

Microgrids Overview and Performance Evaluation on Low-voltage Distribution Network

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ABSTRACT: Besides the increase in global energy demand, access to clean energy, reduction in greenhouse gas emissions caused by conventional power generation techniques, energy security, and availability of electricity in remote villages in emerging nations are some of the factors that foster the use of renewable energy sources (RESs) in generating electricity. One of the aims of initiating microgrids (MGs) is to maximize the benefits of RES while alleviating grid-connect issues. Microgrids are interconnected RESs and electrical loads within clearly delineated electrical limits that operate as individual controllable units on the electrical network. It can operate independently and be grid-connected. The paper presents a review and performance assessment of renewable energy-based microgrids under various operating scenarios in stand-alone, grid-connected, and transitioning modes of operation. Fault occurrences, an increase in micro-source generation, a load increase, and the sudden disconnection of a micro-source are some of the simulated scenarios. Microgrid network components' performance, such as the bidirectional DC-DC converter and energy storage system (ESS), was evaluated. The simulated microgrid architecture includes a small hydroelectric plant, wind farm, and ESS. The work provides valuable information to energy stakeholders on the performance of microgrids in low-voltage distribution networks. The microgrid is coupled to a low-voltage distribution network (0.415 kV) via a PCC. The system under investigation is modeled and simulated using MATLAB/Simulink. From the simulation analysis, the fault effect was felt on the utility and did not escalate to the microgrid side during stand-alone operation. Power quality issues, such as voltage rise, are some of the challenges identified during the transition from one mode of operation to another. However, the energy storage system responds to disturbances and maintains system stability. The originality of this paper is based on evaluating different modes of operation of microgrids and comparing system performances under various operating conditions.

Keywords: Microgrid; Small hydropower plant; Wind farm; Battery energy storage systems; Grid-connected; Stand-alone mode; Power quality



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1. Introduction

Population growth, technological innovation, access to clean energy, and environmental concerns are some of the factors that compelled governments and scholars across the globe to hunt for alternate ways to generate electricity to fulfill the world's continual increase in energy demand. Furthermore, due to considerations such as geographical location, lack of accessibility, and transportation infrastructure restrictions, a considerable proportion of rural and remote areas in Sub-Saharan Africa lack access to a steady power supply [1–3]. Some of the conventional tactics deployed by the utility to address these challenges have not yielded positive outcomes. However, with the recent advancement in technology, renewable energy sources (RESs) are one of the possible solutions to these issues. Renewable energy provides cleaner energy and is capable of supplying electricity to rural areas and communities [4]. Integrating RESs into distribution networks offers utilities and electricity consumers different technical, conservational, and financial benefits [5–7]. The direction of power flow on the grid has also changed from unidirectional to bidirectional due to the emerging technology of grid integration of RESs. Power distribution operators and consumers are impacted positively and negatively by the change in the flow of power [8,9]. The concept of renewable energy-based microgrids was developed by researchers and governments to maximize the benefits and alleviate grid integration limitations [10,11]. Microgrid enhances grid integration of renewable energies, reduces transmission and distribution losses, and offers a dependable electricity supply. According to [4], a microgrid is a power network unit that uses small power-generating sources, such as RESs and other distributed generation sources, connected with energy storage devices to meet the load demand. Microgrids can be classified into AC microgrids, DC microgrids, and hybrid microgrids. AC microgrid can be integrated into an existing traditional utility network

without a special control system. DC microgrid is a distribution network comprising DC loads, energy storage systems, and renewable energy sources which are mainly DC output voltage. A hybrid microgrid is a group of interconnected conventional and renewable energy resources that are connected to end users and regulated by systems to enhance effective energy storage and use. The hybrid AC-DC microgrid enables simultaneous connection of variable AC and DC sources and their corresponding loads while reducing the number of power conversions required in individual AC or DC microgrids. According to [12], DC microgrids based on distributed generation allow DC electricity to be utilized directly in DC household appliances. Because these systems eliminate the need for the AC-DC conversion step and improve electricity consumption, they have become more and more popular in a variety of fields. Furthermore, according to [12], the use of DC microgrids can be grouped into three different modes. Mode A is the DC microgrid powered by the commercial network. A standalone DC microgrid with energy storage as power supply to the load is considered model B, while a standalone DC microgrid with energy storage for energy support is considered model C. Some of the technical issues associated with low-voltage DC microgrids such as Instability issues at LVDC-MGs, harmonics, virtual resistors, over-voltage, under-voltages, low inertia, and bidirectional power flow are discussed in [13]. Authors in [14] provide an overview of the comparison of existing DC microgrid and AC microgrid systems. The purpose of the study is to assess the feasibility of the low-voltage direct current distribution system and its effects on the development of society. In addition, the study provides valuable information for renewable energy planners and provides insights or solutions to bridge the gap between the current energy grid and future DC microgrids. The general overview of microgrids and performance evaluation of the system when connected to the power grid and off-grid, considering various power issue scenarios, are presented in this paper and the paper focuses mainly on AC microgrid. The microgrid under investigation consists of wind farms, a small hydroelectric power plant, and energy storage systems. The use of solar farm is not considered in this paper; however, it will be considered in the next paper. Some of the simulated instances for performance evaluation include stand-alone mode, grid-connected mode, and transition from one mode of operation to another. In the standalone mode of operation, the utility grid is intentionally decoupled from the microgrid so that both networks supply power to the connected loads independently. In grid-connected mode, the microgrid is directly coupled with the utility grid, and the system's performance was investigated. In the transition from one mode of operation to another, the system was suddenly changed from grid-connected to stand-alone mode and the system performance was observed. Fault occurrences, an increase in micro-source power generation, an increase in loading systems, and sudden disconnection of RESs from the microgrid are some of the simulated and evaluated scenarios in each case. The network under investigation is modeled and simulated using MATLAB/Simulink. Fault conditions, increased power generation, increase in loading systems, and sudden disconnection of renewable energy sources from the microgrid are some of the simulated and evaluated scenarios in the paper. The results of the simulations demonstrated the performance of the microgrid system under various scenarios on the grid. Also, the simulation results show the effectiveness of the battery storage system in stabilizing and restoring the network stability during various disturbances on the grid. The paper is structured as follows: Section 2 provides a comprehensive overview of microgrids. Section 3 discusses the network under investigation and simulation scenarios, Section 4 presents simulation results and discussion, while microgrid limitation, conclusion, and future works are presented in sections 5 and 6 respectively.

2. Microgrids Overview

Scholars have assigned several meanings to microgrids. A microgrid is described by the US Department of Energy as a set of unified distributed generation sources (DGs) and loads within definite electrical restrictions that can operate as an independent controlled entity on the electrical grid [5–7]. European Union research project defines microgrids as a low-voltage (LV) distribution network consisting of DGs, energy storage units, and variable loads that can operate when coupled or decoupled from the utility grid [15,16]. Furthermore, in [17,18] a microgrid (MG) is said to be a moderate power network with DGs, monitoring circuits, and 71 electrical loads. Generally, the given definitions recognized the significance of distributed energy sources in microgrids and their ability to function as an independent entity on the grid.

2.1. Components and Classification of Microgrids

Microgrid comprises electricity generation sources, energy storage systems, and electrical loads that are electrically interconnected [16,17,19,20]. Figure 1 shows the fundamental structure of a microgrid. Microgrids (MGs) generate electricity using renewable energy sources like solar, wind, small hydropower plants, and micro-turbines. Another essential component of MGs is energy storage units. Energy storage systems (ESSs) ensure an uninterrupted and continuous power supply to the loads and contribute to the stability of the microgrid due to the irregular supply from the RESs. Storage systems can enhance the power quality by maintaining the grid's nominal voltage. BESSs are commonly used with microgrids [17,21]. Different loads, such as AC, DC, linear and non-linear, and dynamic loads, can be integrated into microgrids. Load management systems are vital components in microgrid systems. Microgrid energy loads have a wide range of controllable characteristics, from critical loads to adjustable loads. The use of critical loads, such as hospital loads, cannot be shaded; the use of adjustable loads, like heating or cooling, lighting, and pool filters, can temporarily be shaded for peak load reduction. Other loads, like business buildings with backup power sources and residential buildings, should be shaded during emergencies to maintain microgrid reliability and avoid power outages [22,23]. Power conditioning units (PCUs), energy management systems, and control systems are other essential elements of MG. In MG,

energy conversion units comprise transformers (step up and step down) and PCUs that convert produced power to the necessary and suitable power and voltage to be provided directly to the grid or end user [24]. Hybrid microgrids require an energy management system (EMS) due to the range of intermittent energy sources involved. The EMS must be able to control all interconnected power generation sources and provide swift responses to situations on the grid [24–26].

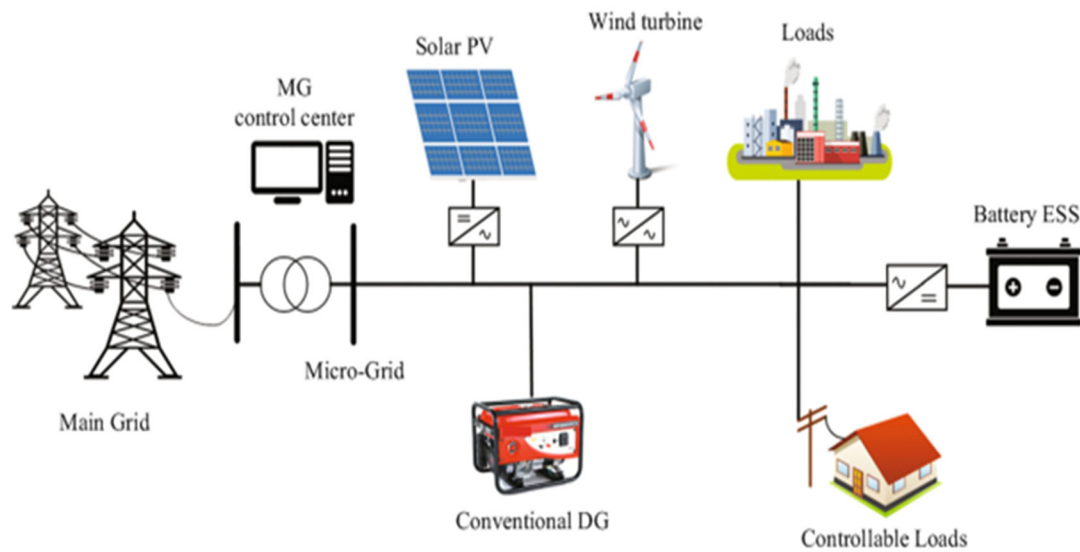


Figure 1. Basic structure of a microgrid.

2.2. Microgrid Classification

Microgrid Classification Microgrids are classified based on architecture, supervisory control, modes of operation, and phases [27,28]. However, classification based on the microgrid architectures and voltage characteristics is reviewed in this paper [29–34].

- AC Microgrid
- DC Microgrid
- Hybrid Microgrid

2.2.1. AC Microgrid (ACMG)

This is the most implemented MG. In this category, various forms of renewable energy sources are integrated into the grid using a power electronic converter (PEC) [35]. The AC microgrid offers minimal modifications for integration into the existing grid. It is commonly used in medium- and low-voltage distribution networks to enhance current flow and minimize power loss in transmission lines. In addition, the ability to integrate with traditional distribution networks or operate in stand-alone mode makes the system flexible, allowing it to operate directly with AC distribution devices such as AC loads. It does not require any inverters for AC loads, and the protection system is cost-effective. However, system integration causes stability and power quality issues for distribution operators [32,36,37]. Lower conversion efficiency, high DC-AC conversion costs, controllability challenges due to frequency factors, voltage regulation, unbalanced compensation, and poor power supply reliability, which can impede device performance, are some of the challenges of an AC microgrid [38–41]. However, the use of advanced control technology solves these problems [32,36,42].

2.2.2. DC Microgrid (DCMG)

Due to modern advancements in electrical power generation techniques, several power conversion units have been employed for various applications in power systems [24]. Furthermore, DC-based RESs and various forms of ESS technologies provide new opportunities for the development of DC microgrids. Benefits of DC microgrids include limited energy conversion processes and reactive current restrictions [32,43,44]. DC/AC PCU is required for connecting a DC microgrid to an existing traditional power distribution network. DC and AC microgrids are very similar in their operating modes. The main difference is that DC microgrids use DC buses for connectivity, while AC buses connect DGs and utility network loads together. The ideal operating voltage for a DC bus is between 350 and 400 Volts. The main DC bus can be separated into other low-voltage buses to meet the low-voltage prerequisites of electronic loads. In contrast, DC-type microgrid high-voltage DC-DC converters increase the connectivity of low-voltage sources like solar modules with a voltage range between 20 to 45 volts by supplying them with high voltage from the DC bus bar. DC-Microgrid offers several advantages to distribution operators over AC-Microgrid. Transmission efficiency due to non-reactive power, supply reliability even in remote locations, relatively small wiring due to high voltage at low temperatures, and convenient system control without causing complications such as synchronization, harmonics, reactive power, and frequency

regulation are some of the advantages of DC microgrids [45,46]. However, some disadvantages include inconsistent AC load proportional to the number of AC loads and large voltage drop in the absence of a reactive power source, especially for large systems [37,47–51].

2.2.3. Hybrid Microgrids (HMGs)

HMGs are achieved by integrating ACMG and DCMG on the same distribution network. In HMG, AC, and DC elements are separately integrated into their respective sections, therefore grid harmonization is not required for the energy generation and storage components. Since AC and DC elements are separately integrated into their respective sections in HMG, grid harmonization is not required for the energy generation and storage segment [52–54]. Combining the advantages of ACMG and DCMG, HMG enhances the network's reliability and efficiency and enables easy integration of different RESs and ESSs into the existing distribution network [27,55,56]. HMG reduces the number of energy conversion processes and thus reduces power loss [57,58]. However, the high cost of complex storage and control systems poses challenges for the microgrid. Furthermore, MGs may be grouped according to their usage into utility, institutional, commercial, industrial, and transport microgrids [11,59].

2.3. Microgrid Mode of Operations

Microgrids can operate in both stand-alone and grid-connected modes [60–62].

2.3.1. Grid-Connected Modes

The microgrid is connected to the grid through a common point coupling (PCC). Depending on the amount of power generated and customers' demand, excess power generated can be shared with the utility grid through PCC [19,63]. Distribution network feeders must be adequately equipped for this purpose.

2.3.2. Stand-alone Mode of Operation

This is a situation where MGs operate autonomously with connected loads when detached from the main utility power network. Microgrids can be intentionally or unintentionally disengaged from the utility network to operate independently. In this condition, MG supplies electricity to the connected loads through the micro-sources. The intentional disconnection of microgrids is predefined and follows a predefined process, while unintentional islanding can be a result of unwanted situations such as faults on the grid. During this time, the microgrid can automatically switch from grid-tied to stand-alone mode through a protective device. In autonomous operation, differences in the generated power and load demand cause voltage and frequency fluctuations in the network. In renewable energy-based MG, the output power of each micro-source must be effectively coordinated to enhance the stability of the system. Microgrids must be adequately equipped with monitoring systems for a smooth transition from stand-alone to grid connection mode to obtain voltage-frequency information on the utility grid [41,64–66]. Maintaining constant voltage-frequency amplitude and sustaining power balance in MG are the main challenges of islanding mode in microgrids.

3. Technical Benefits and Challenges of Microgrids

This section discusses the general overview of the technical benefits and challenges of microgrids.

3.1. MGs Technical Benefits

Some of the technical advantages of MGs as presented by different researchers are reviewed in this section. The technical benefits are presented in Table 1 [17,67–72].

Table 1. Technical Benefits of Microgrid.

Parameter	Description
Stable and reliable power supply	As a stand-alone power supply unit, the microgrid provides support to the utility grid whenever there is an electricity generation shortage or outage until the grid is restored. MGs enhance voltage-frequency stability for all local loads by operating autonomously.
Reduce transmission and distribution losses	Reduction in the long transmission line, transmission, and distribution losses due to nearness to the customers.
Reduce system capacity	Microgrids enhance the high penetration of RESs to distribution networks. It provides additional power to local loads during peak demand, thus reducing strain on distribution lines.
Bidirectional power flow	Integration of the microgrids into the existing distribution networks alters the direction of power flow from the traditional unidirectional to bidirectional, thus improving system reliability and stability. It permits efficient utilization of excess power generated.

3.2. Technical Challenges of Microgrids

- **Microgrid Stability**

Microgrids in grid-tie mode affect the microgrid's stability due to power-sharing support for the network's instantaneous balance. Renewable energy-based MG in stand-alone with flexible loads causes grid instability. The microgrid transition from grid-connected to stand-alone leads to power imbalance and voltage variation. A stand-alone microgrid requires a reliable energy management system with storage, efficient control systems, and management to maintain stable operation. The ability to compensate for reactive power and fault voltage ride-through capability is required in stand-alone mode to ensure voltage stability [2,73,74].

- **Microgrid control:**

MG depends on energy storage devices to maintain an efficient energy balance between generating sources and connected loads. An accurate charge and discharge control system is essential for the microgrid to operate efficiently. The choice of microgrid management systems such as centralized control, distributed control, decentralized control, or coordinated control are challenges facing microgrid systems [25,75–77]. A synchronized control system is pivotal for the microgrid's security and unfaltering working. The control frameworks can be centralized or decentralized and may be actualized with or without a communication interface [32,78,79].

- **Harmonics:**

The major cause of harmonics in a microgrid system is the high-power conditioning units (PCUs) involved in the conversion system of renewable energy-based microgrids. It can have various effects on the system's reliability and stability and pose a threat to the effectiveness and safety of the ESSs [80,81]. Different filtering systems are used to reduce the impacts of harmonics on the grid [82–85]. In DC microgrids, the heat created by capacitor charging and discharging worsens harmonics. Therefore, the effectiveness of ESS is jeopardized because of its sensitivity to harmonics. Microgrid optimization in autonomous and grid-tie scenarios is critical for system reliability [86].

- **Microgrid protection issues:**

Advanced protection techniques are required for the electrical grid and MG's power-sharing to function properly. Additionally, the MG protection system must respond quickly to isolate the system to safeguard the grid components during a power failure and guarantee continuous power delivery to the loads [37,84–86].

- **Power quality:**

Power quality is one of the elements to be managed in a grid-tied microgrid. The measurement, investigation, and enhancement of the bus voltage to maintain a sine waveform at the rated voltage and frequency constitute power quality [87]. The significant increase in the use of power electronics-based switching devices and the presence of nonlinear loads on the grid cause power quality problems in distribution networks. Furthermore, the variation in some RESs impacted the quality of microgrid power. In both islanding and grid-connected modes, unconventional control approaches are used to counteract the negative impacts of intermittent renewable energy-based microgrids [88,89].

4. System Under Investigation

MATLAB/Simulink software was used to simulate the utility grid and microgrid that make up the system under study. The MG is coupled to the utility grid at a low-voltage distribution network (0.415 kV) via PCC. The microgrid will be operated in both grid-connected and stand-alone modes to allow for effective system performance analysis. The utility grid and microgrid system operate at 50 Hz.

4.1. Utility Grid

The utility grid consists of a utility substation, 6 buses, and 5 loads. The utility substation is a step-down transformer with a capacity rating of 1 MVA, 11/0.415 kV. In addition, the system comprises a backup power storage at the point of PCC which supports the grid and microgrid during power shortages and disturbances on the grid. The storage at PCC is referred to as utility storage in this paper. The loads are scattered across the 5 buses on the network. The total active power on the utility grid is 185 kW, while the reactive power is 151 kVar. Figure 2 depicts the utility grid under investigation's one-line diagram, and Table 2 lists the grid's loads and line parameters.

Table 2. Utility grid load and line parameters.

Load Parameters	Utility Grid Load and Line Parameters					
	Load Parameters		Line Parameters			
	Active Power (kW)	Reactive Power (kVar)	Line	Length (km)	Resistance (Ω/km)	Inductance (H/km)
Load 1	40	38	Line1	0.15	0.0127	0.000814
Load 2	35	25	Line2	0.15	0.0127	0.000814
Load 3	40	38	Line 3	0.15	0.0127	0.000814
Load 4	35	25	Line 4	0.15	0.0127	0.000814
Load 5	35	25	Line 5	0.15	0.0127	0.000814
			Line 6	0.15	0.0127	0.000814
			Line 7	0.15	0.0127	0.000814

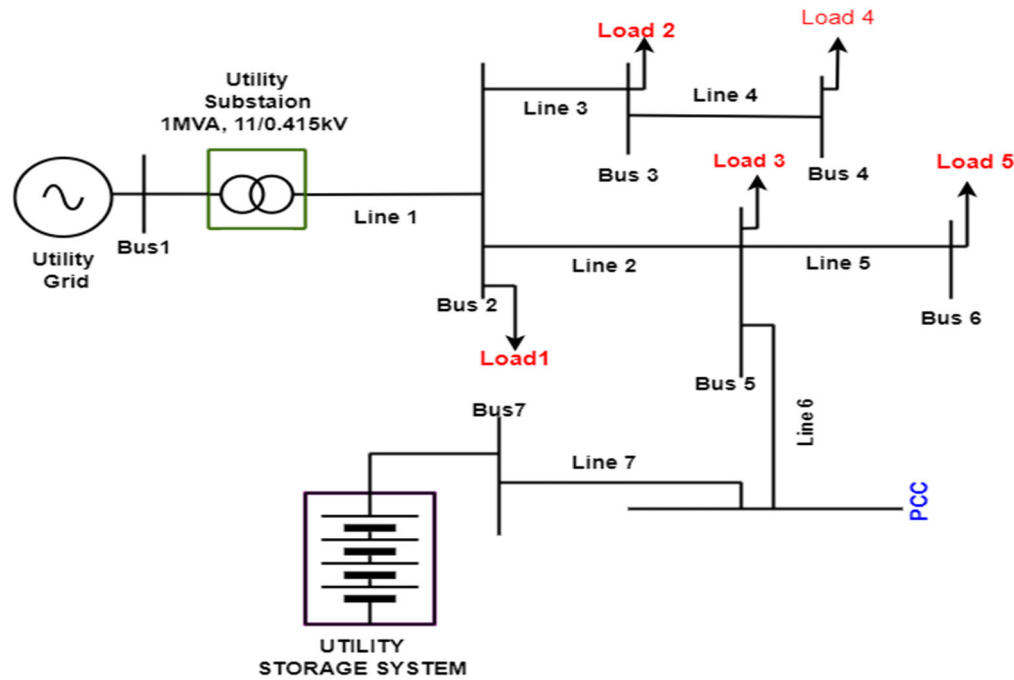


Figure 2. One-line diagram of the utility Grid under investigation.

4.2. Microgrid Under Study

The one-line diagram of the microgrid architecture under investigation is shown in Figure 3. The system is coupled to the main utility low-voltage distribution network by a circuit breaker via PCC. The circuit breaker regulates all system functions, including the switching of the MG from on-grid to self-operating modes. The microgrid comprises a wind farm, small hydropower plants, and an energy storage system (ESS) interconnected to electrical loads. In this paper, it is presumed that each load represents different streets in the community.

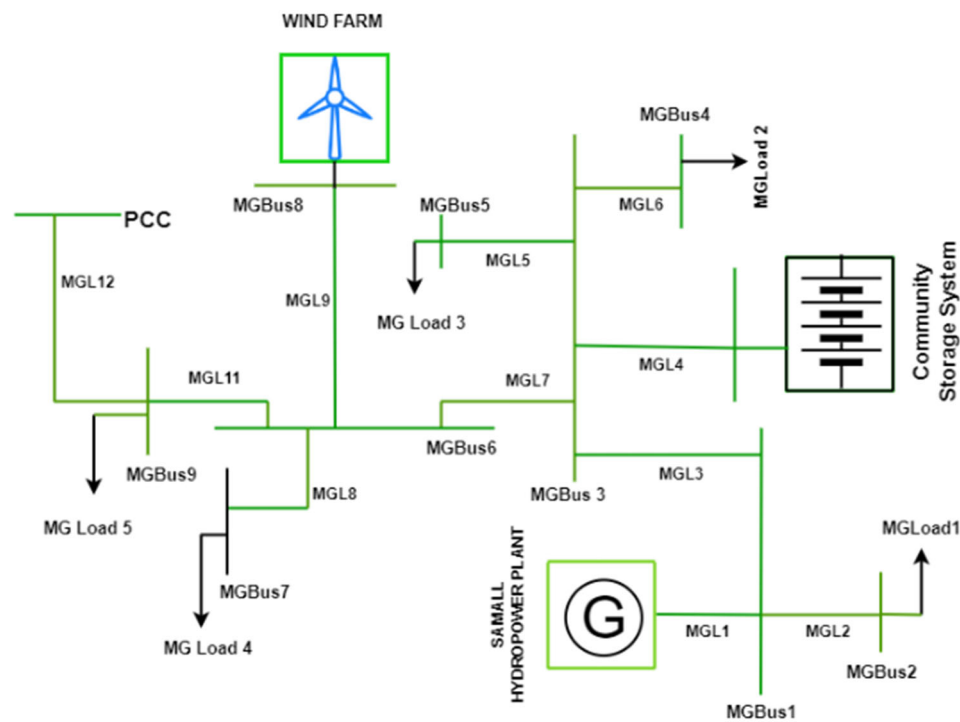


Figure 3. Microgrid under investigation.

5. Microgrid Components Modelling and Control

5.1. Wind Energy Conversion System Modeling and Wind Farm Layout

A wind turbine (WT), a doubly fed inductor generator (DFIG), rotor-side converters, and grid-side converters constitute the wind energy conversion system. While the rotor windings are linked to the prime mover via back-to-back converters, the stator windings are attached to the grid directly. The converter at the rotor side regulates the power (active and reactive) at the grid output; the DC link and grid voltages are controlled by the network-side converter. Wind power is transformed from mechanical power to electrical energy, which is then connected to the utility system. The wind farm is made up of six similar wind turbines (WTs) integrated into a distribution network via 0.415 kV. To reduce mechanical stress on the turbine during gusts, the wind speed must be regulated; DFIG extricates maximum power at a reduced wind speed [37,90–92]. Figure 4 shows the one-line schematic diagram of the wind power conversion system, while Figure 5 depicts the association between turbine output and speed.

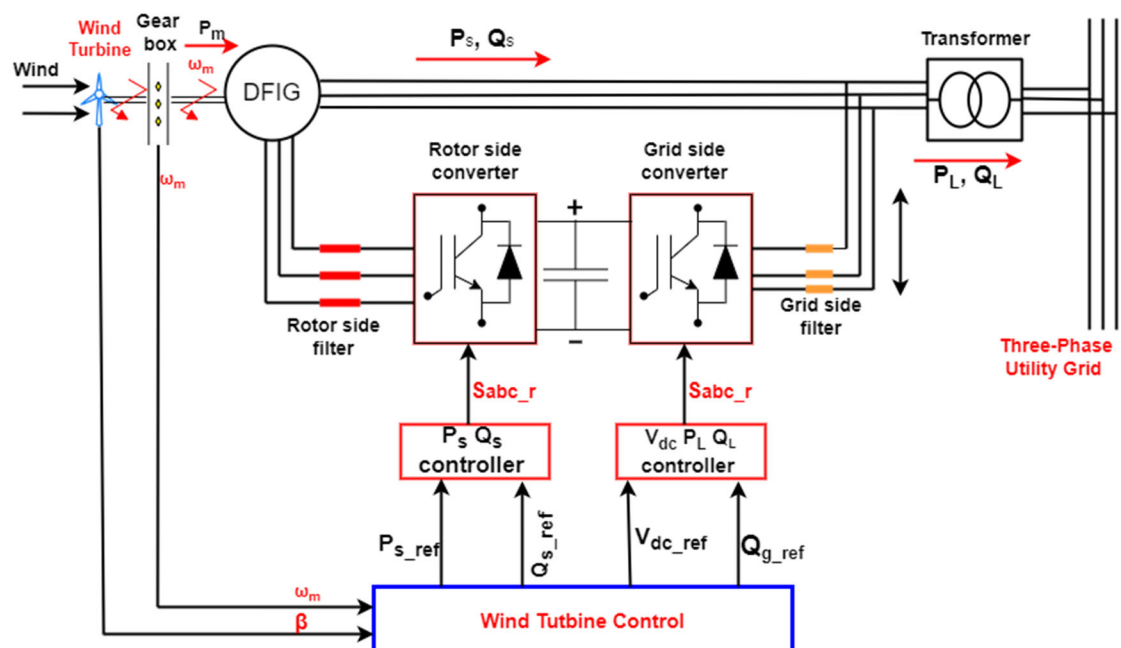


Figure 4. Wind energy conversion system with control system.

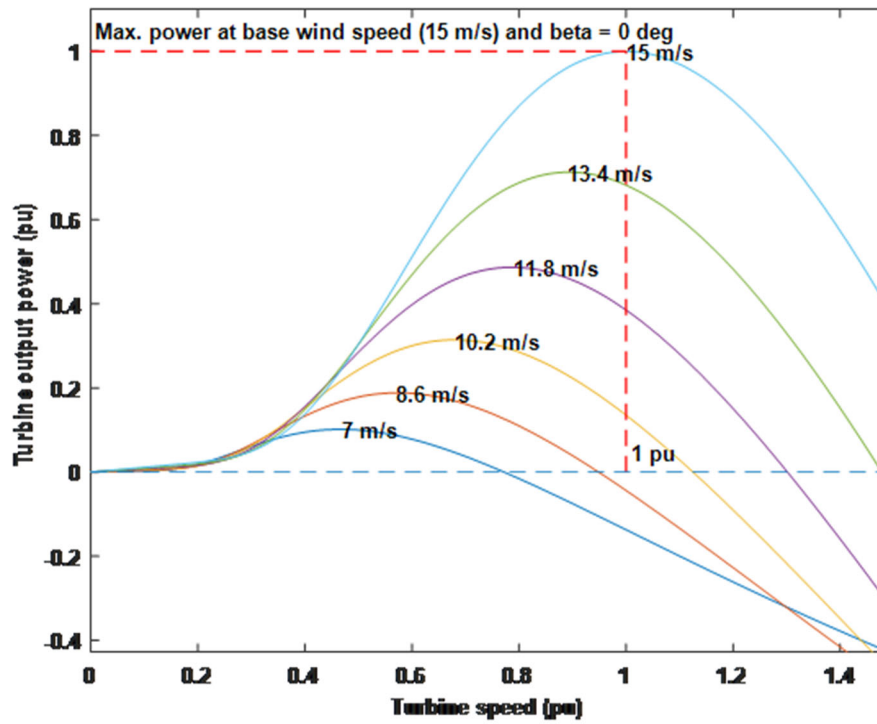


Figure 5. Wind turbine and Rotor speed characteristics.

The interaction of the rotor and wind velocity determines the extricated power of the wind turbine. The power generated from the wind turbine is given in Equation (1).

$$P_w = 0.5\rho\pi r^2 C_p(\lambda, \theta) V^3 \quad (1)$$

where P_w is the generated power by the wind, the air density is ρ (kg/m^3), the turbine blade radius is r , wind speed is V (m/s), C_p is the wind turbine power coefficient. The tip-speed ratio λ is given in Equation (2) [93,94].

$$\lambda = \frac{r\omega}{V} \quad (2)$$

ω (rad/s) is the angular velocity, and the air velocity on the rotor is V . Using Equations (1) and (2), the wind turbine's maximum output power is specified in Equation (3).

$$P_{w,max} = K_{opt} \omega_{t,opt}^3 \quad (3)$$

where K_{opt} and $\omega_{t,opt}$ is given in Equations (4) and (5).

$$K_{opt} = 0.5\rho\pi r^2 C_{p,max} \left(\frac{r}{\lambda_{opt}} \right)^3 \quad (4)$$

$$\omega_{t,opt} = \frac{\lambda_{opt} V_w}{r} \quad (5)$$

A wind farm is an assembly of installed WT that generates electricity within a certain geographic location. Its size varies from a few turbines to hundreds of turbines distributed across a wide area. Wind farms can be onshore or offshore; however, this study focuses on onshore wind farms. The wind farm under investigation consists of four equal wind turbines with power ratings of 1.5 MW each, adding up to 6 MW; coupled to a low-voltage distribution network. Figure 6 depicts a one-line representation of the wind farm architecture, while Table 3 summarizes the wind turbine and wind farm parameters.

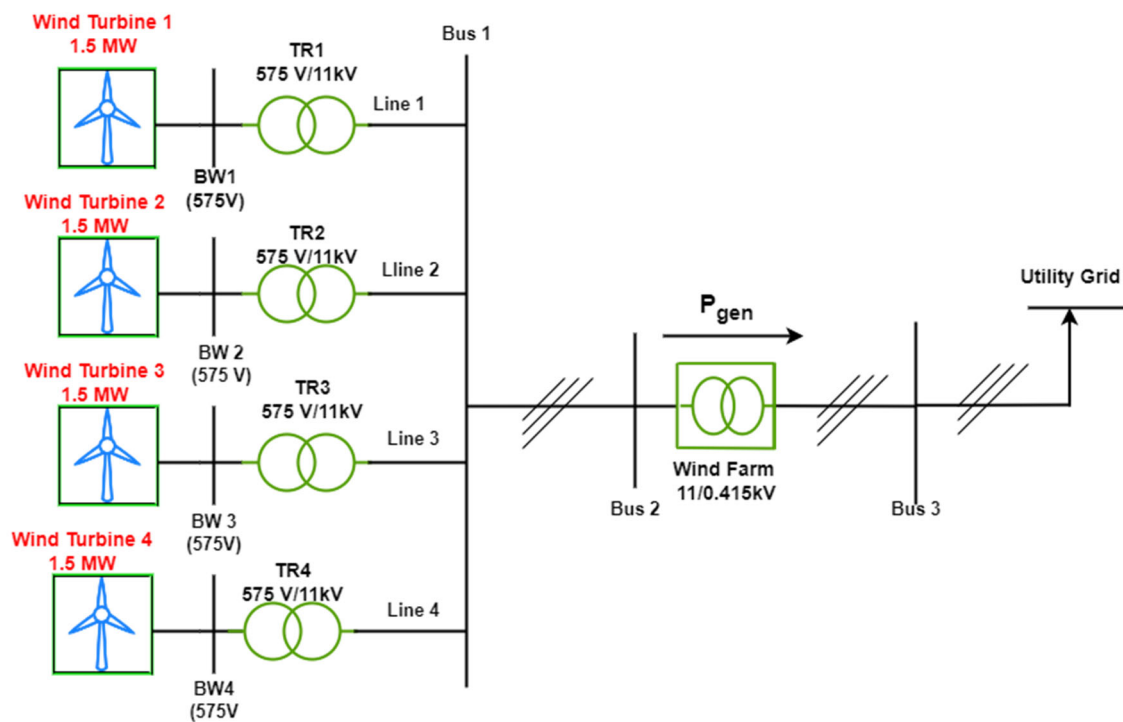


Figure 6. Schematic diagram of wind farm layout.

Table 3. Wind turbine and wind farm parameters.

Turbine Parameters	Value	Unit
Nominal output power	1.5	MW
Rated Voltage	55	V
Stator Resistance	0.004843	pu
Stator Inductance	0.1248	pu
Rotor Resistance	0.004377	pu
Rotor Inductance	0.1791	pu
Magnetizing Inductance	6.77	pu
Friction Factor	0.01	pu
Base Wind Speed	15	m/s
Cut-in Wind Speed		m/s
Maximum Pitch Angle	45	
Generator Pole Pairs	3	
Power Coefficient	0.48	
Wind Farm Rating	6	MW

5.2. Small Hydropower Plant

The small hydroelectric power plant is considered a source of renewable energy because it requires a significantly small amount of water to operate and its harmful impacts on the environment are minimal compared to large hydropower plants [95,96]. Small hydroelectricity, in most cases, does not require dams or water storage. It is a cost-effective source of energy to consider for developing countries [95–97]. The main electrical and mechanical components of a small hydroelectric plant are the water turbine and the generator(s) [98,99]. Synchronous and asynchronous generators are two types of generators commonly used in technology. Synchronous generators can work independently, while asynchronous generators work together with other generators. Synchronous generators are used in small, stand-alone hydroelectric applications. A hydraulic turbine consists of a pressure hose, tunnel, servo motor, turbine, and pressure reducer. Figure 7 depicts a modest hydropower system with a permanent magnet synchronous generator (PMSG) and a power conditioning unit [100].

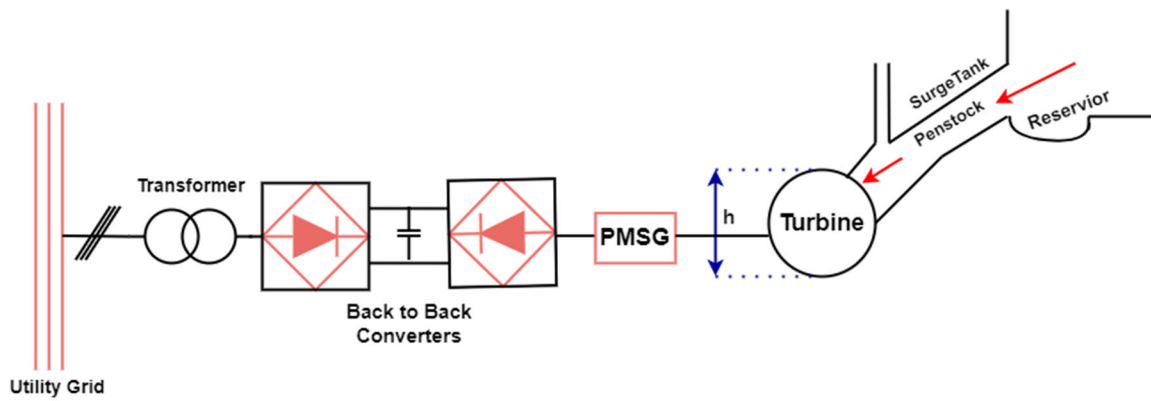


Figure 7. Layout diagram of a small hydropower energy conversion system.

The small hydropower plant regulatory system is shown in Figure 8. The main components are a hydraulic turbine, PMSG, and a back-to-back converter with pulse width modulation (PWM). The control system is grouped into motor and grid sides. Voltage-current dual closed-loop control systems are used to control the grid side. The direct current voltage of the back-to-back converter is regulated by a voltage loop system, while both active and reactive powers are coordinated by the current loop. The voltage controller determines the value of the active component for the current (i_{gd}^*) based on the discrepancy between the real voltage (V_{dc}) and reference (V_{dc}^*) voltages. The power factor specification is used to adjust the reference value of the reactive current. Similarly, the difference between the reference current value and the actual value is used by the current controller, and the voltage reference value is required with the feedforward compensation. The converter switches are driven by a pulse signal generated by the Space Vector Pulse Width Modulation (SVPWM), allowing the converter output current to follow the DC bus power variation in real time, thus enhancing the management of energy production associated with the network [101]. On the generator side, a double closed-loop speed and current control approach are used, taking the velocity of the hydraulic turbine as the controller. The control algorithm that tracks the output power of the hydro-turbine is determined by the target speed of the generator. The difference between the desired and real speed (n^*) is fed into the speed's supervisory system, and the output is the reference value of the torque current component (i_{rd}^*). The reference value of the excitation current component is set to 0. The variation in the reference values (i_{rd}^*, i_{rq}^*) and the actual value (i_{rd}, i_{rq}) is transmitted to the current regulator, thus the voltage reference value (u_{rd}^*, u_{rq}^*) and the feedforward correction is acquired. To synchronize the output current and power variation in real-time and enable energy conversion and transmission, the SVPWM generates a signal that energizes the converter. The pulse modulation of the motor and grid-side converters using the SVPWM algorithm increases the DC voltage usage rate, reduces losses, and increases the effectiveness of the system [102–104].

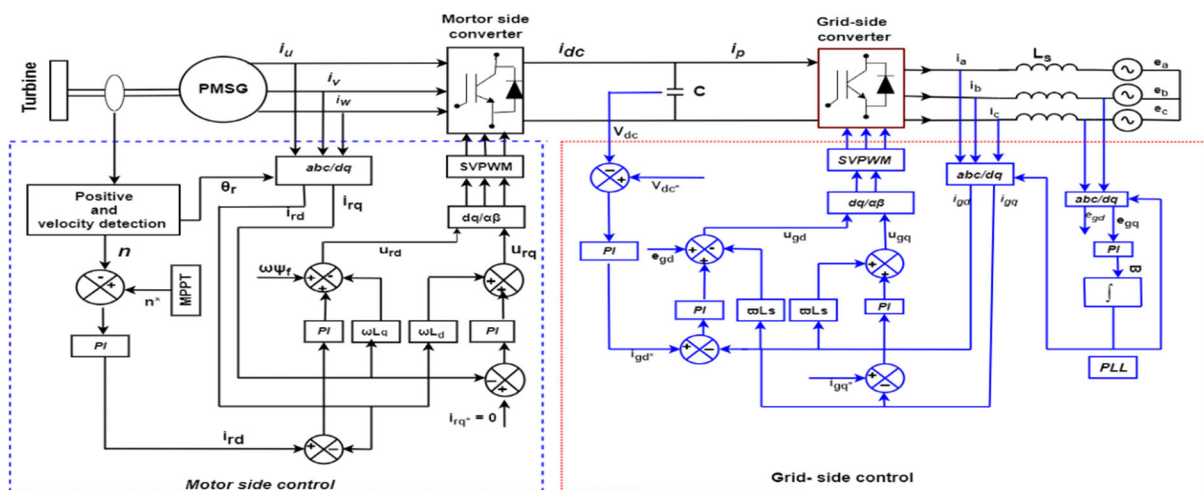


Figure 8. Complete schematic diagram of small hydropower plant control system.

In the synchronous rotation coordinate system, the equation for the voltage on the grid-side converter component is given as:

$$\begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -\omega_e L_s \\ \omega_e L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + \begin{bmatrix} e_{gd} \\ e_{gq} \end{bmatrix} \quad (6)$$

The output voltage vectors (u_s) are u_{gd} and u_{gq} , the current vectors (i_s) are given as i_{gd} and i_{gq} and the grid voltage vector components of the ds-axis of the converter are e_{gd} and e_{gq} . The grid-side inductance and resistance are L_s and R_s , ω_e is the angular

frequency. To increase the efficacy of the control system, the internal current loop of the grid-side converter implements PI with feedforward decoupling control method in the on-grid. The reference values u_{gd} , and u_{gq} of grid-connected voltage are produced by inserting the feedforward components of the current i_{gd} , and i_{gq} to compensate u_{gd} , and u_{gq} from Equation (6), we have Equation (7).

$$\begin{bmatrix} u_{gd}^* \\ u_{gq}^* \end{bmatrix} = \left(K_p + \frac{K_i}{s} \right) \begin{bmatrix} (i_{gd}^* - i_{gd}) \\ (i_{gq}^* - i_{gq}) \end{bmatrix} + \begin{bmatrix} -\omega_e L_s i_{gq} + e_{gd} \\ \omega_e L_s i_{gd} + e_{gq} \end{bmatrix} \quad (7)$$

where K_p and K_i are the proportional-integral (PI), and integral gain respectively. The grid voltage vector is expected to correlate with the d-axis of the dq coordinate to accomplish active-reactive power separation in a grid-connected regulator. The do-axis components thus fulfill $e_{gd} = e$, and $e_{gq} = 0$ respectively. The active power (P) and reactive power (Q) are:

$$P = \frac{3}{2} (i_{gd} e_{gd} + i_{gq} e_{gq}) = P = \frac{3}{2} i_{gd} e \quad (8)$$

$$Q = \frac{3}{2} (i_{gd} e_{gq} - i_{gq} e_{gd}) = -\frac{3}{2} i_{gq} e \quad (9)$$

The grid receives active power when P is positive, and inductive reactive power when Q is positive.

5.3. Electrical Energy Storage and Bi-directional Converter

Batteries, supercapacitors, compressed air, superconducting magnetic, and flywheels are all forms of energy storage. However, battery energy storage systems (BESS) are used for the investigation in this paper. The storage systems are coupled to the grids using a bidirectional DC-DC converter. The configuration ensures the charging and discharging of the ESSs. The structure of the bidirectional system with the control is shown in Figure 9. The converter's ability to operate in both directions is provided by switches S1 and S2, which are triggered by additional signals from the controller. The operation of switch S1 is for charging when it brings V_{dc} on the right side down to V_b , while the operation of switch S2 is for discharging, which operates during boost mode [101,105].

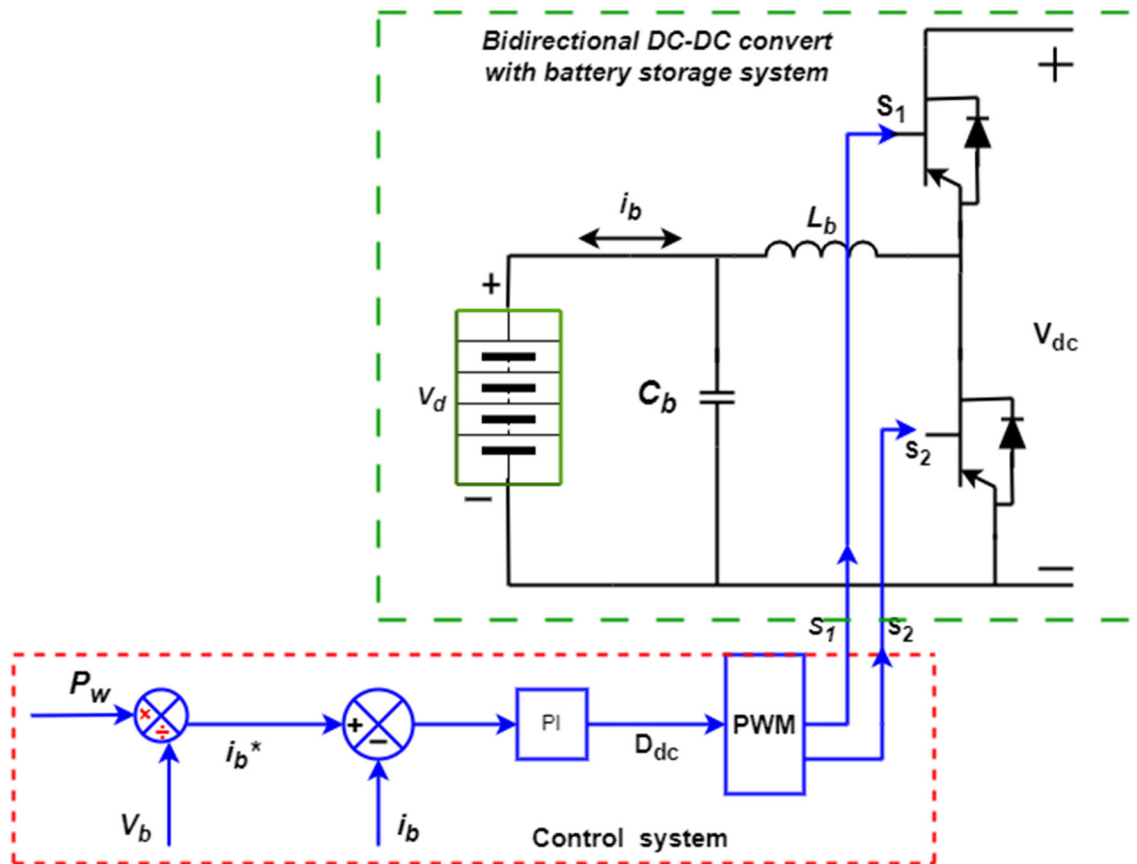


Figure 9. Bidirectional battery storage system with controller.

From the above figure, the inductor L_b and capacitor C_b are given in Equations (10) and (11) respectively.

$$L_b = \frac{V_{dc} - V_b}{2\Delta i_L f_s} D_1 = \frac{V_b}{2\Delta i_L f_s} D_2 \quad (10)$$

$$C_b = \frac{\Delta i_L}{8\Delta V_c f_s} \quad (11)$$

where V_{dc} is the DC-link voltage, V_d is the battery nominal voltage, inductance ripple current is Δi_L , and f_s is the switching frequency. Buck and boost converters duty ratio are given in Equations (12) and (13) respectively.

$$D_1 = \frac{V_b}{V_{dc}} \quad (12)$$

$$D_2 = 1 - \left(\frac{V_b}{V_{dc}} \right) \quad (13)$$

The PI control block is cascaded with the battery current loop to provide the D_{dc} duty ratio. Switch S1 and S2 are operated by the PWM, which receives the duty ratio. The duty ratio is defined in Equation (14):

$$D_{dc} = (i_{b^*} - i_b) \left(K_p + \frac{K_i}{s} \right) \quad (14)$$

The battery reference current is given as i_{b^*} , P_w is the active power reference. The PI controller proportional and integral gains are K_p and K_i . The battery state of charge (SOC) is given in Equation (15) [107,108].

$$\text{SOC} = 100 \left(1 + \frac{\int I_{bat} dt}{Q} \right) \quad (15)$$

The battery capacity is Q and I_{bat} is the battery current. The battery charging and discharging depend on the generated power and the energy restriction which are controlled by the SOC limit [107,108]. The charge and discharge equation are in Equations (16) and (17):

$$C(t+1) = C(t) - \Delta t P_t^e \quad (16)$$

$$|P_t^e| \leq P_e^{max}$$

$$C_{min} \leq C(t) \leq C_{max} \quad (17)$$

where P_t^e is the battery output power, P_e^{max} is the maximum charge or discharge rate, total power at time t is $C(t)$, Δt is the time interval, C_s stored energy, C_{min} and C_{max} are the minimum and maximum stored energy.

6. Voltage Constraints

The designed system must work synchronously with the existing grid and maintain standard voltage limits. The integration RESs must be complied with the IEEE standards [111]. Equation (18) defines the allowable voltage fluctuation range for the designed system.

$$V_{min} \leq V_n(t) \leq V_{max} \quad (18)$$

where V_n is the voltage at buses, V_{min} is the lowest voltage threshold, and V_{max} is the maximum allowable voltage.

In this paper, the minimum and maximum voltage were set to 0.88 pu and 1.1 pu.

Figure 10 depicts the full one-line diagram of the system under investigation connected to a utility low-voltage distribution network via PCC using a circuit breaker.

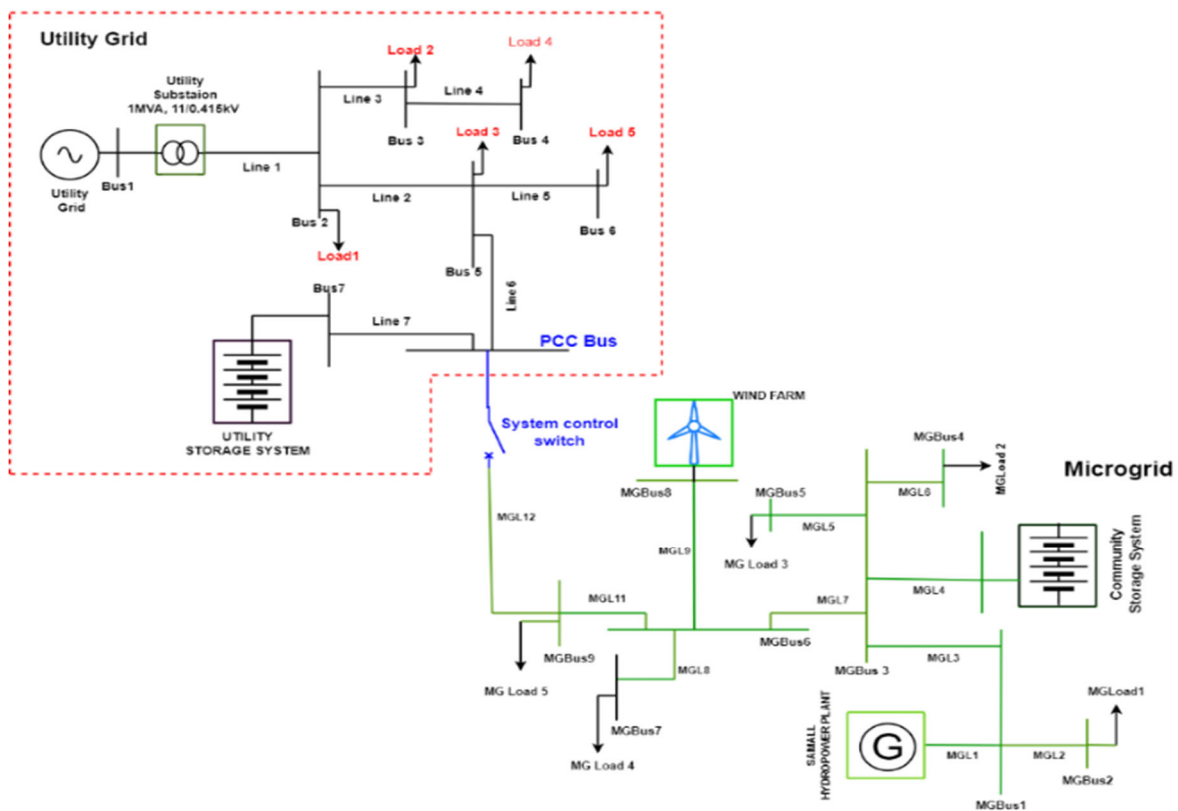


Figure 10. Complete a one-line diagram of the system under investigation.

7. Simulation Results Discussion

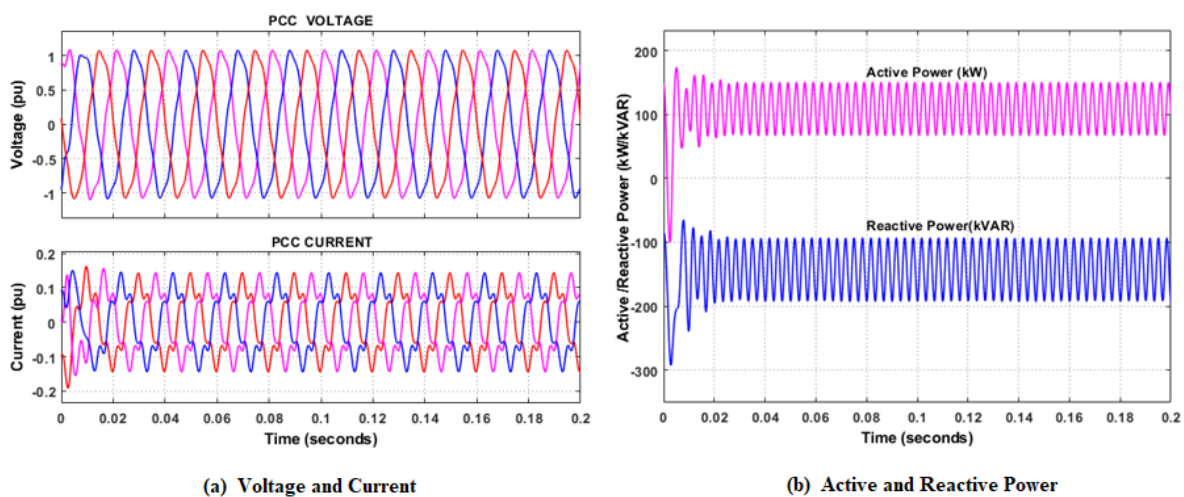
The paper aimed to assess the performance of the designed systems under various operating conditions. Some of the simulated instances for performance evaluation include stand-alone mode, grid-connected mode, and transition from one mode of operation to another. In each case, normal operation, fault occurrences, increase in power generation, increase in loading system, and sudden de-energized of RESs are some of the simulated and evaluated in each instance.

7.1. Stand-alone Mode of Operation

In this scenario, the utility grid is intentionally decoupled from the microgrid so that both networks supply power to the connected loads independently. In this mode, two cases were simulated and analyzed.

- Case1: Simulation of Normal Operation

The system parameters were simulated without considering any disturbances on the utility and microgrid. The storage systems were set to charging modes. The simulation results are shown in Figure 11(I–III).



(I)

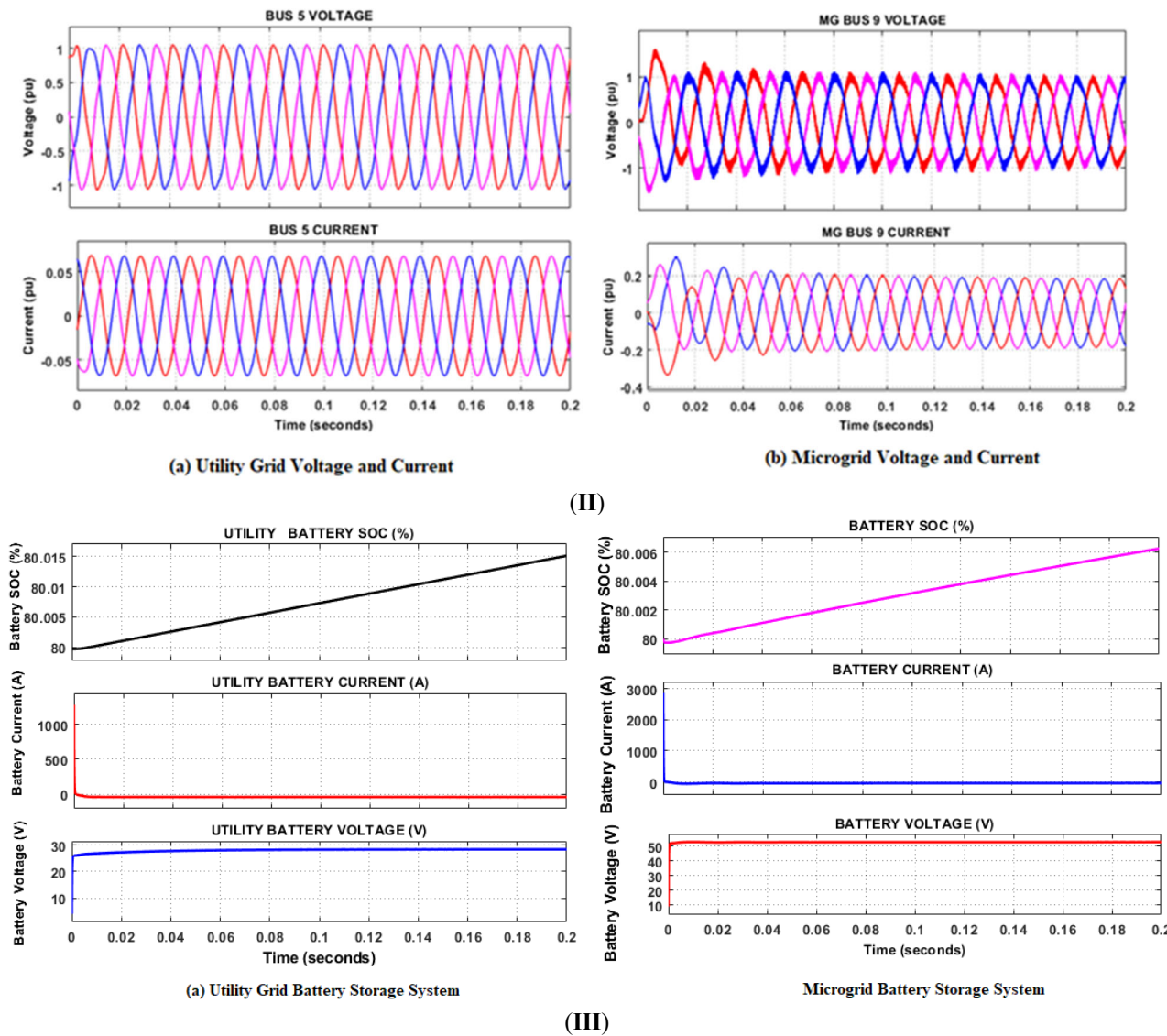


Figure 11. System performance during normal operation in stand-alone mode. **(I)** PCC voltage, current, and power; **(II)** Utility and microgrid voltage and current; **(III)** Utility and Microgrid energy storage characteristics.

Figure 11(I) shows the voltage, current, and power (active and reactive) measured at the PCC; Figure 11(II) depicts the voltage and current measured at some selected buses from the utility grid and MG, and Figure 11 (III) shows the utility grid and microgrid battery energy storage characteristics. As indicated in Section 6, the designed system must be operating within the acceptable minimum and maximum voltage ranges of 0.88 pu and 1.1 pu respectively. From Figure 11(I–III), the systems complied with the maximum and minimum voltage ranges because there were no disturbances, such as faults or changes in the loading system, on the grids.

- **Case 2: Simulation of Fault**

In this case, the system is subjected to a three-phase fault at line 4 between buses 3 and 4 on the utility grid. Figure 12(I,II) shows the response of the system at PCC and the selected buses on the utility grid and microgrid during the fault. As can be seen, the fault affected only the utility grid and PCC for a period of 0.08 to 1.12 s. However, the effect of the fault did not spread to the microgrid side, as indicated in Figure 12(II) microgrid voltage and current.

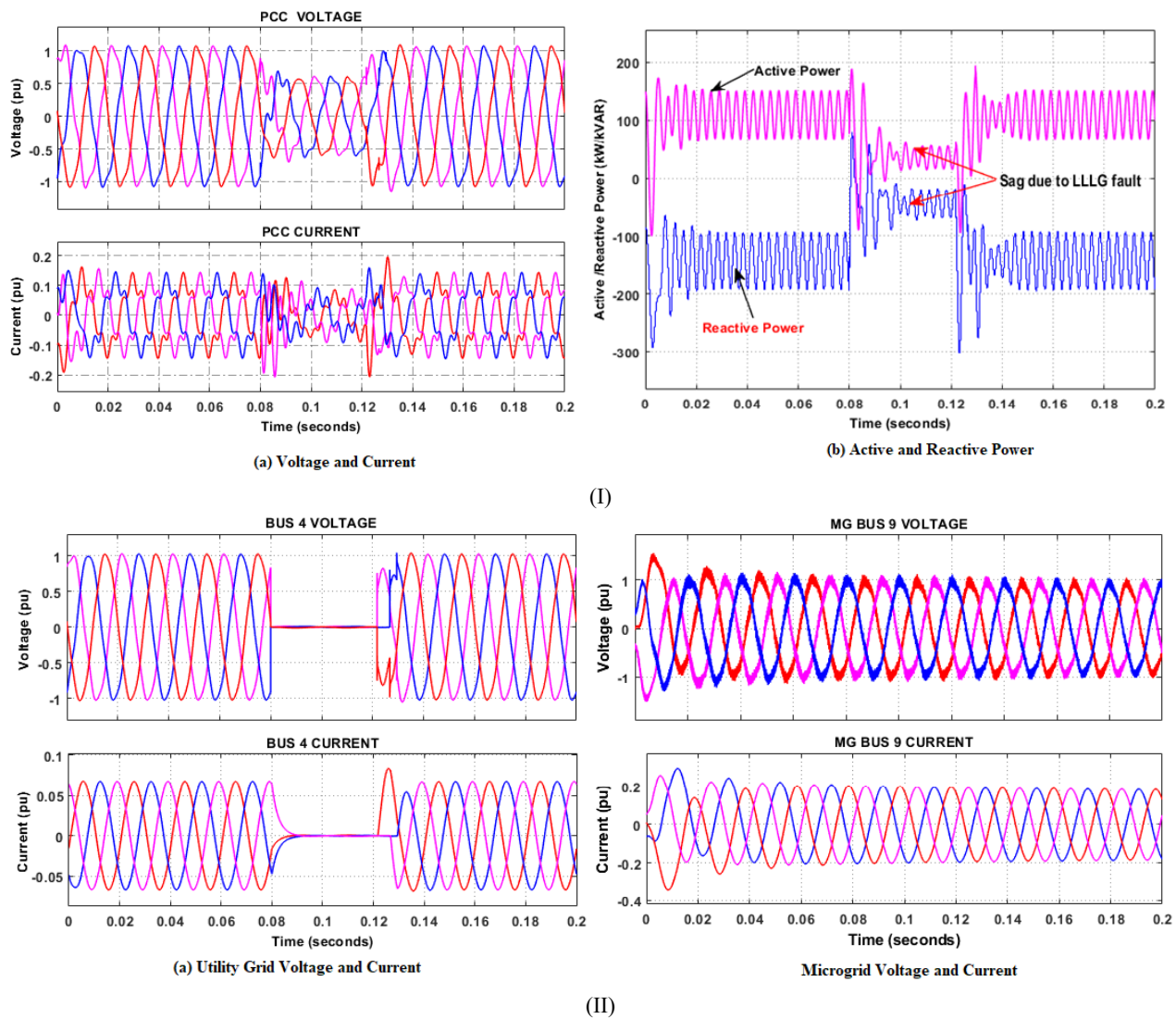


Figure 12. Three phase-phase fault at the Utility grid during stand-alone mode: (I) Voltage, current, and power at PCC; (II) Voltage and current at some selected buses on the utility grid and microgrid sides.

7.2. Grid-connected Mode

The system's grid-integrated simulation results are presented in this section. The simulated scenarios in this mode of operation include faults, transitions from autonomous mode to grid-connected, increases in total generation on the microgrid, sudden disconnection of a micro-source, and changes in the loading system of the microgrid.

- **Scenario 1: Fault occurrence on the utility grid**

The system is exposed to a three-phase fault between Bus 5 and 6 on the utility grid. Figure 13(I,II) shows the performance of the system during the three-phase fault. The voltage, current, and power waveforms at PCC are shown in Figure 13(I), while Figure 13(II) shows the response of the utility grid and microgrid to the fault. The fault is set to occur within 0.08 s and 0.12 s on the system, and it was observed that the fault effect spread all over the utility grid and microgrid, as shown in Figure 13(I,II).

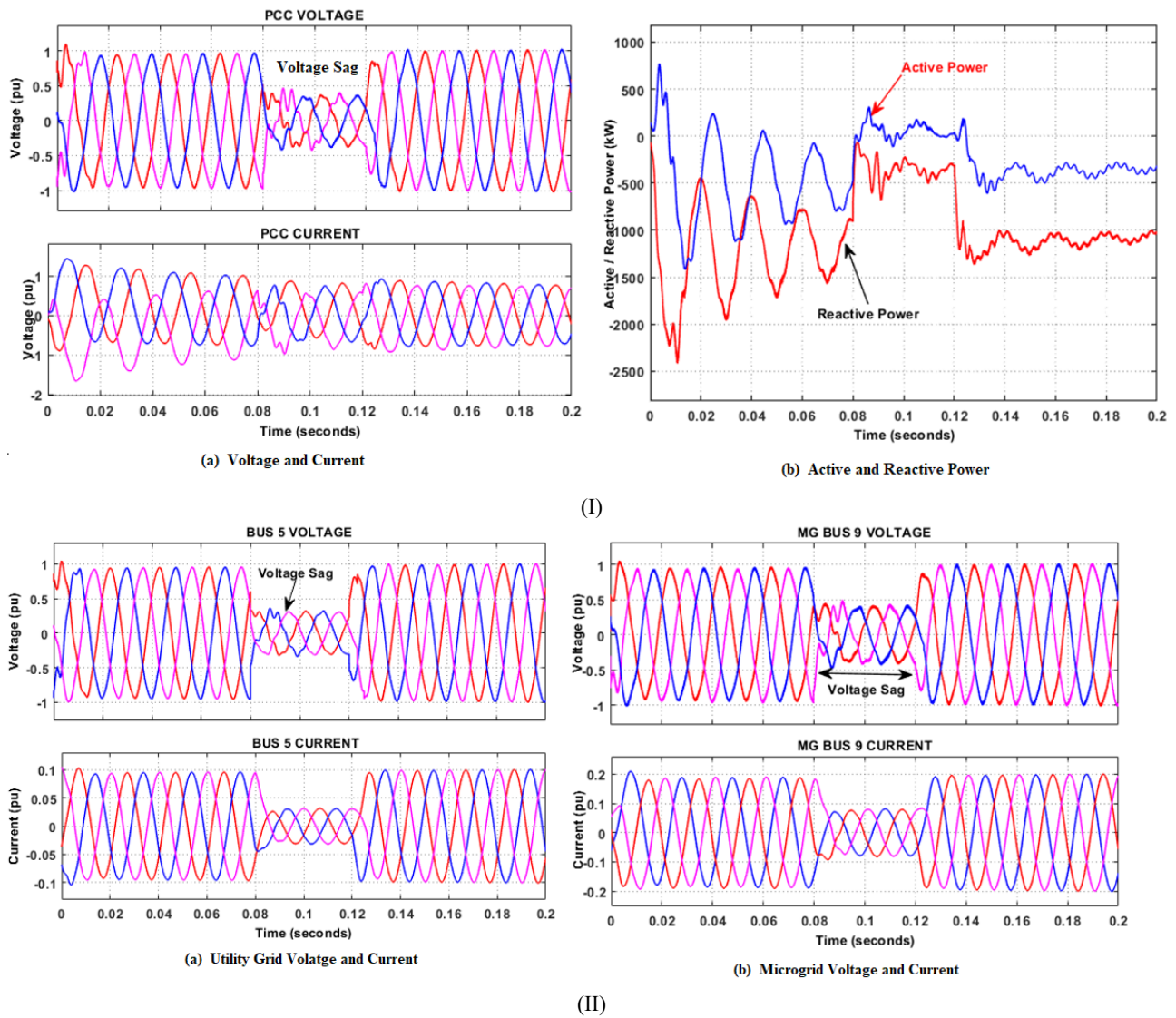
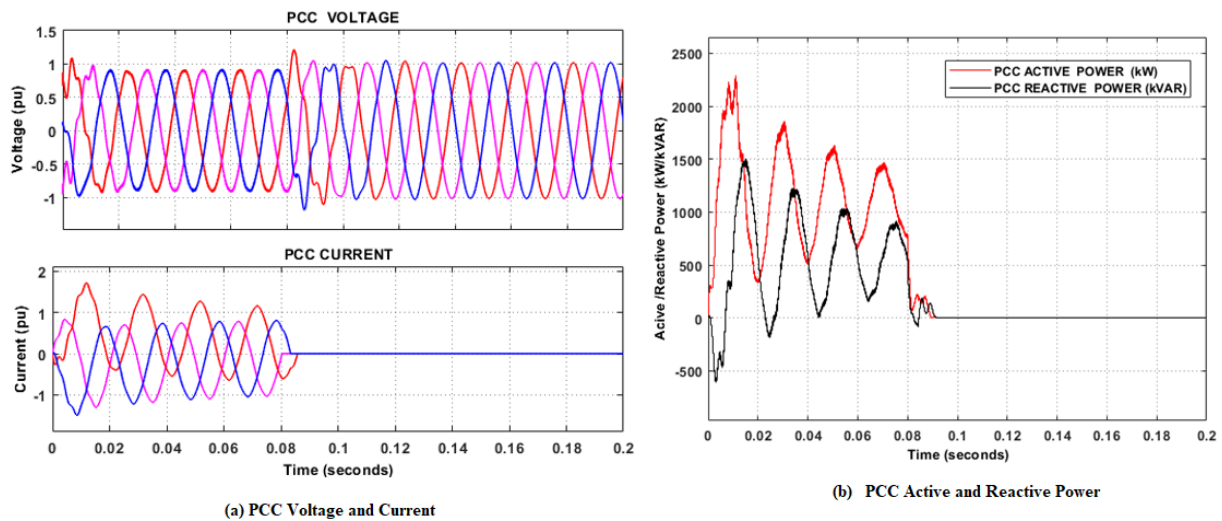


Figure 13. Three phase-phase fault at the utility grid during grid-connected mode of operation; (I) Voltage, current, and power at PCC, (II) Voltage and current at selected buses on utility and microgrid sides.

- Scenario 2: Transition from Stand-alone to Grid Connected

This section analyzes the sudden transition of the system from grid-connected to stand-alone. Figure 14(I–III) shows the utility grid response to the scenario, while Figure 14(III,IV) shows the microgrid performance during the scenario.



(I)

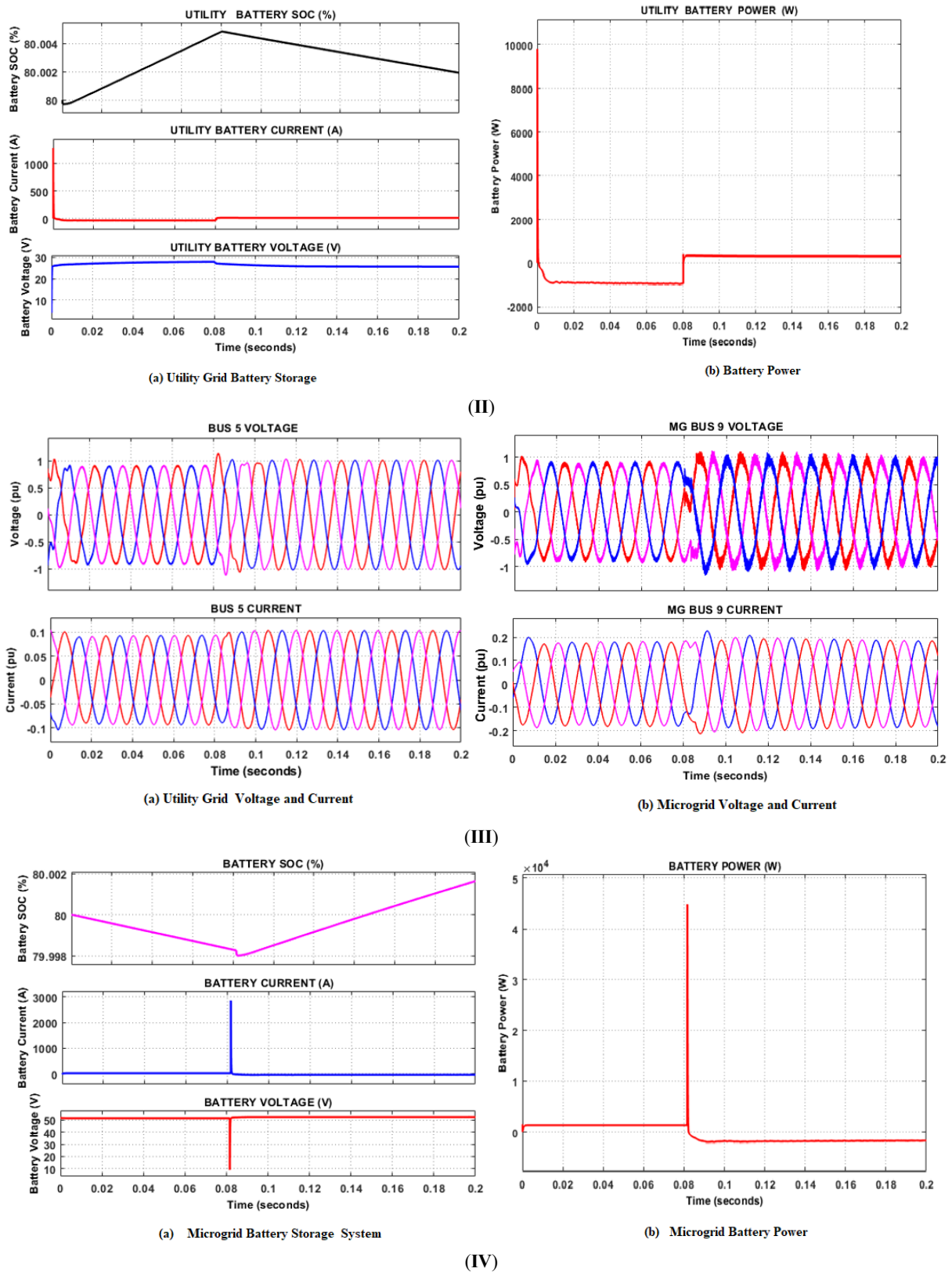


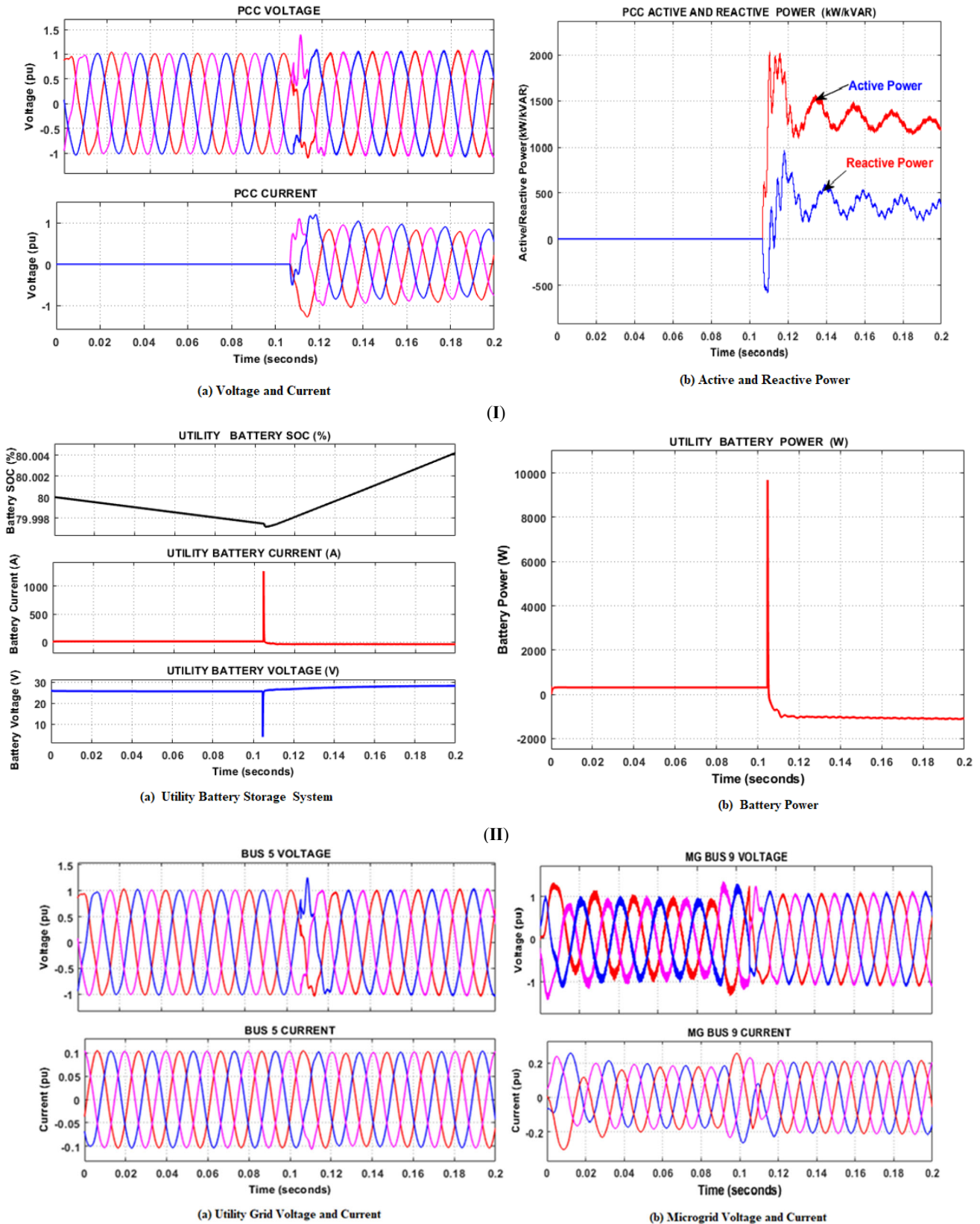
Figure 14. System performance during transition from grid connected to stand-alone mode: (I) PCC and utility grid Bus 5 voltage and current (II) Utility energy storage characteristics (III) Microgrid MGBus 3 Voltage and Current, (IV) Microgrid battery storage waveforms.

To ensure a smooth transition and ensure grid stability, storage systems were activated to support the grid. As can be observed in Figure 14II, after a few seconds of transition, the utility grid storage system was engaged to deliver extra power to the MG. The upward movement of the SOC indicates the charging mode of the battery, while the downward movement indicates that the battery was discharging, delivering extra supply to the system. To avoid overvoltage on the microgrid side, the utility battery was switched to charging mode, as shown in Figure 14IV. Figure 14I shows voltage, current, and powers at PCC during the transition from grid-

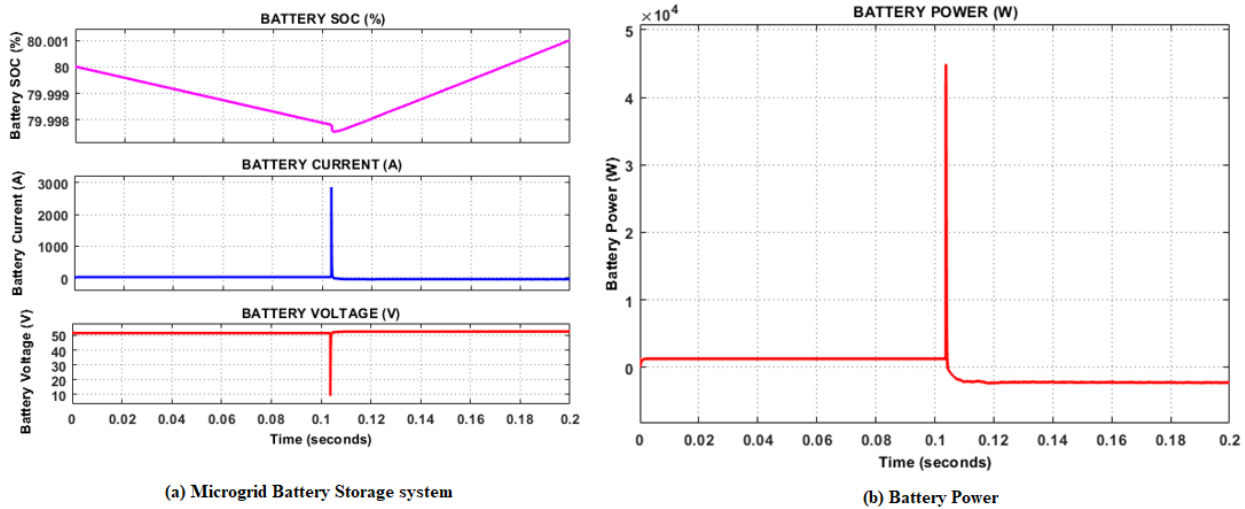
connected to stand-alone mode of operation. At $t = 0.08$ s, the shift from grid-connected to stand-alone mode was activated during this period, and there were occurrences of ripple on the entire system voltage before the system became stable again.

- Scenario 3: Increase in Microgrid Generation

In this case, the small hydropower plant source increases its power generation by 0.9 MW at 0.12 s for almost half a second, after which the storage systems are activated to provide support to the grid. Figure 15(I–IV) shows the system performance during an increase in microgeneration sources.



(III)



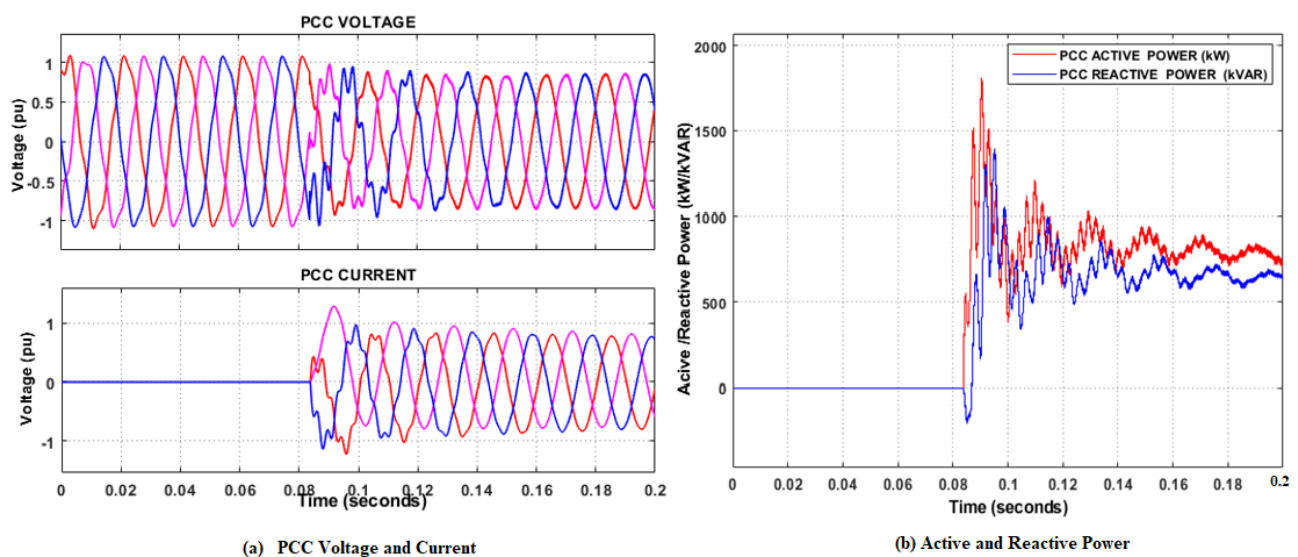
(IV)

Figure 15. System performance during increases in microgrid generation; (I) PCC voltage current and power; (II) Utility grid energy storage characteristics (III) Utility grid and Microgrid (MGBus 3) Voltage and Current (IV) Microgrid Battery storage characteristics.

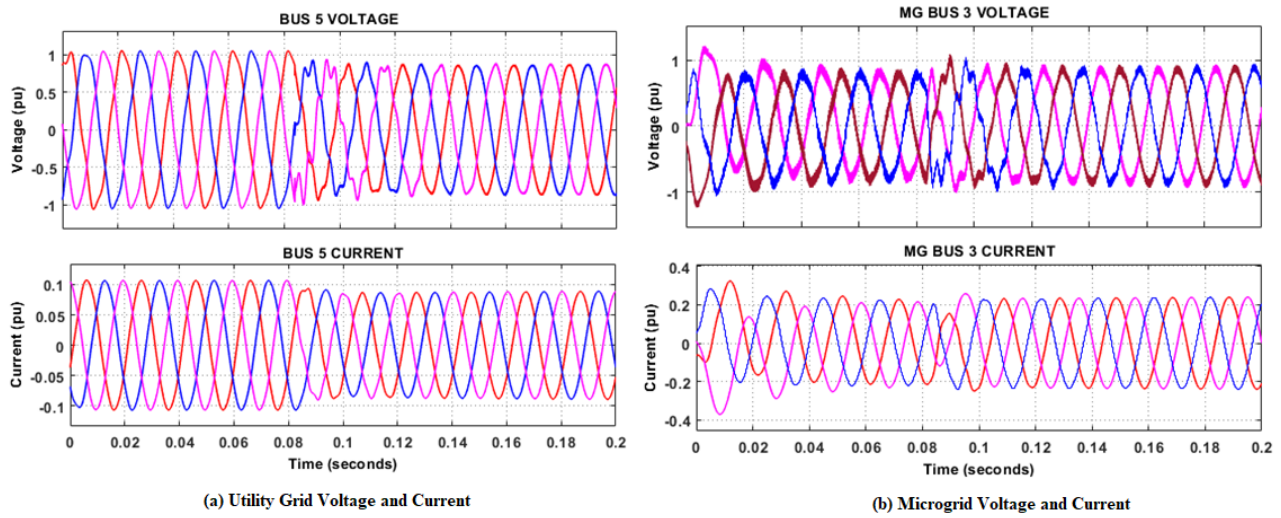
The microgrid system experienced overvoltage for the period of for a period of 0.1 s before the storage system was activated, as seen in Figure 15(III). Figure 15(I) shows the response of the system at PCC; during the scenario. The active and reactive power increased before the system storage was activated, and the microgrid system also switched to grid-connected mode. To ensure system stability during the increase in power generation, energy storage system switches were energized to charging mode to store the excess power generated, as shown in Figure 15(II,IV).

- Scenario 4: Change in System Loading

The variations in the system loading are discussed and analyzed in this section. Figure 16(I,II) shows the performance of the system during an increase in the microgrid loading system, while Figure 17(I,II) shows the response of the system during a reduction in system loading. The system response to the scenario at PCC is shown in Figure 16(I). During an increase in microgrid system load, there is a reduction in microgrid voltage and current from 0 s to 0.8 s; on the contrary, the utility grid maintains its normal voltage and current level during the period. At 0.08 s, energy storage systems were activated to discharge mode to provide support to the microgrid; thus, the microgrid system adjusted itself back to normal voltage and current, as can be seen in Figure 16(II), nevertheless, the microgrid voltage experienced a little ripple. However, the utility grid suffers a reduction in voltage and current scenario; but still operates within the acceptable voltage range of 0.85 pu to 1.0 pu. Figure 17(I,II) shows the performance of the system during a reduction in the microgrid load.

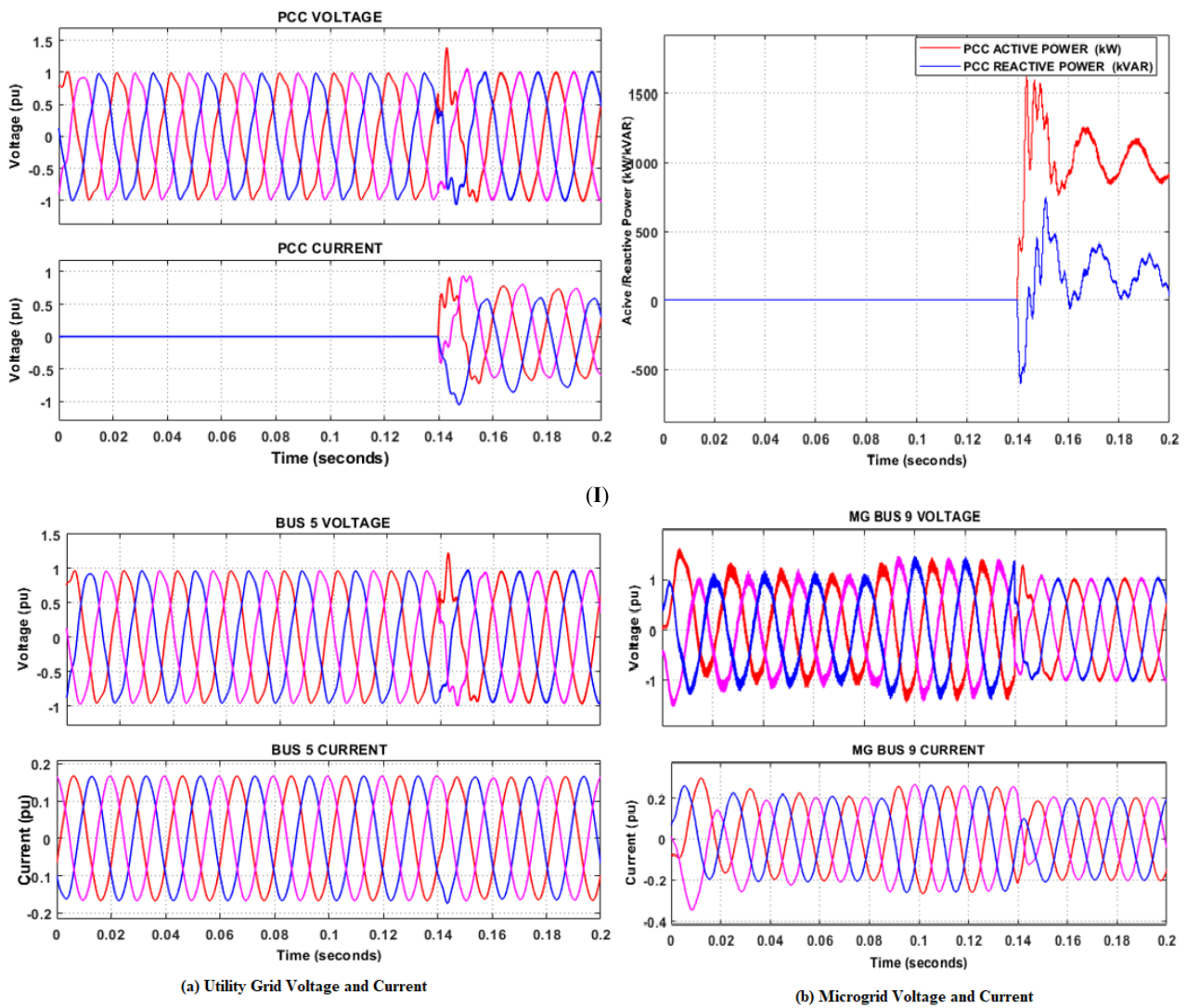


(I)



(II)

Figure 16. System performance during an increase in microgrid load; (I) PCC voltage, Current, and Power; (II) Utility grid and Microgrid voltage and current.



(II)

Figure 17. System performance during a reduction in microgrid loading system; (I) PCC voltage current and power; (II) Utility grid and Microgrid voltage and current.

- Scenario 5: Sudden De-energized of a Micro-source

In this case, the small hydropower plant was suddenly out of service. Figure 18(I,II) shows the system's response to the situation. Figure 18(I) shows single-phase voltage and current at the PCC. As can be seen, the system experiences a voltage and current reduction for a period of 0.1 s when the micro-source is suddenly out of service. Furthermore, Figure 18(II) shows the utility grid response to the situation; the system experiences voltage and current reduction from the period of the micro-source deactivation. Also, the microgrid experiences voltage sag for the period of 0.08 s to 0.1 s. However, the microgrid was unable to restore to its normal operating condition even though the storage systems were active to support the system, as shown in Figure 18(II).

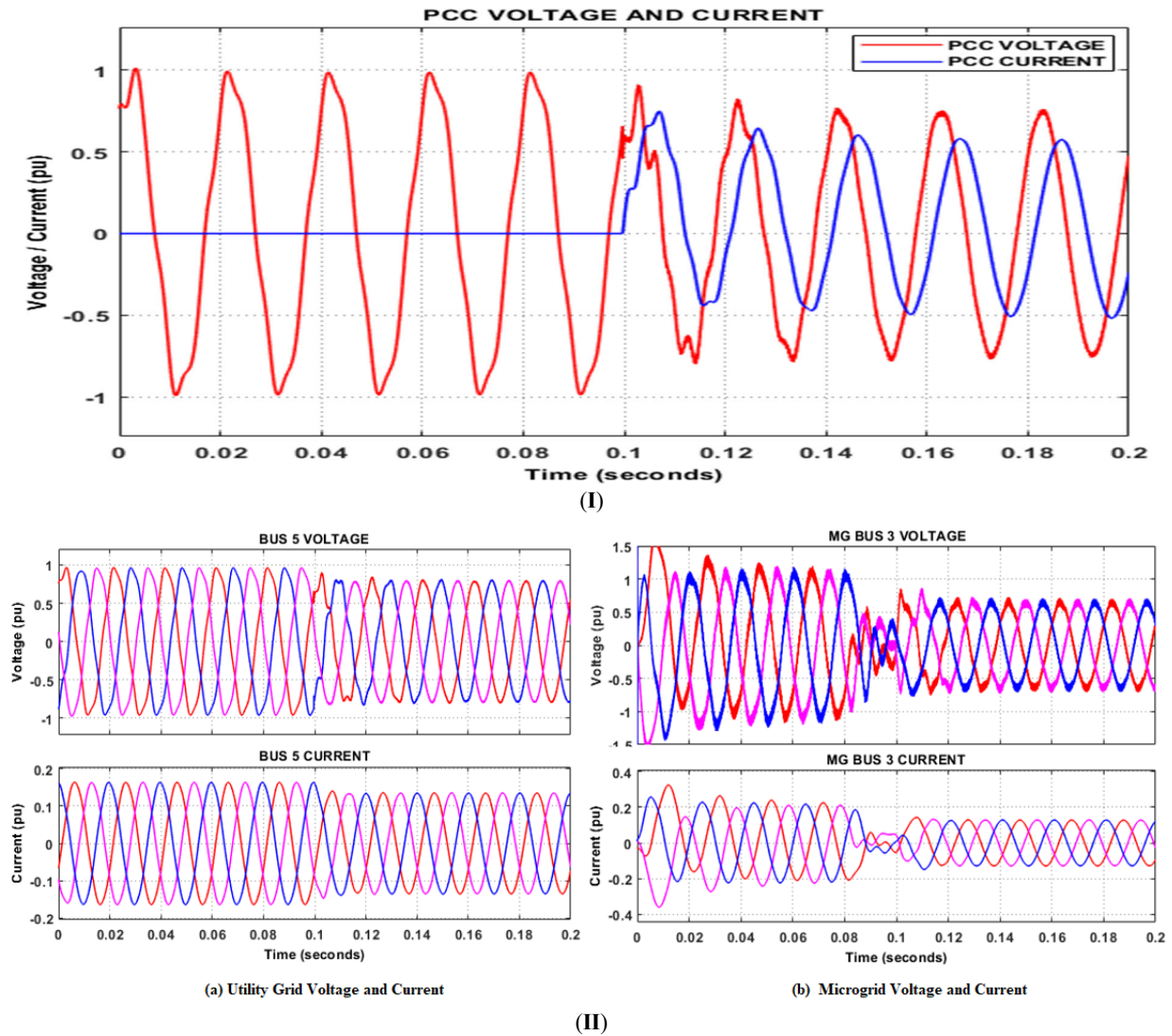


Figure 18. System performance to sudden disconnection of a micro-source from the microgrid; (I) PCC voltage and current (II) Utility grid and microgrid voltage and current.

8. Overview of Microgrid Limitation

The inconsistency of power supply from diverse RESs, like solar and wind, poses a restriction to renewable energy-based MGs. It is also challenging to resynchronize and coordinate the microgrid with the utility grid when the fault on the grid has been cleared. Another limitation to the utilization of microgrids is the implementation of an effective protection mechanism. Furthermore, power quality issues are another limitation of microgrids [112].

9. Conclusions and Future Works

This paper presents a comprehensive review of MGs and evaluates the system performance when integrated into the low-voltage distribution network, considering different operating scenarios. The paper evaluates the system performance both in grid-connected and island modes of operation. Normal operation, fault analysis, an increase in the generating capacity of microgrids, an increase in system loading, and a sudden loss of energy sources from microgrids are some of the simulated and evaluated cases considered in the paper. In addition, the transition from grid-connected to stand-alone mode, as well as re-synchronization with the main grid, were simulated and analyzed. The simulation results show the performance of the system under various scenarios. In a

stand-alone mode of operation, the effect of the fault was only felt on the utility grid for a period of 0.08 to 1.12 s and did not escalate to the microgrid side. However, the fault spread across the network during grid-connected mode. Also, during the transition from grid-connected to stand-alone the system under investigation experiences a voltage rise for the period of transition. However, activation of the storage system to discharge mode brought stability to the system. In addition, during the simulation of the sudden de-energized of a micro-source, the system experienced under-voltage. However, during this scenario, the system was unable to regain its stability even when the storage system was activated to provide support to the grid; this forms part of future work. Generally, power quality issues, grid synchronization, and protection during the transition from one mode of operation to another are some of the challenges identified during the performance evaluation carried out in this paper. It was observed that the effects of the fault escalated throughout the system during fault analysis on either side of the system during grid-connected mode. However, the effectiveness of the storage system for system stability was proven effective. Nevertheless, interconnected microgrid stability, and prevention of power quality issues during disturbances on the grid, at low-voltage distribution networks using power electronic interface are some of the proposed topics for future works. Finally, the paper also reviewed the limitations of microgrid implementation.

Author Contributions

Conceptualization, E.J.A.; Methodology, E.J.A.; Software, E.J.A.; Validation, K.A.O. and E.J.A.; Formal Analysis, E.J.A.; Investigation, E.J.A.; Resources, K.A.O.; Data Curation, K.A.O.; Writing – Original Draft Preparation, E.J.A.; Writing – Review & Editing, E.J.A.; K.A.O.; Visualization, K.A.O.; Supervision, K.A.O.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

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Declaration of Competing Interest

The authors affirmed that they did not know any competing financial interests or personal ties that might have appeared to have an impact on the research presented in this study.

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