- Molten carbonate fuel cell

FIGURE 4.13
Fuel cell schematic

6.4.1 *Implementation Benefits and Drawbacks*

Even though FCs produce low voltage and they are costly and corrosive for liquid electrolytes, there are no rotating parts. Hence FCs are dependable and efficient resources; the operation is silent and produces no harmful effects on the environment.

6.5 Converters

With prior discussion on different types of microgrid design, the standard features, such as frequency, voltage, and other power quality factor, must be controlled during the conversion process. The conversion of AC/DC or DC/AC plays a significant role, but it is used for the interlinking unit. Apart from the primary conversion that interlinks the AC or DC sides, some other power electronic devices facilitate during the implementation of the hybrid AC/DC microgrids. For example, a boost converter is used for a PV system, and climate dependency such as irradiance and temperature impact the output power of the hybrid AC/DC microgrid. So, integration of an MPPT system is essential, while the boost converter would facilitate this, by regulating its output voltage. Alternatively, a bi-directional converter (DC/DC) and battery bank is as well as the part of the ESS. Pulse-Width Modulation (PWM) control methods are utilized in a buck/boost converter, which is interlinked with the main DC link; also, the battery, to control its SoC, DoD and tracking those controls.

6.6 Electric Vehicle

Today, due to limited FFRs and the environmental issue, automobile energy storage using electric vehicle (EV) in a microgrid has prime importance. EVs can be integrated with the grid as they have a dual nature of producing and consuming energy, thus they can act as energy storage units for a microgrid network. Vehicle to grid (V2G) and grid to a vehicle (G2V) are the two most common ways in which EV are used in the grid network.

Figure 4.14 depicts the EV charging in AC and DC configuration. Such technologies improve the microgrid power quality, stability, reliability, and performance in terms of power management and ESS.
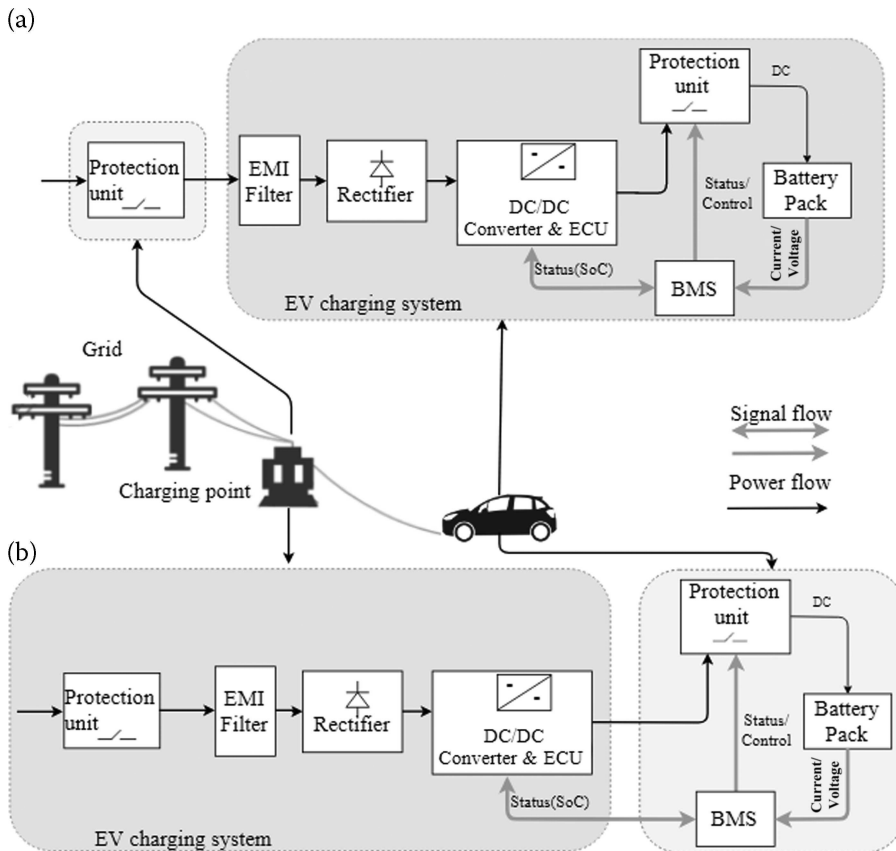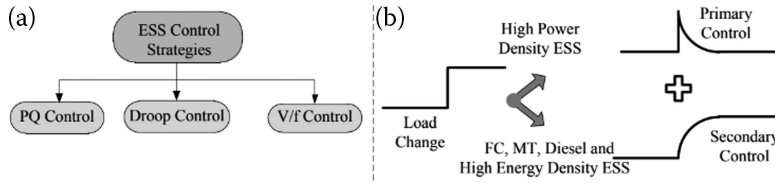

FIGURE 4.14
Electric vehicle charging (a) AC configuration (b) DC configuration

FIGURE 4.15
(a) Energy storage system control strategies and (b) primary and secondary frequency control

6.6.1 Implementation Benefits and Drawbacks

EVs present a few benefits such as load balancing, active power regulation, support reactive power, shaving peak load, voltage and frequency regulator, and current harmonics filtering. However, it is fast discharging, losses during charging, and conversion devices are expensive.

6.7 ESS Control Strategies

The most dynamic feature in controlling ESSs, mainly in hybrid design, is SoC and DoD control. Whenever at least two or more ESSs work parallel in a power system, they ought to charge and discharged at the same time. It causes an expansion in the average lifetime of ESSs and improves the re-action of voltage control. Hence, numerous researches have attempted to equalize the SoC of ESSs. Then again, as referenced, the most significant issue in the microgrid control is its stability. Therefore, in the system operation optimization process, the microgrid stability ought to be considered as an acute condition. In this context, an abstracted representation of the ESS control strategies is shown with its primary and secondary frequency control in Figure 4.15.

7 Simulation Results

A hybrid microgrid-based simulation has been implemented in a MATLAB®/ SIMULINK environment. The operation of the sample system is shown for grid-connected mode. Along with the microgrid, the performance of the wind energy systems, the solar system is also analysed. The simulation output of the components of the microgrid are analyzed in a MATLAB®/SIMULINK environment.
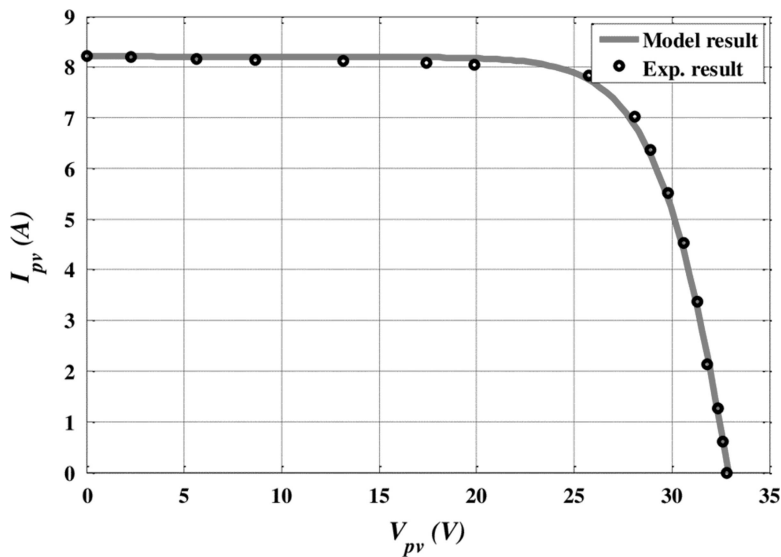
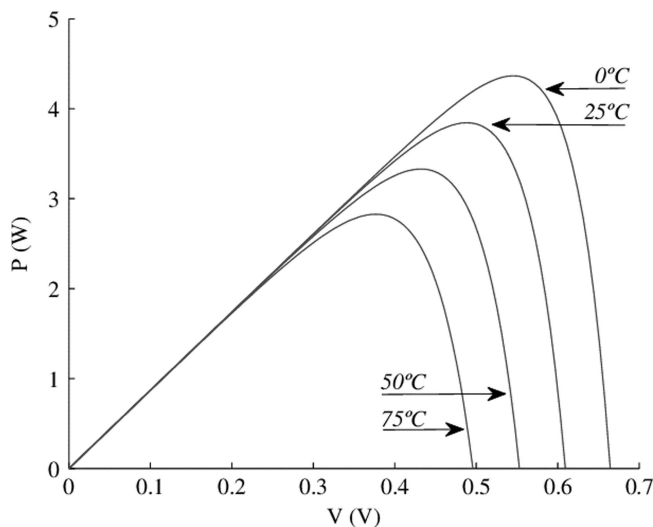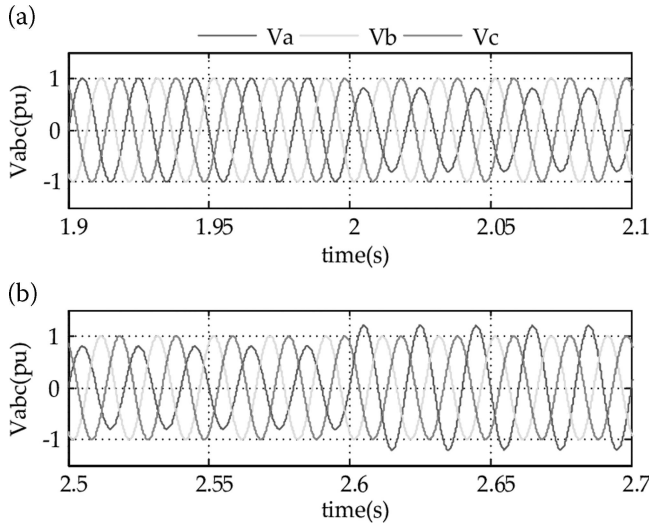**FIGURE 4.16**
I-V output characteristics of photovoltaic array

FIGURE 4.17
P-V output characteristics of photovoltaic array

Proof

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(a)

(b)

FIGURE 4.18
Three-phase stator and rotor voltage of doubly fed induction generator

Taylor & Francis
Not for distribution

7.1 Simulations of PV Array

Figures 4.16 and 4.17 represents I-V, P-V, and P-I characteristics of solar cells. The PV cell is nonlinear in nature, that is, the current output and PV cell produced power depends on the PV panels terminal voltage, the heat produced, and irradiations.
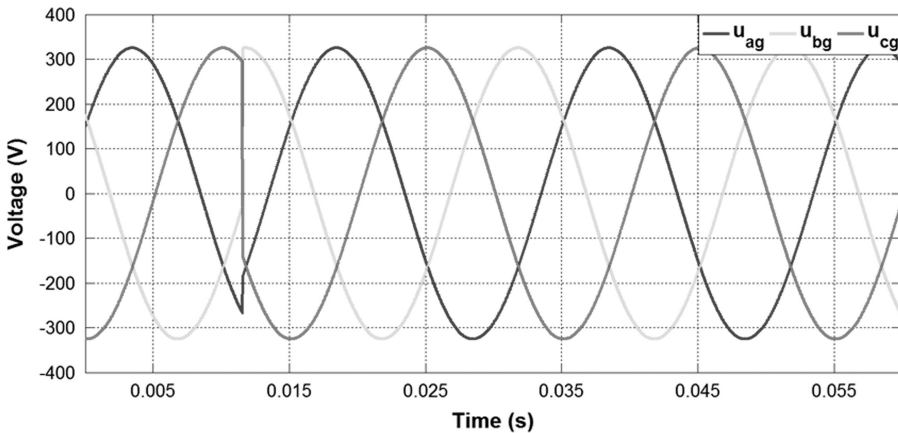
FIGURE 4.19
The output voltage across AC load

Proof
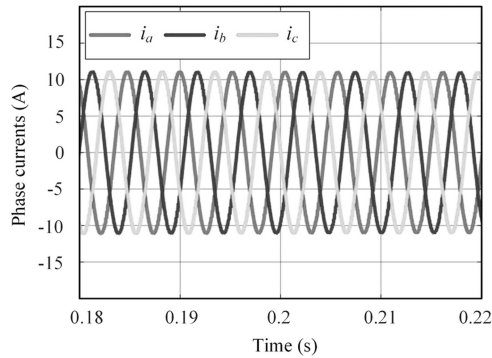
FIGURE 4.20
Output current across AC load

7.2 Simulation of Doubly Fed Induction Generator

The response of induction generators is shown in Figure 4.18. Here the value of wind speed varies as necessary for the study of the performance of an induction generator. The stator voltage is set to 300 V, and the rotor voltage is 150 V.

7.3 Simulations Results of Hybrid Grid

The different characteristics of a microgrid are shown in Figures 4.19 and 4.20. In this sample system the microgrid operates in grid-connected supply. The figures show the voltage and current responses at the AC side of the main converter when the solar radiation value varies between 950 and 1300 W/m^2 with a fixed DC load of 25 kW.