Optimal Control System of Under Frequency Load Shedding in Microgrid System with Renewable Energy Resources

T. Madiba, R.C. Bansal, J.J. Justo and K. Kusakana

Abstract Nowadays many of the power systems are facing serious problems because of the lack of know-how to utilize the available renewable energy resources (RER) so as to balance between the power supply and demand sides. As the consequence of the power unbalancing into their distribution networks, under frequency load shedding (UFLS) which leads to life span reduction of various expensive equipment and deteriorating production in general are of much concerns. Thus, proper control system for the load flow in a system like microgrids (MG) with RER in general is the first thing to carry out the assessment with the aim to solve the power balancing problem within the power system networks. Actually, the major problems which many utilities are facing all over the world are how to utilize the available and future energy resource reserves in order to balance between the supply and demand sides within their power distribution networks. Moreover, because of the quick, improvised and unforeseen increasing number of consumers' power demands and lack of additional macro energy resources plants which can favorably respond to the instantaneous consumer requirements, optimal control strategy (OCS) is inevitable. The OCS is required to maintain the steady-state operations and ensure the reliability of the entire distribution system over a long period. For that case, the OCS is required to principally stabilize parameters such as voltage, frequency, and limit the injection of reactive power into the MG system under stress. Therefore, in this chapter, the OCS is proposed as an approach to be

T. Madiba (✉) · R.C. Bansal · J.J. Justo
Department of Electrical, Electronics and Computer Engineering,
University of Pretoria, Pretoria, South Africa
e-mail: symphomadiba@gmail.com

R.C. Bansal
e-mail: rcbansal@ieee.org

J.J. Justo
e-mail: jackjusto2009@gmail.com

K. Kusakana
Department of Electrical, Electronics and Computer Engineering,
Central University of Technology, Bloemfontein, South Africa
e-mail: kkusakana@cut.ac.za

71

applied in an intelligent way to solve the UFLS and blackout problems (BP) in a typical MG with RER. The proposed control solution is analyzed using emergency power supply reserves integrated with RER. These typical energy resources can be wind and photovoltaic (solar PV) systems associated with the battery energy storage system (BESS), hydro pump storage, biomass power plant and fuel cell systems.

1 Introduction

Energy industry has been the major driving force for the technological development of mankind through the famous biological theme of "survival of the fittest." Actually, the world population grows in arithmetic progress with the demand for energy. The conventional power generating systems utilize fossil fuel (i.e., coal, gas and oil) as their primary input sources to the boiler for combustion. Now, the by-products of the combustion system (such as CO, NO_x, and SO_x) are the major causes of environmental pollution which is detrimental to both human and animal health. In fact, the carbon dioxide (CO_2) emitted during combustion has been identified as the main cause of global warming which result in undesirable climate change. Thus, to eliminate the dependent on fossil fuels as the primary source of energy and mitigate their environmental consequences, renewable energy resources (RER) like photovoltaic (PV), biomass and wind energy are the promising solutions [1].

More specifically, a small-scale power generating system close to the customers is considered as a microgrid (MG) system. Technically, small capacity power generating units such as those using RERs can be integrated in the MG system. Some of the advantages of adopting the concept of the MG system include reduction of line losses, network congestion and line costs by increasing the energy efficiency [2]. On the other hand, there are challenges which hinder the direct implementation of the RERs in the form of MG system into the existing power networks. These challenges are voltage and frequency control, intelligent energy management systems, power converters control systems which link various power generating units in the MG system, and investment cost practical implementation as well as the social acceptability. However, the higher level of flexibility and reliability provided by the MG system when run both in grid-connected and islanded modes of operations outweigh the above-mentioned challenges when observing from the grid perspectives. In that case, the MG system and its components may physically be close to customers and distributed geographically depending with their energy resource allocation [3].

The concept of the MG is that many micro generators are connected to grid with the objective to reduce the need of the network distribution system [4]. However, the MG can be integrated with the network system but this can produce a problem to the safety and reliability of the grid due to the net loss of line flow, voltage and power quality [5]. Generally, the MG operates in two modes which are islanded and grid-connected. For single MG, different control strategies are used to stabilize the output which utilizes *P-f* and *Q-V* control modes for grid-connected and isolated mode [6]. The combination of a series of control strategies are utilized to enable stable operation of the MG in each mode and switch smoothly between the two modes [7]. A blackout in a power system refers to the absence of power supply in a given area/community for a short or long period. These power blackouts can occur due to natural disasters or technical reasons. The stable operation of a power system requires frequency and voltage to be constant [8]. When power grid fails to supply sufficient power [9], the appliances of under frequency load shedding (UFLS) models could improve the system frequency dynamic response and enhance the stability of power grid and in the past many researchers have focused on this subject [10]. The UFLS models describe the detailed procedures of how many steps should be taken and how much load should be shedded at each step [11]. Load shedding scheme based on frequency alone has several disadvantages, among which are the load may be tripped unnecessarily at low import level and too much load tripped at high import level [12]. The traditional or conventional load shedding approach does not provide optimum load shedding solution and cannot deal efficiently with modern and complex power systems [13, 14].

To address these problems, the application of half-adapted and adapted methods UFLS with less amount of loads being shed compare to the conventional systems have been presented [15]. Although, nonlinear optimization model can solve this problem more accurately, this method is very lengthy, that is, it increases computational complexity when practical results are of interests as it takes longer time [16]. Alternatively, computational intelligence techniques which have robust and flexible properties when dealing with complex nonlinear systems could be an option in addressing this problem [17]. The limitation of computational intelligence techniques restricts their applications in load shedding in real time [18]. Because of this reason, this chapter discusses a solution regarding load shedding and blackout problems into the MG power system, and proposes a method of controlling the voltage and frequency within the MG system when operating in grid-connected mode as well as in islanded mode.

The chapter is organized as follows: the general introduction about the chapter which includes the problem statement, literature review on MG concept and control methods is provided in Sect. 1. In Sect. 2, the general configuration of the MG system is prevailed with brief description of its various components including renewable and nonrenewable energy technologies while Sect. 3 presents their detail operating characteristics. The contribution of renewable and nonrenewable resources into the MG system is explained in this section by highlighting the

problem statement, objective function, system constraints and later on simulation studies are presented. The conclusion and technical challenges to further improve the performance of the MG systems are briefly explained in Sect. 4.

2 General Configuration of the MG System

The main work with electric utilities is to design and implement Community MGs that utilize local renewable energy resources to provide a reliable and cost-effective foundation for a modern grid. The operation principles the MG system technologies is based on the number of its main components applied at supply and customer sides [19]. The fundamental of realizations activities for different types of renewable energy technologies and others sources of energy include the major points listed as follows: land clearing for site preparation and access routes; excavation, blasting, and filling; logistic aspect of materials and fuels; construction of foundations involving excavations and placement of concrete; operating cranes for unloading and installation of equipment; construction and installation of associated infrastructure [20], construction and reticulation plans of power cables; and closeout and decommissioning activities may include removal of project infrastructure and site rehabilitation [21]. The next subsections present the details characteristics of a MG system containing various renewable energy technologies which can be used in the MG system.

2.1 MG System General Model

This section explains an overview of the MG with various renewable energy technologies (RETs) looking on the principles of their operating characteristics and limitation. Their configuration when operating as MG system with power electronics interfaces is also briefly highlighted in the Fig. 1 The MG shown is containing RETs such as diesel generator, micro-hydropower, hydro pump storage, wind turbine generator, PV system, inverters, bidirectional converter and a battery storage system in case of power shortage when there is no power from any of the supply sources. From the demand side, there are a certain number of loads to be feed with power during the specified period of the day according to the daily consumption needs.

As said before, the subsections of the Sect. 2.1 give the brief descriptions and the operating principles of some of the RETs to be applied into the MG system with the objective to keep the power system operating continuously.
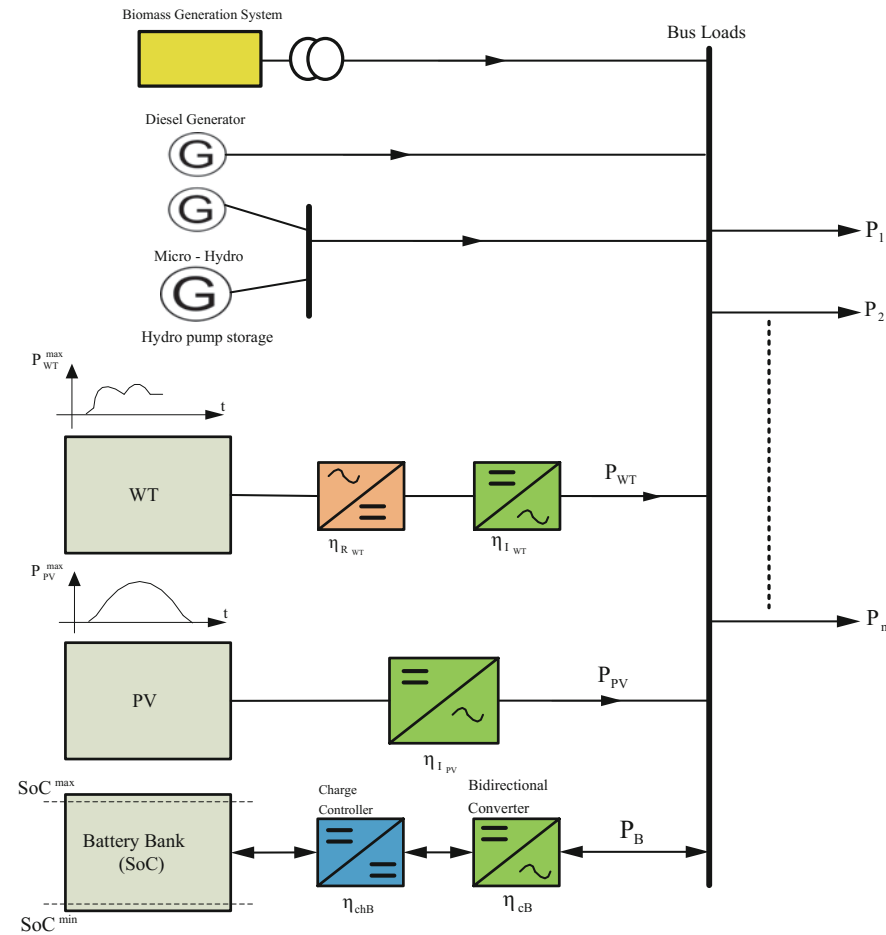
Fig. 1 Representation of a MG system general model

2.1.1 Micro-Hydropower System

The micro-hydropower requires water from the river to be channeled through a basin where sediment which may damage the turbine is removed. The water is then passed to a tank before flowing downhill through a pipe called a penstock. A turbine is located at the bottom of the penstock and is driven by the force of the falling water to produce electricity [22]. The communities should be made to participate fully from the beginning in order to own the project and maintain it through its lifetime. Once the system is in operation, the local people pay a small charge to use the electricity, which is used to cover maintenance and the eventual cost of replacement. The locals are also involved in the construction which will enable them to maintain the facility [23]. Today, small hydropower projects offer

emissions-free power solutions for many remote communities throughout the world such as those in Nepal, India, China, and Peru as well as for highly industrialized countries, like the United States. The energy head in the water flowing in a closed conduit of circular cross section, under a certain pressure, is given by Bernoulli's equation [24]:

$$H_1 = h_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} \tag{1}$$

where H_1 is the total energy head, h_1 is the elevation above some specified datum plane, P_1 the pressure γ the specific weight of water, V_1 the velocity of the water, and g the gravitational acceleration. The total energy head at point 1 is then the algebraic sum of the potential energy h_1, the pressure energy P_1/γ, and the kinetic energy $V_1^2/2g$, commonly known as the "Velocity head." For an open channel, the same equation applies, but with the term P_1/γ replaced by d_1, the water depth [25].

2.1.2 Photovoltaic System

PV technology system seems to be the simple and desired method because of its easier method of maintenance, installation process, which is highly important in a small, remote island nation with limited technical expertise or access to replacement parts. It can be developed as a distributed system of small-sized systems, which can spread benefits widely and has the potential for widespread replication. The flexibility of the grid stability and grid management is increased by the predictable PV system. The major opportunities to develop PV technology is significant in private sectors where the systems seems to be economical and competitive compared with other options and the government expects it to become more so in the near to mid-term [26]. Figure 2 represents a diagram of PV system supplying the AC load via inverter and the DC load via a controller.
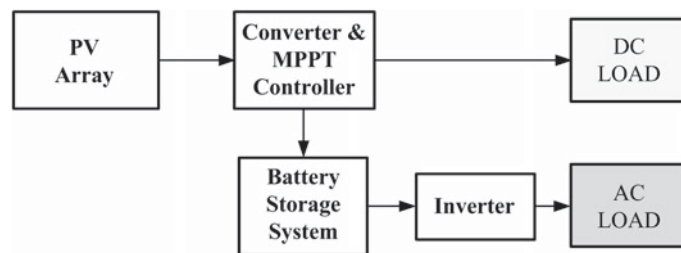

**Fig. 2** PV generator system diagram layout

2.1.3 Biomass System

The value of a particular type of biomass depends on the chemical and physical properties of the large molecules from the source [27]. More recently, fossil biomass has been exploited as coal and oil. However, since it takes millions of years to convert biomass into fossil fuels, these are not renewable within a time-scale mankind can use [28]. Burning fossil fuels uses "old" biomass and converts it into "new" CO_2; which contributes to the "greenhouse" effect and depletes a nonrenewable resource [29]. Burning new biomass contributes no new carbon dioxide to the atmosphere, because replanting harvested biomass ensures that CO_2 is absorbed and returned for a cycle of new growth [30]. One of the dilemmas facing the developed world is the need to recognize this time delay and take appropriate action to mitigate against the lag period [31]. Biomass can be converted into three main types of products such as electrical or heat energy, transport fuel, and chemical feedstock but of particular interest in this study, the main purpose here is the generation of electricity [32]. The biomass system typical plant diagram layout is presented in Fig. 3 As this can be seen in the diagram, the biomass heat system is characterized by the input parameter Q_{in} and outputs such as the energy from the turbine W_t, cooling water Q_{out}, and the pump W_p. The design of a biomass plant technology is based on these four main factors as shown in the Fig. 3 [31, 32].

2.1.4 Battery Bank System Characteristics

Without batteries to store energy, it would only be possible to have power when renewable energy sources are available or the diesel generator running [33–36]. It must also be decided how many days' worth of energy must be stored in the battery bank. Generally, system designs allow for an autonomy range of 2–5 days. In the case of the example, an autonomy capacity of 2 days will be taken into account. The total battery energy of a certain number of kW is multiplied by two and results

Fig. 3 Biomass system plant layout
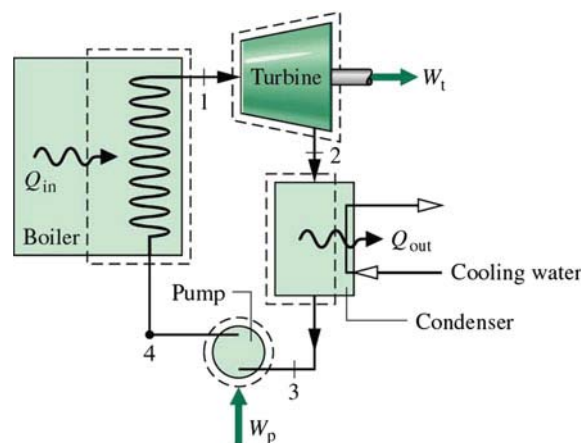
in kWh, which then gives system autonomy of 2 days [37–39]. When designing MG system, solar power generation systems, the designer must pay specific attention to the selection of PV modules, batteries, inverters, and installation material and labor expenses, and specifically be mindful of the financial costs of the overall project. The designer must also assume responsibility to assist the end user with rebate procurement documentation [40]. Figure 4 shows how a storage battery system unit is installed into the grid system with the objective to compensate with power in case of shortage of energy for the household system.

2.1.5 Wind Turbine Generator Characteristics

Many rural areas have an ideal situation for developing community sized wind projects on their reservations. Frequency control requires real-time balance between generation and load, with system frequency deviation maintained within a certain range and for a large interconnected system, frequency control performance is important because of reliability concerns [41]. Figure 5 shows the wind turbine generator system with the objective to give the idea of the operating principle of this technology.
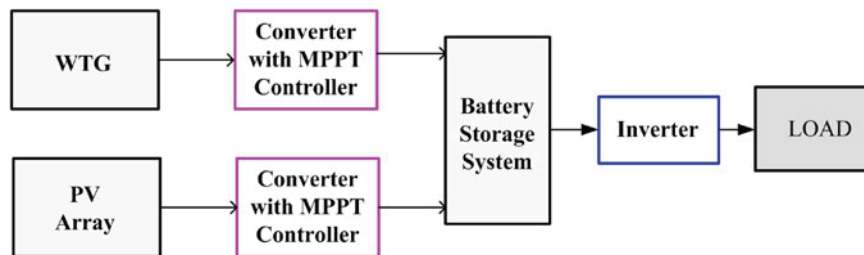

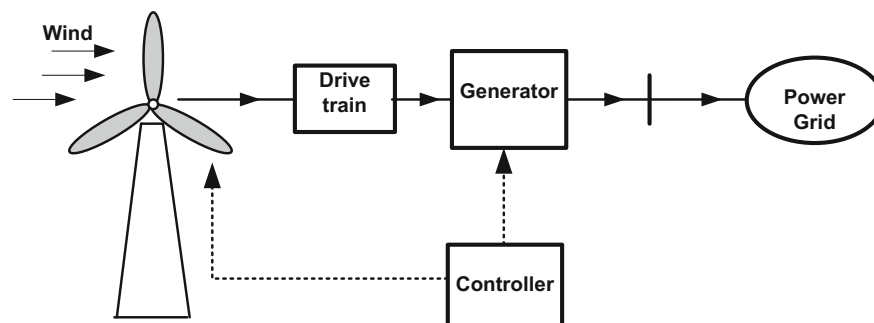**Fig. 4** Storage batteries diagram system interfacing DER

Fig. 5 Wind turbine generator system layout [41]

The operation of wind system requires adequate knowledge of average wind conditions as well as the information on the turbulent nature of the wind [42]. The knowledge of wind turbulence of a given site is necessary for cost optimization of modern large wind turbines and it is crucial in the designing of the supporting structures for wind turbines [43]. It also helps in the design of appropriate control system that can mitigate the impact of structural loading on wind turbine resulting from the turbulent wind [44].

One of the most important criteria for determining the feasibility of a wind project is the level of wind resource available. The amount of energy that can be harnessed from the wind is greatly dependent on the wind speed. Small to medium size wind turbines generally need at least a class two wind resource, which averages 4.1–4.9 m per second. To easily explain the wind turbine design and its aerodynamic characteristics, first consider the speed of wind as a random variable. The Weibull distribution function with two parameters is commonly used to describe a wind speed data [45]. It provides a convenient representation of the wind speed data for wind energy calculation purposes. The general representation of the Weibull distribution is given by:

$$F(V_{\text{wind}}) = (\eta/c)(V_{\text{wind}}/c)^{\eta-1} \exp(-(V_{\text{wind}}/c)^{\eta}) \tag{2}$$

where V_{wind} is the wind speed (m/s), c is the scale factor of the Weibull distribution with unit of speed, and η is the shape factor of the Weibull distribution, which is dimensionless. There are several methods for calculating the parameters of the Weibull wind speed distribution for wind energy analysis. Generally, we can calculate the two parameters using the following expression:

$$\eta = (\sigma_{\text{w}}/V_{\text{mean}})^{-1.086} \text{ and } c = \frac{V_{\text{mean}}}{\gamma(1+1/\eta)}, \tag{3}$$

where the γ is the gamma function, V_{mean} is the average value of wind speed data, and σ_{w} is the standard deviation of the wind speed data.

The mechanical part of the wind turbine consists of a yaw system, a pitch system, blades, a tower, and a gearbox in which the extracted wind power from air moving mass is transmitted to electrical system, i.e., generator for electric power generation. The extracted power can be expressed as [46, 47]:

$$\begin{cases} P_{\text{m}} = \frac{\rho}{2} A_r V_{\text{wind}}^3 C_{\text{p}}(\lambda, \beta) \\ \lambda = R_T \times \omega_T / V_{\text{wind}} \end{cases}, \tag{4}$$

where P_{m} is the mechanical active power in watts, ρ is the air density in kg/m^3, A_r represents the surface area swept by the blade in m^2, V_{w} stands for the wind velocity in m/s, and $C_{\text{p}}(\lambda, \beta)$ is the power coefficient which is a function of the tip speed ratio (i.e., λ) of the turbine blade and its pitch angle (i.e., β) in degree. Also, R_T represents the radius of the rotor in meter while ω_T is the mechanical speed of the rotor in rad/s.

Based on (4), the torque output by the wind turbine can be expressed as [48]:

$$T = \rho \pi R^3 C_p(\lambda, \beta) V_{wind}^2 / 2\lambda. \tag{5}$$

Therefore, referring to (4) above, the rotor speed can be regulated to maintain λ at its optimum value λ_{opt} and C_p at its maximum designed value C_{pmax}. In this case, the maximum power captured by the wind turbine is given by [49]:

$$P_{max} = \rho \pi R^5 C_{p\,max} \omega_{opt}^3 / 2\lambda_{opt}^3 = k_{opt} \omega_{opt}^3 \tag{6}$$

and the maximum torque is

$$T_{max} = \rho \pi R^5 C_{p\,max} \omega_{opt}^2 / 2\lambda_{opt}^2 = k_{opt} \omega_{opt}^3 \tag{7}$$

where k_{opt} is the constant which is determined by the wind characteristics. The coefficient C_p can be approximated using the wind turbine characteristics [48, 49]:

$$\begin{cases} C_p(\lambda, \beta) k_1 \left(\frac{k_2}{\lambda_1} - k_3\beta - k_4\right) e^{\frac{-k_5}{\lambda_i}} + k_6\lambda, \\ \frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{cases}, \tag{8}$$

where the coefficients k_1–k_6 depend on the wind turbine design characteristics which are given by $k_1 = 0.5176$, $k_2 = 116$, $k_3 = 0.4$, $k_5 = 21$, and $k_6 = 0.0068$ [50].

Therefore, it is important to install the turbine where the wind resource is at high speeds. It should also be noted that wind speed increases with elevation. The wind shear is a variable that describes how much the speed differs with elevation. Data collection of wind speeds and direction will need to be conducted for a minimum of 1 year [49–51].

2.1.6 Fuel Cell

A fuel cell consists of two electrodes, the anode and the cathode, separated by an electrolyte [52]. Thin layer of platinum or other metals, depending on the type of the fuel cell, is coated on each electrode to activate the reaction between oxygen and hydrogen when they pass through the electrodes. The overall reaction is shown by the equation below [53]:

$$H_2\,(g) + \frac{1}{2}O_2\,(g) \rightarrow H_2O(1) \quad \Delta H = -287 kJ\,mol^{-1}. \tag{9}$$
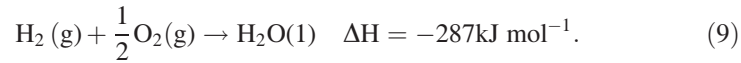
There are five major types of fuel cells generally available in the market. All of them have the same basic design as mentioned, but with different chemicals used as the electrolyte [54]. These fuel cells are the following: Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC),

Solid Oxide Fuel Cell (SOFC), and Proton Exchange Membrane Fuel Cell (PEMFC). These fuel cells require fairly pure hydrogen fuel to run. However, large amount of hydrogen gas is difficult to transport and store [55].

2.1.7 Gas-Fired Power Stations

Gas-fired power stations generate electricity by burning natural gas. A distinction must be made between gas turbine power stations and gas-fired steam power stations. Quick-start plants of this nature are used especially when power fluctuations or grid outages have to be made up for in short order and more electricity has to be made available extremely quickly [56]. What is special about gas-fired power stations is that they are among the few types of power station that are peak load-capable. In other words, gas-fired power stations can be run up from stationary to peak capacity in a matter of minutes. Quick-start plants of this nature are used especially when power fluctuations or grid outages have to be made up for in short order and more electricity has to be made available extremely quickly [57].

2.1.8 Diesel Generators

A standby generator consists of an engine-driven generator that is used to provide auxiliary power during solar blackouts or when the battery power discharge reaches a minimum level. The output of the diesel generator is connected to the auxiliary input of the inverter and engines that drive the motors operate with gasoline, diesel, natural gas, propane, or any type of fuel [58]. As an option, the diesel generators can be equipped with remote monitoring and annunciation panels that indicate power generation data log and monitors the functional and dynamic parameters of the engine, such as coolant temperature, oil pressure, and malfunctions [59]. Engines also incorporate special electronic circuitry to regulate the generator output frequency, voltage, and power under specified load conditions [60]. The diesel Generators are best used for backup power during long periods of little or no wind. Under these circumstances the diesel generator runs just long enough to provide the batteries with their bulk stage charge and for a portion of the absorption charging stage [61, 62].

2.2 *Comparison of Production Energies Options*

Apart from its own merits, PV technology system is considered the best option for many projects because of the potential state of development of other RETs in the most of the countries. PV power is estimated to be the most expensive RET option and micro-hydro is attractive on a cost basis [63]. Table 1 provides a summary of

Table 1 Comparison of various energy production options [64]

Factors	PV	Fossil fuels	Wind turbines	Micro-hydro	Municipal solid waste/biomass
Stakeholder interest Leadership and/or investment—government	High	Not applicable	High	Medium	High
Stakeholder interest Private sector and general public	High	Not applicable	Medium	Low	High (5 companies, 3 foreign, 2 local, have participated in tender)
Cost Overall cost per unit of electricity	High (but costs are steadily decreasing)	Medium (with risk of significant cost increases)	High	Low	Low
Cost Up-front capital costs	High	Medium	High	High	High
Cost Availability of financing	Low	Medium (Govt. subsidies to end)	High (grant)	Low	High (financing in place)
Technical feasibility Complexity of technology	High (simple, proven technology)	High (already exists)	Medium (complex, new to country)	High	Low
Technical feasibility Grid compatibility	High	Very high (already exists)	Medium	expensive	average
Technical Feasibility Site suitability	High (many sites can be used)	Very high (already exists)	Low (few sites possible)	Low (very few sites)	High (existing landfill)
Technical feasibility Reliability of supply	High	High (although risk exists of supply disruptions)	Low (winds are highly seasonal)	Low (rainfall is highly seasonal)	Medium
Social benefits Job creation	High	Medium	Low	high	high
Social benefits Human health (air quality)	High	Low	High	High	Medium
Social benefits National energy security	High (if there is widespread adoption)	Low (vulnerable to price fluctuations; supply disruptions)	High	Low (total potential is 1.8 MW)	Medium

the strengths and weaknesses of the various RETs in comparison to one another, and to the existing fossil fuel-based energy production system.

This is with regard to the financial costs of solar PV and other renewable energy technologies (RETs) as compared to the existing fossil fuel-based energy production in many developed countries. PV systems are currently a competitive option for energy production in many of the countries in the world.

3 Contribution of Renewable and Nonrenewable Resources into the Microgrid System

In this section of this chapter, a microgrid system has been considered as a case of study with the objective to show how the voltage and the frequency can be controlled when there are disturbances with the plan to keep the system running properly.

3.1 Microgrid System Configuration

Figure 6 presents the typical MG system to be taken into consideration during performance evaluation. The main components of the MG system are the Wind, PV, diesel systems, batteries energy storage system (BESS) and loads. The BESS is entitled to supply power to the system when there is lake of power from both diesel generator and PV systems.

3.2 Problem Formulation

3.2.1 System Description

The MG used in this work is presented in Fig. 6. The system is composed of three energy sources namely, a diesel generator, PV system, and their associated battery storage systems. Additionally, from the consumer's side, there are two identical loads which are noncritical P_{L1} and $P_{L_2}^c$. The power from the diesel generator system is considered to be produced at lowest cost and to keep its value as long as the MG is operating. The aim is to meet the demand with the capacity of power delivery and the control of voltage and frequency to the hybrid system. The modeling of the MG under frequency load shedding (UFLS) scheme can be done according to the logical method of solving this kind of problem.
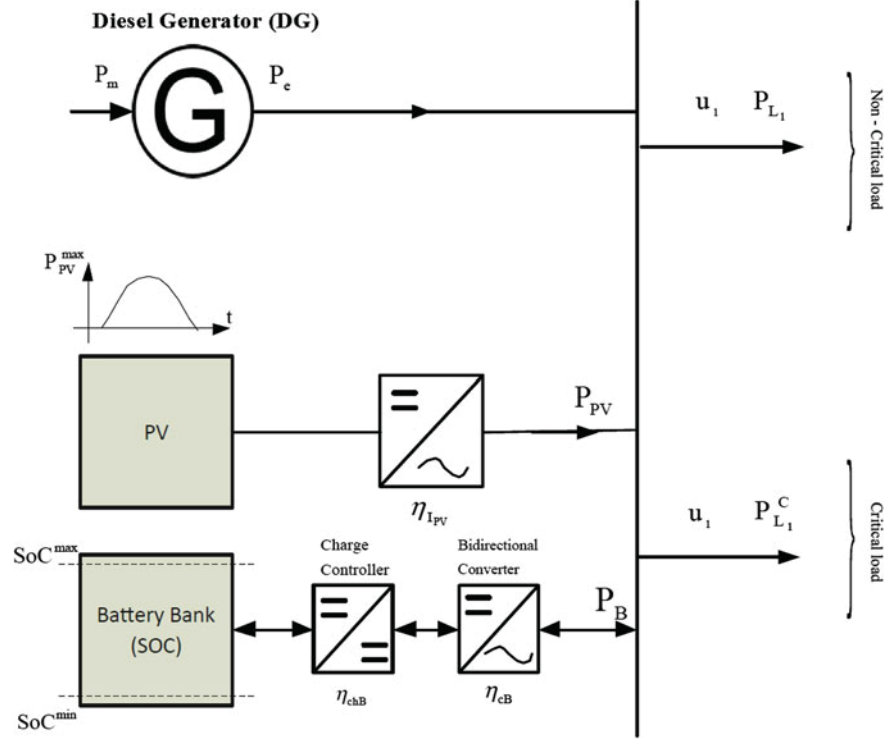
Fig. 6 Typical configuration of microgrid system with renewable energy resources

3.2.2 Objective Function

The objective of this work is to minimize the cost of the fuel and the noncritical power consumption by incorporating switches as control devices to the model operating on ON/OFF. Both switches are applied to the number of variables in accordance with number of samples N_s during the operation period of the hybrid system. Mathematically, this can be written as optimal control problem where the control objective is the minimization of the cost of the total daily energy produced by the diesel generator to the loads. This problem can be characterized by the Eq. (10) as follow:

Objective function:

$$\min C_f \sum_{i=1}^{N_s} [aP_{DG}^2(j) + bP_{DG}(j) + c] \times \Delta t, \quad (1 \leq i \leq N_s), \tag{10}$$

where C_f is the cost of the fuel used to run the DG; a, b, and c are respective factors applied to the fuel properties; Δt is the variation of time during what the hybrid system will be operating daily; P_{DG} is the output power from the diesel generator

system to the hybrid system; i is the number of horizon, and N_s is the number of samples considered for the optimization study of the hybrid system.

3.2.3 Constraints

The constraints equations of the system are characterized by the main expressions which are power balance, frequency constraint, state of charge of the battery bank, and boundary constraints of the control variables considered for this study into the MG system.

(a) *Power balance equation*

The power balance generated at the common point of the connections should be greater or equal to the total power demand at the same point. We can write the Eq. (11) as follows:

$$P_e(k) + P_{PV}(k) \pm P_B(k) \geq \sum_{i=1}^{n^{\text{Load}}} P_L \times u_i, \quad \left\{ \begin{array}{l} 1 \leq i \leq n^{\text{Load}} \\ 1 \leq k \leq N_s \end{array} \right\} \tag{11}$$

where $P_L(t)$ is the power demand of the ith critical load at time t; $P_e(k)$ is the electrical power from the diesel generator, $P_{PV}(k)$ is the output power from the PV system, $P_B(k)$ is the output power from the battery system, u_i is the switch applied to each load, and n^{Load} is the number of loads to be supplied into the hybrid system.

(b) *Frequency constraint*

The speed of the diesel generator in the MG power system changes in direct proportion to frequency. As frequency drops in the system, the selected diesel generator will turn slower and supply less energy. The accelerated power of the small hydropower generator is written by the expression (12) as follows [60]:

$$\begin{cases} P_a = M\dfrac{d\omega_d}{dt} = P_m - P_e \\ M = \dfrac{GH}{\pi f_s} \\ \omega_d = \omega_e - \omega_s \end{cases}, \tag{12}$$

where G is the machine rating (base) expressed in MVA; H is the inertia constant in MJ/MVA; f_s is the synchronous frequency expressed in Hz, and the considered value is (60 or 50 Hz); M is the moment of inertia in MJ/MJ/rad/s; ω_d is the electrical rotor speed displacement from synchronously rotating reference frame; ω_s is the synchronous speed of the synchronous machine; ω_e is the electrical rotor speed of the machine.

The motion Eq. (12) of the generator can also be expressed in the discrete-time domain and is written as the expression (13):

$$M \frac{\omega(k) - \omega(k-1)}{\Delta t} = P(k-1) - P(k-1), \tag{13}$$

In another form, Eq. (13) can be rewritten as (14) below:

$$\omega_d(k) = \omega_d(k-1) + \frac{\Delta t}{M} [P_m(k-1) - P_e(k-1)]. \tag{14}$$

By recurrence manipulation, the displacement speed $\omega_d(k)$ can be expressed in terms of its initial value, $\omega_d(0)$ as follows:

$$\omega_d(k) = \omega_d(0) + \frac{\Delta t}{M} \sum_{\tau=1}^{k} P_m(\tau) - \frac{\Delta t}{M} \sum_{\tau=1}^{k} P_e(\tau). \tag{15}$$

The boundary constraints of the frequency constraints are therefore written as follows:

$$\omega_d^{\min}(k) \leq \omega_d(0) + \frac{\Delta t}{M} \sum_{\tau=1}^{k} P_m(\tau) - \frac{\Delta t}{M} \sum_{\tau=1}^{k} P_e(\tau) \leq \omega_d^{\max}(k). \tag{16}$$

(c) *State of charge of battery bank*

The state of charge of the battery bank as shown in Fig. 6 can be expressed in discrete-time domain, by the following equation:

$$SoC(k) = SoC(k-1) - \frac{\Delta t}{C_n} P_B(k-1), \tag{17}$$

where C_n is the nominal capacity of the battery bank. The state of charge (SoC) can be expressed in terms of its initial value, SoC(0) by the following expression:

$$SoC(k) = SoC(0) - \frac{\Delta t}{C_n} \sum_{\tau=1}^{k} P_B(\tau). \tag{18}$$

The lower and upper limits on the state of charge of the battery bank are expressed as:

$$SoC^{\min}(k) \leq SoC(0) - \frac{\Delta t}{C_n} \sum_{\tau=1}^{k} P_B(\tau) \leq SoC^{\max}(k). \tag{19}$$

(d) *Boundary constraints of control variables*

The boundary constraints of the considered variable parameters into the MG system under frequency load shedding scheme are explained and written by their appropriated from Eqs. (20)–(23) as follows:

The active power of the DG is defined as the real part of the complex variable of the apparent power. This quantity is physically limited in the selected generator. The lower and upper generator active power limits are expressed by Eq. (20) as follows:

$$P_e^{\min} \leq P_e(k) \leq P_e^{\max} \quad (1 \leq k \leq N_s). \tag{20}$$

The power generated by PV system is defined to be the real variable. This quantity is physically limited in the selected PV plant. Thus, the lower and upper boundaries of PV active power limits are expressed as in Eq. (21):

$$P_{PV}^{\min}(k) \leq P_{PV}(k) \leq P_{PV}^{\max}(k), \quad (1 \leq k \leq N_s). \tag{21}$$

The output power of the battery bank is also defined as the real-active power. This quantity is physically limited in the selected batteries. The lower and upper capacities limits are expressed by the Eq. (22) as follows:

$$P_B^{\min}(k) \leq P_B(k) \leq P_B^{\max}(k), \quad (1 \leq k \leq N_s). \tag{22}$$

The variations of the network frequency and voltage variables must be maintained under certain limits. These quantities are physically limited for the selected equipment into the MG system. In this case, the lower and upper limits of frequency and voltage can be expressed by taking the system nominal frequency and voltage as in Eq. (23) with the following structure:

$$\begin{cases} f^{\min}(k) \leq f_{nom}(k) \leq f^{\max}(k) \\ V^{\min}(k) \leq V_{nom}(k) \leq V^{\max}(k), \quad (1 \leq k \leq N_s) \end{cases} \tag{23}$$

3.3 Simulation Results

For the adequate study, additional load data need to be provided in order to complete the design of power supply resources. The main the objective is that the supply side must meet the demand side capacities. Finally, the simulation results of the MG model under frequency load shedding scheme are presented in this section.

3.3.1 Optimization Algorithm

Several optimization methods of algorithm can be applied for the resolution of the concerns defined in this work. The mathematical modeling of the problem of the MG power system is a nonlinear objective function and there are some assumptions to be taken into account. The fmincon function in MATLAB is proposed to find the minimum of a constrained nonlinear multi-variable function. Otherwise fmincon finds a constrained minimum of a function of several variables. Because of these reasons, the fmincon function of MATLAB R2015 Optimization Toolbox is implemented to solve all the issues of this problem. The equation can be solved by this function is expressed as:

$$\min f(X) \tag{24}$$

subject to

$$\begin{cases} AX \leq b \,(\text{linear inequality constraint}), \\ A_{\text{eq}}X = b_{\text{eq}}(\text{linear equality constraint}), \\ C(X) \leq 0 \,(\text{nonlinear inequality constraint}), \\ C_{\text{eq}}(X) \leq 0 \,(\text{nonlinear equality constraint}), \\ L_{\text{b}} \leq X \leq U_{\text{b}} \,(\text{lower and upper bounds}). \end{cases} \tag{25}$$

For the optimal control equation, the vector X contains the feeders speed for all sampling intervals. The linear inequality constraints are integrated into A and b. The lower and upper boundary constraints Eqs. (20)–(23) are incorporated into L_{b} and U_{b}. The MATLAB code implemented to solve this problem has been applied using closed loop control system.
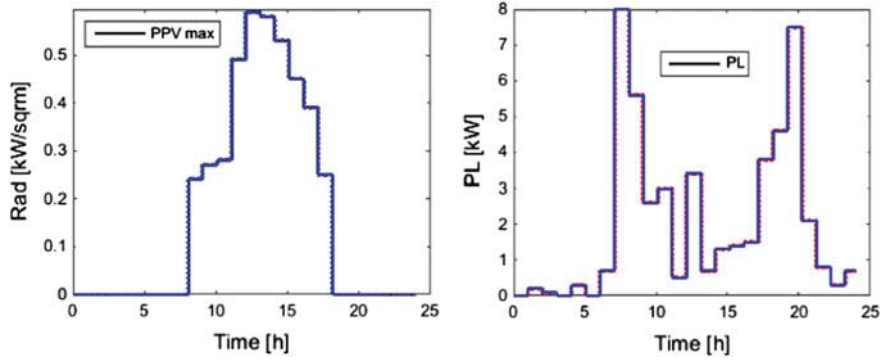

Fig. 7 Daily variations of global radiation and total load profile

Table 2 Simulation parameters [65, 66]

Item No	Parameter	Value
1	Diesel Generator	6 kW
2	Sampling time	1 h
3	Battery nominal capacity Battery maximum SOC Battery minimum SOC Battery discharging efficiency Battery charging efficiency	4 kWh or 84 Ah or 1 kW 95% 40% 100% 80%
4	Accepted Frequency Accepted Voltage	(50 ± 1.5) Hz (1 ± 0.05) pu
5	Diesel fuel price	1.4 $/l
6	Diesel Generator parameters	$a = 0.246$, $b = 0.0815$
7	PV system	0.7 kWmax

3.3.2 Typical Application

The total variation of the typical daily load profile PL [kW] of the consumers and the variation of the global radiation per square meter Rad [kW/sqm] for solar are given of in the Fig. 7.

Additionally, for doing the study of the MG system described in Fig. 6 presented under Sect. 3, it is required to have other parameters to be applied into the simulation of the power system that are given in the Table 2.

3.4 Results and Discussions

After simulating the MG system described in Fig. 6 of Sect. 3 with consideration of all the supply sources are operating at their full supply capacity, the results of the variation of the energy resources are given in the Fig. 8. From the results shown in Fig. 8, it seems that system is operating normal. We can also note that there is no need to shed any of the load as the system is running at full capacity with the main power supply from the diesel generator, PV unit compensated by battery system, making the system run without any problem. Additionally, the saving on the fuel is evaluated to 30% of the daily total consumption of the nominal consumption of the diesel generator. As the effect of variation of frequency and the voltage of the hybrid system are good and this can be seen from the Fig. 9. The results are characterized by two types of legends. The dashed red lines mean the maximum values while the black lines mean the normal values of parameters.

When the deliverable capacities of the supply system are not meeting their maximum capacities because of some of the disturbances such as default of the radiation, storage capacity problem, and malfunctioning of the diesel generator set for some reasons, these have impact on the frequency and voltage as shown in Fig. 10.
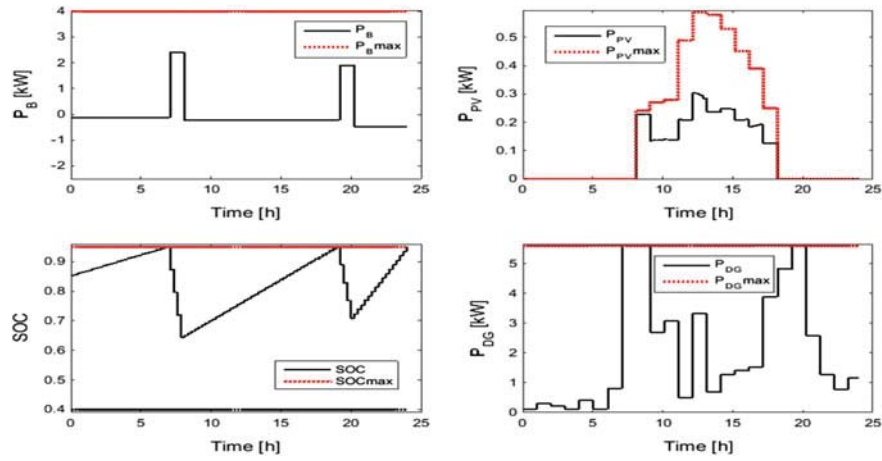
Fig. 8 Variation of the supply capacities of the hybrid system at full capacity
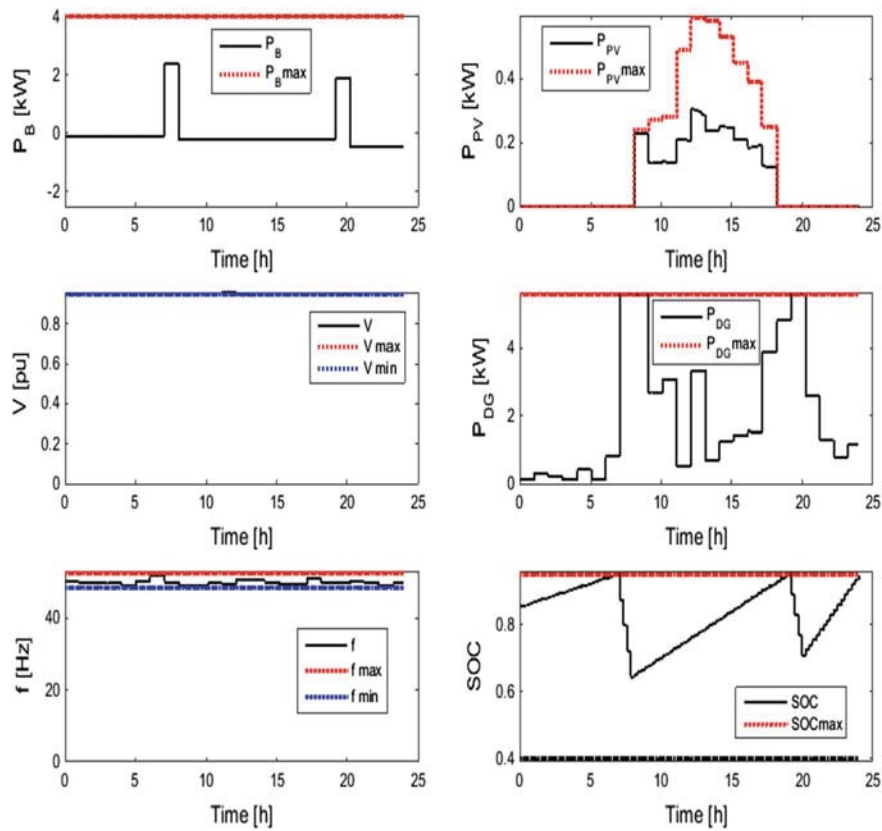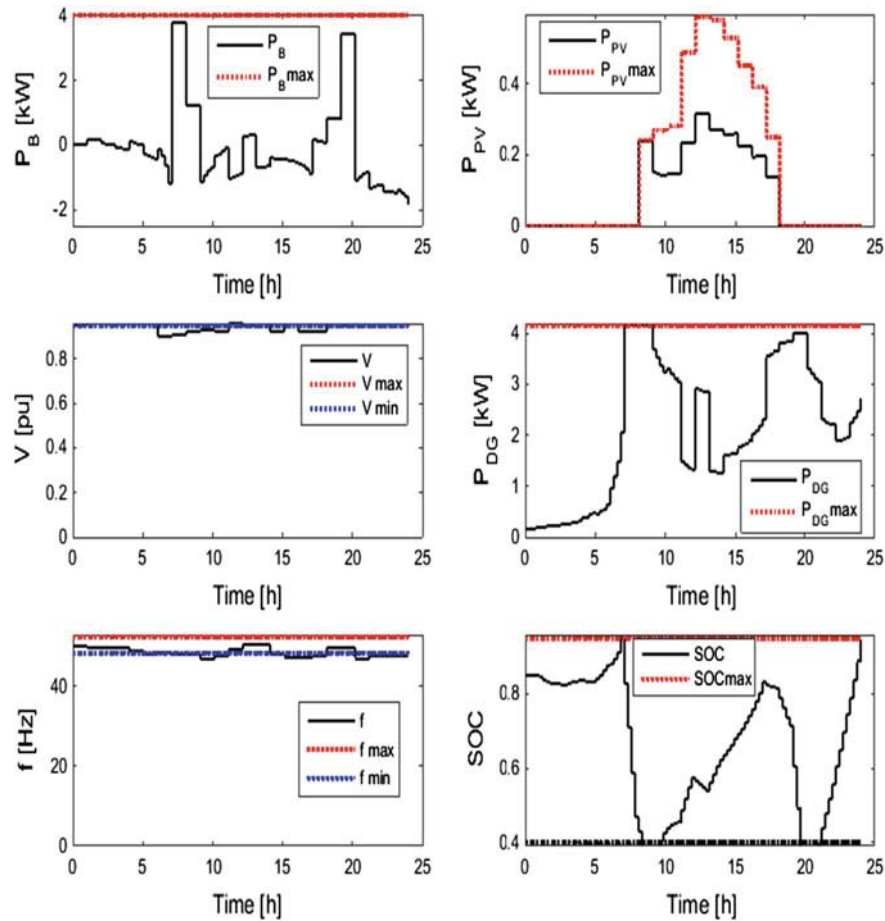

Fig. 9 Variation of the all the parameters of the hybrid system

Fig. 10 Variation of parameters of the hybrid system when the DG set and the PV are not running at its full capacity

The disturbance is caused especially when both the diesel generator and PV systems are running at 80% of their installed capacities and both loads are still connected to the bus. As consequence, the variations voltage and the frequency of the hybrid system are under the lower boundaries limits which is very dangerous for the system and this has effect on the shedding of one of the load.

As this can be seen in the Fig. 10, the variations of voltage, frequency and the State of Charge are not following the rules because of lack of power as both suppliers are not running at their full capacities. For that, the need to equilibrate the system is necessary. Therefore, the system is running under frequency load shedding and the only way to solve the problem is to compensate the supply side in such a way it still be at its required capacity for to balance the MG system.
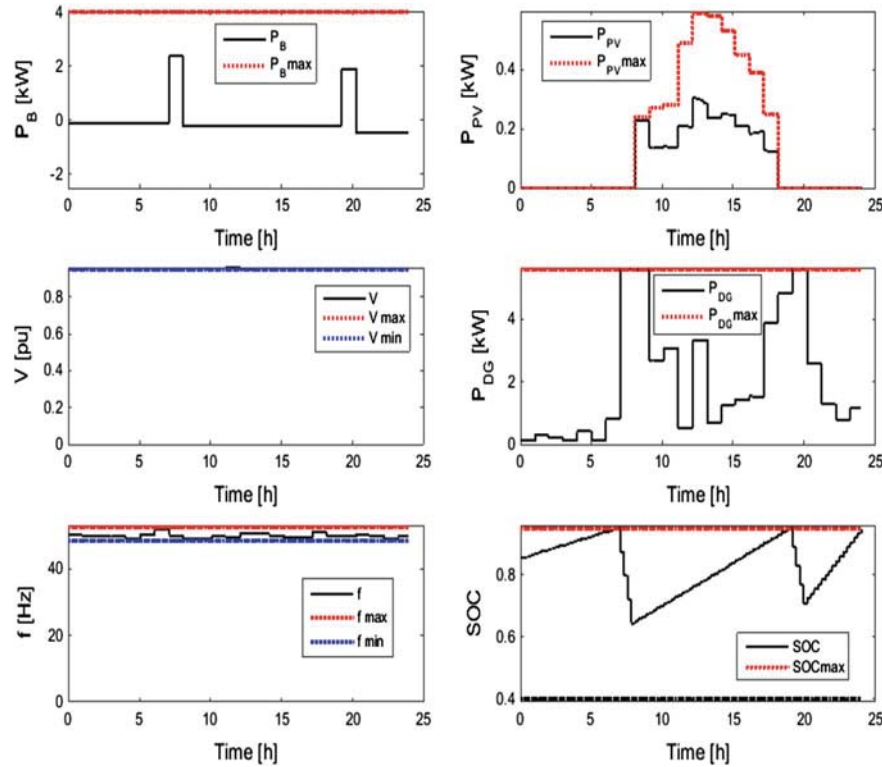
Fig. 11 Adjustment of the supply capacities to correct the voltage, the frequency and the state of charge of the hybrid system

After adjustment of the power from diesel generator set as shown in Fig. 11, the frequency and the voltage variations parameters have become normal which mean both parameters ranging between the average percentage limits of the nominal required values. In other words, no load shedding simply because the supply capacity has met the demand and it is concluded that the hybrid system is running under balancing condition.

4 Conclusion and Technical Challenges

The hybrid power system needs to be appropriately controlled with the objective to keep the system operating continuously. Especially when the main power supply is considered to be provided from the diesel generator, the reliability of the system is highly recommended in for the success of the both supplier and consumers. The fluctuations of the both frequency and the voltage into the microgrid system affect

the productivity of the system. When there is no additional source of power to compensate the existing sources of energy, this implies the elimination of one of the loads to avoid the unbalancing of the microgrid power system. In case of both critical and noncritical loads are still connected with supply side operating at its less required capacity, the consequence of this is the under voltage which automatically implies under frequency problem into the distribution system. The good way to solve the variation of the frequency and voltage into the microgrid system when there is unbalancing between the supply side capacity and demand side is to carefully control the system in such a way that in case of disturbance at the generator side as main supply capacity, the renewable energy need to compensate with additional power to keep very small the variation of the voltage and frequency. During the daytime, it always preferable to have the diesel generator set and PV running at their full capacities so that when nighttime will come the battery can still be able to supply the based load in the microgrid system. The effect of this, will keep the variation of both frequency and voltage very low and there will be no need to shed the load. The fluctuation of both frequency and voltage in the hybrid systems are not a factor to consider because this aspect has bad effect on the lifespan equipment used in term of maintenance and operating costs. Additionally, after this problem is well solved, also the productivity and the rentability of the hybrid system are achieved. As future recommendations for both off-grid and grid-connected microgrid systems, it is always preferable to provide a reserve renewable source of energy which may be efficient in price such as solar PV system to compensate the existing suppliers and to save the operating cost of the diesel generator. A second generator unit as a spare supplier source of energy is not preferable because of the increase of the operating cost of the system which will affect the rentability of the power system and the pollution of the atmosphere. Finally, to prevent the increase of carbon emission, the use of quick renewable energy such as PV system is the best and simple solution to be applied as described in this chapter which is considered as clean energy to keep both the population and environment safe.

References

1. Ochoa LF, Harrison GP (2011) Minimizing energy losses: optimal accommodation and smart operation of renewable distributed generation. IEEE Trans Power Syst J 26(1):198–205
2. Frias P, Gomez T, Cossent R, Rivier J (2009) Improvement in current European network regulation to facilitate the integration of distributed generation. Electr Power Energy Syst J 31:445–451
3. Zobaa AF, Bansal RC (eds) (2011) Handbook of renewable energy technology. World Scientific Publishers, Singapore
4. Chowdhury AA, Agarwal SK, Koval DO (2003) Reliability modelling of distributed generation in conventional distribution systems planning and analysis. IEEE Trans Ind Appl J 39(5):1493–1501
5. Zobaa AF, Cantelli M, Bansal RC (eds) (2011) Power quality-monitoring, analysis and enhancement. INTECH-Open Access Publishers

6. Tsikalakis AG, Hatziargyriou ND (2008) Centralized control for optimizing microgrids operation. IEEE Trans Energy Convers J 23(1):241–248
7. Sao CK, Lehn PW (2008) Control and power management of converter fed microgrids. IEEE Trans Power Syst J 23(3):1088–1098
8. Bansal RC, Bhatti TS (2008) Small signal analysis of isolated hybrid power systems: reactive power and frequency control analysis. Alpha Science International, Oxford, U.K
9. Gil HA, Joos G (2008) Models for quantifying the economic benefits of distributed generation. IEEE Trans Power Syst J 23(2):327–335
10. Hung DQ, Mithulananthan N, Bansal RC (2013) A combined approach of DG, capacitor placement and reconfiguration for loss reduction in distribution networks. Appl Energy J 105:75–85
11. Qiang L, Lin Z, Ke G (2011) Review on the dynamic characteristics of micro grids system. In: IEEE conference on industrial electronics and applications, Singapore, 18–20 July 2011
12. Andersson G, Donalek P, Farmer R et al (2005) Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve System Dynamic Performance. IEEE Trans Power Syst J 20(4):1922–1928
13. Nagliero A, Mastromauro RA, Monopoli VG, Liserre M, Dell'Aquila A (2010) Analysis of a universal inverter working in grid-connect, stand alone and microgrid. In: IEEE international symposium on industrial electronics, Bari, 4–7 July 2010
14. Mazheruddin HS, Zeineldin HH, El Moursi MS (2013) Grid code violation during fault triggered islanding of hybrid micro-grid. In: IEEE PES international conference on innovative smart grid technologies, Washington DC, 26–27 Feb 2013
15. Radzi NH, Bansal RC, Dong ZY, Hassan MY, Wong KP (2013) An efficient distribution factors enhanced transmission pricing method for Australian NEM transmission charging scheme. Renew Energy J 53:319–328
16. Pan QK, Wang L, Qian B (2009) Review on operation of micro grids and virtual power plants in the power markets. In: IEEE international conference on adaptive science and technology, Ghana, 14–16 Jan 2009
17. Wang J, Wang Z, Xu L, Wang Z (2012) A summary of application of D-FACTS on microgrid. In: IEEE international conference on Asia Pacific power and energy engineering, Shanghai
18. Gidwani L, Tiwari H, Bansal RC (2013), Improving power quality of wind energy conversion system with unconventional power electronic interface. Electr Power Energy Syst J 44(1): 445–453
19. Xue-Song Z, Li-qiang C, You-jie M (2011) Research on control of microgrid. In: Third IEEE international conference on measuring technology and mechatronics automation, Shanghai, 6–7 Jan 2011
20. Laghari JA, Mokhlis H, Bakar AH, Mohamad H (2013) Application of computational intelligence techniques for load shedding in power systems: review. Energy Convers Manage J 75:130–140
21. Mahat P, Zhe C, Bak-Jensen B (2010) Under frequency load shedding for islanded distribution system with distributed generators. IEEE Trans Power Deliv J 10(25):911–918
22. Rudez U, Mihalic R (2009) Analysis of under frequency load shedding using a frequency gradient. IEEE Trans Power Deliv J 26(2):565–575
23. Bhatti TS, Bansal RC, Kothari DP (eds) (2004) Small hydro power systems. Dhanpat Rai & Sons, India
24. Katiraei F, Iravani R, Hatziargyriou N, Dimeas A (2008) Microgrids management. IEEE Power Energy Manage J 6(3):54–65
25. Bernhard S, Marland G (1997) The role of forest and bioenergy strategies in the global carbon cycle. Biomass Bioenergy 10(5–6):275–300
26. Bansal RC (2013) Renewable energy systems. In: Beaty HW (ed) Standard handbook for electrical engineers, 16th edn. McGraw-Hill, pp 11-5–11-10
27. Bernde G, Monique H, Richard VDB (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy J 25(1):1–28

28. Levron Y, Guerrero JM, Beck Y (2013) Optimal power flow in microgrids with energy storage. IEEE Trans Power Syst J 28(3):3226–3234
29. Sigrist L, Egido I, Rouco L (2013) Principles of a centralized UFLS scheme for small isolated power systems. IEEE Trans Power Syst J 28(2):1779–1786
30. Song Z, Liu J, Liu1 Y, Bazargan M (2013) A method for the design of UFLS scheme with dynamic correction. Energy Power Eng J 5:442–447
31. Rao YS, Laxmi AJ, Kazemineha M (2012) Modeling and control of hybrid photovoltaic conversion system. Int J Adv Eng Technol J, 2231–1963
32. Valenciaga F, Puleston PF (2005) Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy. IEEE Trans Energy Convers J 20(2):398–405
33. Kim XJ, Guerrero JM, Rodriguez P, Teodorescu R, Nam K (2011) Mode adaptive droop control with virtual output impedances for an inverter-based flexible AC microgrid. IEEE Trans Power Electron J 26(3):689–701
34. Rostamirad S, Wang K, Marti JR (2011) Power management in disasters: application of load shedding and wind turbine controllers. In: IEEE Canadian conference on electrical and computer engineering, connecting engineering applications and disaster management workshop, Niagara Falls, Ontario
35. Lu X, Guerrero JM, Sun K, Vasquez JC (2014) An Improved droop control method for DC microgrids based on low bandwidth communication with DC bus voltage restoration and enhanced current sharing accuracy. IEEE Trans Power Electron J 29(4):1800–1812
36. Biswas MM, Kamol KD, Baqee IA, Mohammad AH, Farhad HMS (2011) Prospects of renewable energy and energy storage systems in Bangladesh and developing economics. Glob J Res Eng J 11
37. Islam MS, Mondal T (2013) Potentiality of biomass energy for electricity generation in Bangladesh. Asian J Appl Sci Eng 2(2):2305–2915
38. Mamun MRA, Kabir MS, Alam MM, Islam MM (2009) Utilization pattern of biomass for rural energy supply in Bangladesh. Sustain Crop Prod J 4(1):62–71
39. Gonzalez-Espin F, Chang N, Valdivia-Guerrero V, Foley R (2013) Configuration, modelling and control of a microgrid for commercial buildings application. In: 15th European conference, power electronics and applications (EPE), Lille, 2–6 Sept 2013
40. Antar B, Hassen B, Babes B, Afghoul H (2015) Fractional order PI controller for grid connected wind energy conversion system. In: 4th international conference, electrical engineering (ICEE), Boumerdes, 13–15 Dec 2015
41. Majumder P, Ghosh A, Ledwich G, Zare F (2011) Power management and power flow control with back-to-back converters in a utility connected microgrid. IEEE Trans Power Syst J 25(2)
42. Govindaraj T, Hemalatha D (2014) Dynamic reactive power control of islanded microgrid using IPFC. Innov Res Electr Electron Instrum Control Eng J 2(1)
43. Zhang Y, Ruan J, Zhan T (2012) Electromagnetic force analysis of a driving coil. In: 16th international symposium on electromagnetic launch technology (EML), Beijing, 15–19 May 2012
44. Peng Q (2010) Harmonic coil design, fabrication and commissioning for European XFEL linear accelerator superconducting magnets field measurements. IEEE Trans Appl Supercond J 20(3):2015–2018
45. Polak M (2006) Properties of a YBCO pancake coil operating with AC current at frequencies up to 1000. IEEE Trans on Appl Supercond J 16(2):1423–1426
46. Jardini JA, Tahan CMV, Gouvea MR, Ahn SU, Figueiredo FM (2000) Daily load profiles for residential, commercial and industrial low voltage consumers. IEEE Trans Power Deliv J 15(1):375–380
47. Mohideen R (2012) The implications of clean and renewable energy development for gender equality in poor communities in South Asia. In: IEEE conference on technology and society in Asia, Singapore, 27–29 Oct 2012
48. Pfluger B, Wietschel W (2012) Impact of renewable energies on conventional power generation technologies and infrastructures from a long-term least-cost perspective. In: 9th international conference on the European energy market, Florence, 10–12 May 2012

49. Mehrizi-Sani A, Iravani R (2010) Potential-function based control of a microgrid in islanded and grid-connected modes. IEEE Trans Power Syst J 25(4):1883–1891
50. Lamberti T, Sorce A, Di Fresco L, Barberis S (2015) Smart port: exploiting renewable energy and storage potential of moored boats. In: IEEE conference OCEANS, Geneva, 18–21 May 2015
51. Lopes VS, Borges CLT (2015) Impact of the combined integration of wind generation and small hydropower plants on the system reliability. IEEE Trans Sustain Energy J 6(3):1169–1177
52. Ammar M, Joos G (2013) Impact of distributed wind generators reactive power behavior on flicker severity. IEEE Trans Energy Convers J 28(2):425–433
53. Borkowski D, Węgiel T (2013) small hydropower plant with integrated turbine-generators working at variable speed. IEEE Trans Energy Convers J 28(2):452–459
54. Gallego JD, Franco CJ, Zapata S (2015) Policies for the utilization of hydropower potential in Colombia using small plants. IEEE Trans Latin America J 13(12):3844–3850
55. Li YH, Rajakaruna S, Choi S (2007) control of a solid oxide fuel cell power plant in a grid-connected system. IEEE Trans Energy Convers J 22(2):405–413
56. Tsourapas V, Sun J, Stefanopoulou A (2009) Incremental step reference governor for load conditioning of hybrid fuel cell and gas turbine power plants. IEEE Trans Control Syst Technol J 17(4):756–767
57. Hawkes AD, Leach MA (2009) Modelling high level system design and unit commitment for a microgrid. Appl Energy J 86(7–8):1253–1265
58. Niwas R, Singh B, Goel S, Jain C (2015) Unity power factor operation and neutral current compensation of diesel generator set feeding three-phase four-wire loads. IET Gener Transm Distrib J 9(13):1738–1746
59. Yang WH, Zhao SN, Wang KH, Li W, Ma JY (2009) Greenhouse effect reduction in biomass power plant: a case study. In: 3rd international conference on bioinformatics and biomedical engineering, Beijing, 11–13 June 2009
60. Chakraborty S, Weiss MD, Simoes MG (2007) Distributed intelligent energy management system for a single-phase high-frequency AC microgrid. IEEE Trans Ind Electron J 54(1):97–109
61. Jalilnezhad Z (2010) Feasibility study of anaerobic digester for biogas plant in FEKA dairy farm. A report prepared by the FEKA dairy farm
62. Hunter R, Elliot G (eds) (1994) Wind-diesel systems: a guide to the technology and its implementation. Cambridge University Press
63. Pouresmaeil E, Montesinos-Miracle D, Gomis-Bellmunt O (2012) Control scheme of three-level NPC inverter for integration of renewable energy resources into AC grid. IEEE Syst J 6(2):242–253
64. Kamiev K, Nerg J, Pyrhönen J, Zaboin V, Tapia T (2014) Feasibility of an armature-reaction-compensated permanent-magnet synchronous generator in island operation. IEEE Trans Ind Electron J 61(9):5075–5085
65. Barklund E, Pogaku N, Prodanovic M, Hernandez-Aramburo C, Green TC (2007) Energy management system with stability constraints for stand-alone autonomous microgrid. In: IEEE international conference on system of systems engineering, San Antonio, TX, pp 1–6
66. Chen C, Duan S, Cai T, Liu B, Hu G (2011) Smart energy management system for optimal microgrid economic operation. IET-Renew Power Gener J 5(3):258–267