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Optimal Power Flow Algorithm-Based Controller for Efficient Switching Between Grid-Connected and Islanded Modes in Hybrid Microgrids

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ABSTRACT: In recent years, there has been a substantial increase in energy production from renewable sources worldwide. In rural areas, microgrids are suitable to support the power supply for the appliances. Solar PV systems have been integrated with the grid to help reduce energy costs. This paper studies an optimal power flow (OPF) algorithm-based controller to enhance power system stability. In microgrid systems, if the solar PV cannot produce enough power to satisfy the load demand, the main grid supplies the necessary power to ensure continued operation. The process requires a controller for continual switching between grid-connected and islanded modes in microgrid. The OPF controller is designed to provide the optimal switching method, confirming a perfect transition between these modes. An AC/DC hybrid microgrid system with AC linear load is used to analyze the performance of the OPF controller in the system. The system contains an OPF controller, a linear load, solar PV with an MPPT controller, and a main grid. The OPF controller receives information from the microgrid system, processes it, and provides a reference value between 1 and 0 for the grid switch to control the microgrid's switching mode. The proposed method was analyzed using MATLAB/Simulink, and the results confirmed the optimal power flow within the microgrid system.

KEYWORDS: Microgrid, Optimal Power Flow, solar PV, Algorithms.

1. INTRODUCTION

Recently, the production of energy has undergone a remarkable transformation, produced by the significant contribution of renewable energy sources [1]. Governments and communities are working together to invest more in cleaner energy sources such as solar PV, wind energy, hydro, and many more to meet energy demand and minimize the use of non-renewable energy resources [2], [3]. The advancement in clean energy technologies, integrated with strong policies and reducing energy costs, has led to a more diverse and rapid growth of renewable energy production. Particularly, solar PV systems have seen an exceptional growth in producing clean energy, benefiting many industries, communities, and businesses by reducing the cost of energy bills. Renewable energy sources often design, and build projects for local economies, especially in rural areas where a large number of solar PV systems are built. Furthermore, this helped many governments create more job opportunities for engineers to research and develop the renewable energy sector.

Despite the developments made in renewable energy technologies, connecting them with the main grids creates challenges due to the intermittent nature of sources such as solar PV and wind power. Therefore, it is necessary to maintain constant monitoring to maintain an efficient and reliable power supply at all times. The world is moving toward a more sustainable future, and the rising number of renewable energy systems represents a great move toward achieving environmental sustainability, economic prosperity, and energy security. This move highlights the importance of continuous innovation and investment in renewable energy technologies to address the urgent global challenges we face today. However, the continuous rise of such systems will pose new challenges that will require more studies to be conducted.

Microgrids are the new generation of technologies that have revolutionized the way power generation is performed. It is self-resilient, and it is able to operate independently or in conjunction with the main grid to generate electricity. In addition, it is a term that combines various types of sources, systems, and loads to supply power even when one of the sources gets disconnected. Microgrids can be AC, DC, and even AC/DC types. Depending on the type of microgrid, engineers design their project to meet power demand. Moreover, solar PV, wind, heat power, and hydro are designed to improve power supply, and energy efficiency. One of the advantages of the microgrid is that it can work both in grid-connected and islanded modes [4]. The switching modes of the microgrid need better controlling techniques to maintain optimal power flow within the system.

Optimal power flow controller play a huge role in microgrid systems to balance the switching between grid-connected and islanded modes in the system [5]. The OPF controller helps the system improve power flow management within the microgrid boundaries, and it can perform independently in any fault condition. Moreover, the OPF controller gives an instant response to the system if one of the sources' behaviors changes due to external impacts on the sources, such as solar irradiance and wind. Hence, the importance of the OPF controller will drive innovation and facilitate the transition to a more sustainable energy landscape.

In the past, there are many papers that have studied microgrid systems. Some papers optimized controlling techniques of the source components, and some papers presented enhanced power flow techniques to improve the performance of the microgrid system. Author in [6] proposed a non-linear stabilizer control method with a non-linear disturbance observer (NDO) to enhance voltage stability in the microgrid. Another author in [7] proposed distributed energy resources (DER) for optimal power flow management in microgrids. The proposed technique helped microgrid systems to run loads at minimal energy costs. The author tested the DER in algorithm-based methods, programming-based methods, and linear programming to select the best option. The proposed method evaluated robust power management strategies in microgrids. Solar irradiance variation plays a significant role in supplying energy to the load. The author claimed that the drop in voltage and power in microgrid systems can be optimized by integrating several energy storage systems (ESS) [8]. The controller helps the system regulate DC-link voltage and ensure better power flow between solar PV and ESS batteries. Hence, none of the authors presented a switching method to enhance the performance of the microgrid system in grid-connected and islanded modes.

This paper analyzes the performance of the microgrid system integrated with solar PV panels, loads, and a main grid. An AREi-225W-M6-G solar PV is used as a renewable source, and a linear load is used in the microgrid. An OPF controller algorithm-based power management is used to control the switching between grid-connected and islanded modes in the system. The simulations are simulated based on MATLAB/Simulink software. The simulation takes a long time to simulate in MATLAB/Simulink, and the time for the simulation lasted for 1 second to show the effectiveness of the controller. Hence, the proposed OPF controller can be tested in any microgrid system in real-time, considering the time spent.

The proposed controller analyzed in three conditions:

- Normal condition where solar irradiance varies between 0.4s and 0.6s.
- When solar irradiance is delivering its maximum value $\frac{1000W}{m^2}$ for 1 second.
- When solar irradiance is too low $\frac{300W}{m^2}$ for 1 second.

2. METHODOLOGY

2.1 AC/DC Microgrid

This research consists of an OPF algorithm-based controller, solar PV, a linear load, and a main grid. Depending on the requirements, an AC/DC microgrid system was employed to simulate the design, and it can work in both grid-connected and islanded modes. Each component performs a specific task to complete the microgrid operation. The solar PV generates a DC voltage, and the voltage level is increased to a desired voltage level by using a voltage boost converter [9]. There are several reasons to employ microgrids in power distribution. It can balance the loads, and sources even when the renewable energy sources do not supply enough power to the system. In addition, the system is called grid-connected when the power is delivered from the main grid, and it is called islanded when it is connected to renewable energy sources. The connect/disconnect control is done by a switch. The mixture of AC and DC components required the system to use an AC/DC hybrid microgrid, and the components are placed in AC and DC based on their configuration. The importance of using an AC/DC microgrid is to minimize the number of converters and buses to maintain the best design.

The loads and sources of the microgrid system are located near the users to avoid excess power losses. The solar PV panels are incorporated into the system to generate electricity during the day when solar irradiance is available. However, the microgrid draws power from the main grid whenever solar irradiance falls below the load's power demand. This ensures the efficiency and reliability of the microgrid system. Figure 1 shows the microgrid system model.

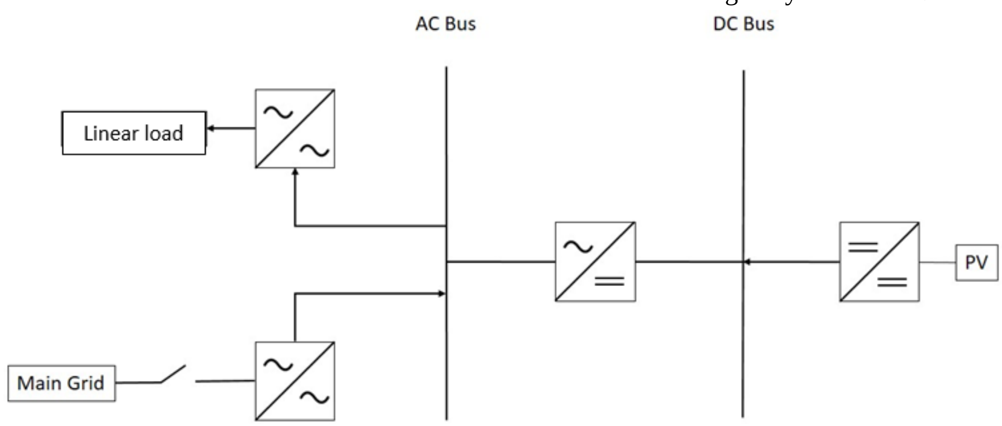

Figure 1. Microgrid system model.

MATLAB/Simulink is used to build the model, and the nominal values for the microgrid are presented as shown in Table 1.

Table 1. Nominal values for the microgrid model.

No.	Item	Nominal value
1	$freq_n$	50 Hz
2	AC V_n	430 V
3	DC V_n	430 V
4	R_{grid}	4
5	L_{grid}	4 μH

A Renewable energy source such as solar PV is connected to the microgrid to supply energy when the system is islanded. The maximum power point of a solar PV is 225.129 W. An individual solar panel cannot generate more than the maximum power point specified by the manufacturer. Therefore, it is necessary for this paper to connect 13 series and 6 parallel solar PV arrays to increase the maximum power point of the solar PV. The maximum power point is calculated by the number of solar irradiances. The maximum power can be achieved from 1 meter square, as shown in equation 1.

$$P_{pv} = \frac{Solar\ Irradiance\ (\frac{W}{m^2})}{1000\ (W)} \times Maximum\ Power\ (W)$$

$$Total\ P_{pv} = Parallel\ strings \times Series - connected\ modules\ per\ string \times P_{pv}$$

The nominal values for the solar panel are presented in Table 2.

Table 2. Specifications of solar PV panel.

Item	Value
P_{pv} (W)	225.129
$Parallel\ strings$	6
$Series - connected\ modules\ per\ string$	13

The linear load nominal value is presented in Table 3.

Table 3. Linear load nominal value.

Item	Value
Linear load (W)	9000

The general algorithm used for maximum power point tracking is P&O. It is generally based on PV array calculation and power variation by reading and sensing the current and voltage in PV cells. According to P&O, if the output power increases or decreases in photovoltaic, then P&O is created on the other side [10]. Once the maximum power point is reached, the PV characteristics start to oscillate and remain around the maximum point. To control the oscillation at its maximum point, it is necessary to reduce the perturbation step size. Different photocells with different solar irradiance generate different curves based on their parameters and requirements.

2.2 Optimal Power Flow Control

The microgrid system is operated based on the OPF control method, and an OPF controller is used to optimize the performance of the microgrid system. The OPF controller takes input from the microgrid system, processes it using the OPF control algorithm, and determines whether the switch needs to connect to the grid or to the solar PV panels. The OPF model is incorporated to minimize excess power losses and costs for the system, ensuring the microgrid utilizes renewable energy sources whenever possible. This OPF control algorithm is more efficient to give a fast response to the dynamic behavior of the microgrid system at any time. Therefore, it tests the code in MATLAB/Simulink and increases the performance of the system. Figure 2 shows the OPF controller with inputs and an output for the switching of the microgrid. The simulation ran for 1 second to show the effectiveness and correctness of the controller in the system.

This paper examines OPF control to minimize power losses and maintain optimal performance for the microgrid system. The values sampled in the OPF controller were solar irradiance, linear load, and time values. The optimized value for the microgrid is switch.

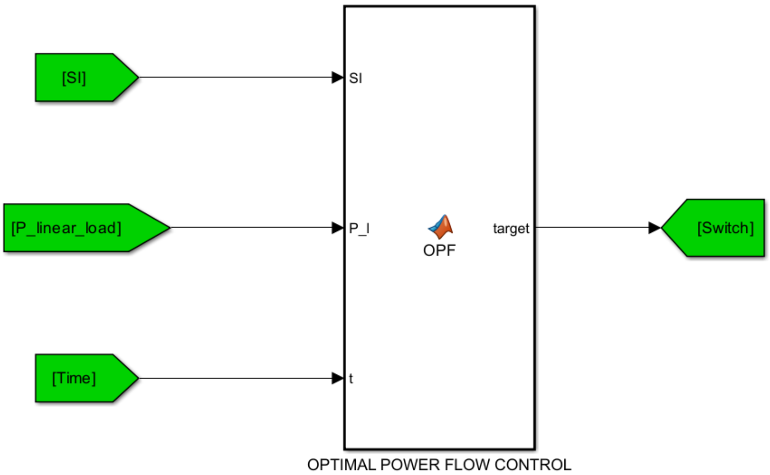

Figure 2. Optimal power flow control for microgrid.

The generated power from solar PV must be higher than the load power to sustain power delivery from renewable energy sources. However, the switch will be connected to the grid if the generated power from the solar PV is less than the load power. The formula is shown below.

$$P_{net} = P_{gen} - P_l \tag{3}$$

Hence, the controller was tested in three conditions to show the effectiveness of the proposed OPF controller.

3. RESULTS AND DISCUSSION

The results show the performance of the optimal power flow controller algorithm-based power management. MATLAB/Simulink was employed to conduct the analysis for the microgrid system. The OPF controller receives information from linear load and solar irradiance to process and provide a reference value for the grid switch. The results present the grid switch outcome, solar PV power, grid power, and linear load power. Finally, the grid voltage, voltage from the DC bus, and current from the voltage source converter were presented. The simulations were conducted based on the following conditions and the results obtained were presented accordingly.

- Normal condition where solar irradiance varies between 0.4 and 0.6 seconds.
- Solar PV delivers power at maximum solar irradiance for 1 second.
- Solar PV power is too low for 1 second.

The results obtained in each case are discussed further in the end.

3.1 Normal condition

The simulation results present the analysis of the OPF controller in a normal situation. Firstly, solar PV delivers maximum power with solar irradiance $\frac{1000W}{m^2}$, and changes between 0.4 and 0.6 seconds. The grid switch changes when solar irradiance drops. The main grid delivers power to the microgrid whenever solar PV does not support the load. The microgrid is connected to the main grid at (switch=0) and connected to the solar PV at (switch=1). Figure 3 presents the performance of the microgrid for the grid switch, grid power, solar PV, and linear load power.

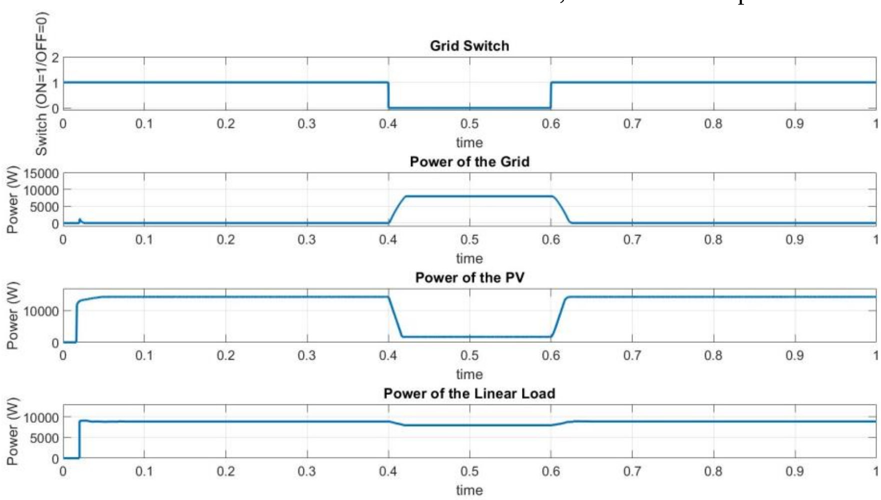

Figure 3. Microgrid grid switch and power performance for the OPF in normal condition.

The simulation results for the grid voltage, VSC current, and DC voltage levels are presented in Figure 4. The microgrid voltage experienced a slight variation when switching changes occurred in the system. The changes occurred at 0.4s and 0.6s. The DC voltage is 430V at all times. Moreover, the current from the voltage source converter does not deliver current to the system when the microgrid is receiving voltage and current from the main grid.

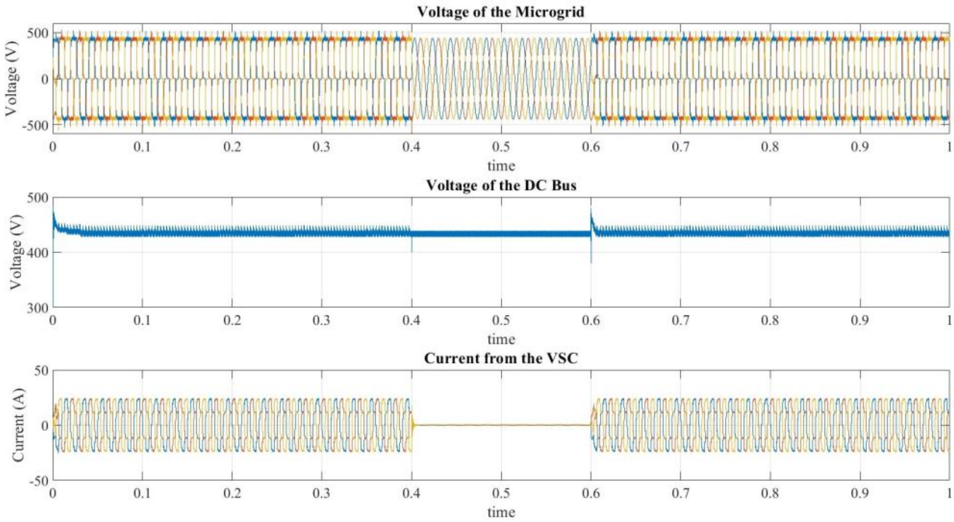

Figure 4. Shows voltage of the microgrid, DC bus voltage and current fromVSC .

3.2 Microgrid system with $\frac{1000W}{m^2}$ *solar irradiance*

The results for the grid switch, power of the grid, power of the solar PV, and linear load power are presented in Figure 5 when solar PV delivers maximum power with $\frac{1000\text{W}}{\text{m}^2}$ solar irradiance. When solar irradiance is at its maximum irradiance point or higher than the load demand, the switch remains islanded. Each time the OPF controller receives information, processes it, and keeps the grid switched on, the solar PV continues to deliver power to the linear load. There are no changes that can be seen in this condition. Hence, the grid switch is remianed islanded (switch=1).

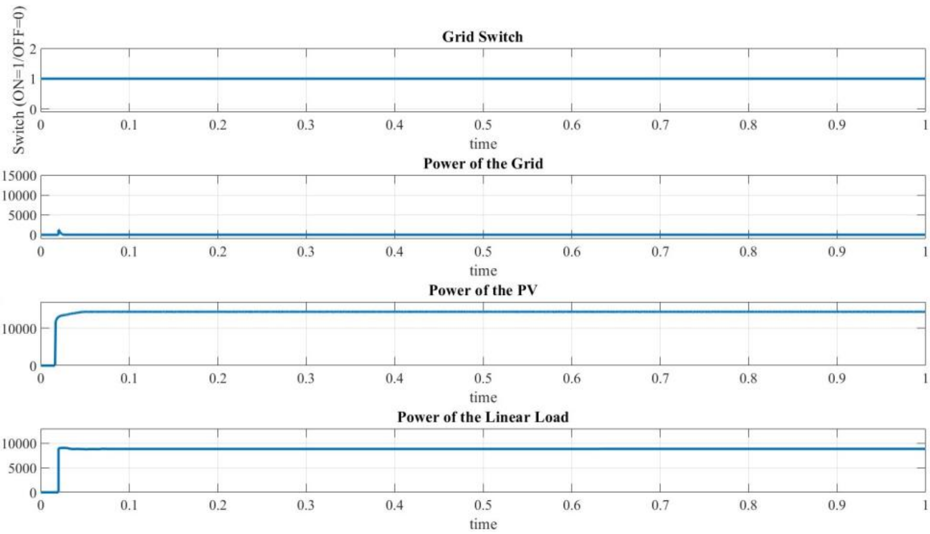

Figure 5. Microgrid grid switch and power performance for the OPF at $\frac{\mathbf{1000W}}{\mathbf{m^2}}$ **solar irradiance.**

The simulation results for the grid voltage, VSC current, and DC voltage levels are presented in Figure 6 when solar irradiance is at $\frac{1000\text{W}}{\text{m}^2}$ for 1s. Moreover, current from the VSC is active at all times when the microgrid receives power from solar PV

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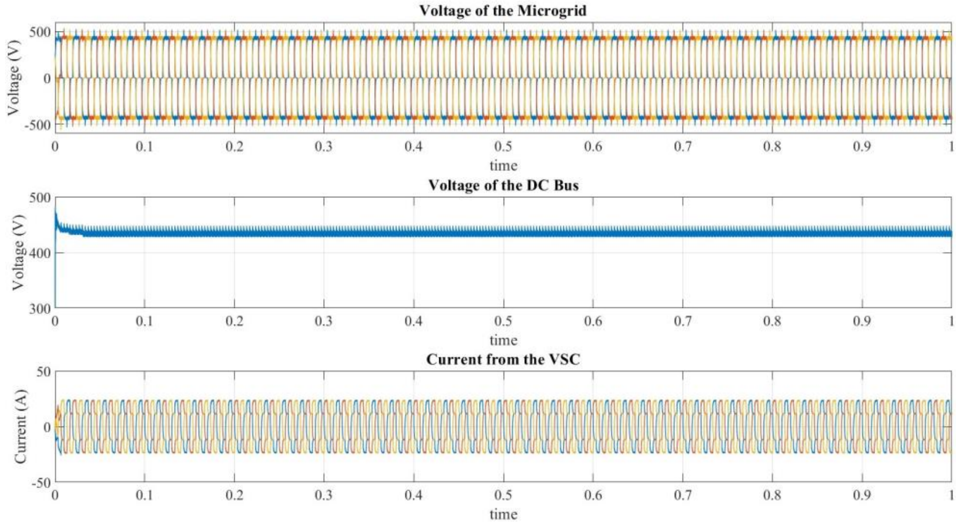

Figure 6. Shows voltage of the microgrid, DC bus voltage and current fromVSC when solar irradiance is $\frac{1000W}{m^2}$ for 1s.

3.3 Microgrid system at $\frac{300W}{m^2}$ solar irradiance

The results for the grid switch, power of the grid, power of the solar PV, and linear load power is presented in Figure 7 when solar PV delivers maximum power with $\frac{300W}{m^2}$ solar irradiance. In this case, the microgrid receives power from the main grid, or the solar PV is not able to provide enough power for linear load. The OPF receives information from the microgrid, processes it, and provides reference to the grid switch. The system remains grid-connected (switch=0) until the solar PV generates more power.

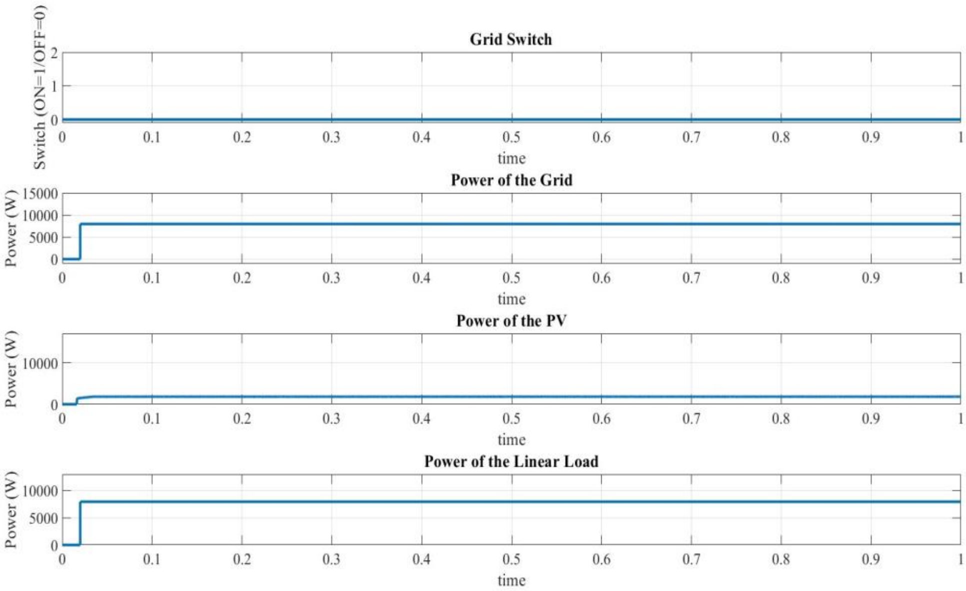

Figure 7. Microgrid grid switch and power performance for the OPF at $\frac{300W}{m^2}$ solar irradiance.

The simulation results for the grid voltage, VSC current, and DC voltage levels are presented in Figure 8 when solar irradiance is at $\frac{300W}{m^2}$ for 1s. The current from the VSC remained zero at all times when the power of the solar PV was too low. Moreover, the voltage of the DC bus remained the same.

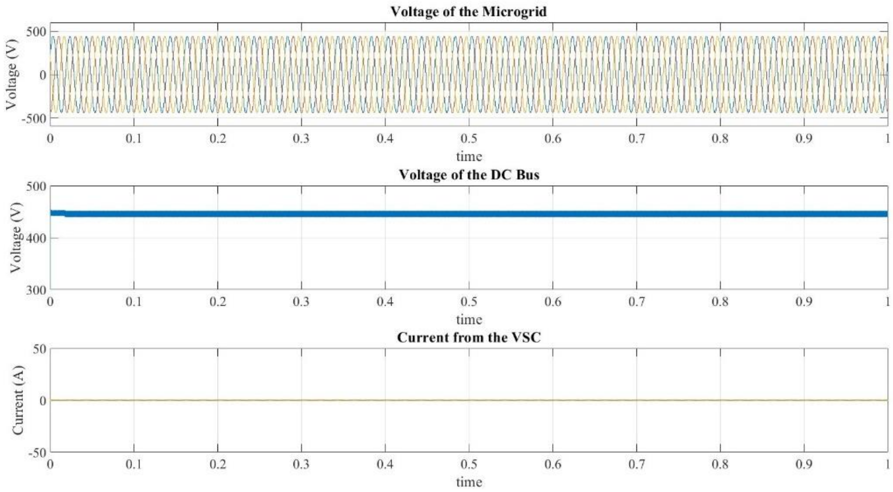

Figure 8. Shows voltage of the microgrid, DC bus voltage and current fromVSC when solar irradiance is $\frac{300W}{m^2}$ for 1s.

The aim of the microgrid system is to balance the power quality, enhance power distribution, minimize power losses, and increase the cost efficacy and reliability of the system. The OPF controller is employed to control the switching of the microgrid between grid-connected and islanded modes. Hence, OPF validated results for the microgrid system and proved its optimal regulation in all conditions.

4. CONCLUSION

The hybrid microgrid systems are going through many challenges, such as power losses, high costs, and unbalanced power quality. It is necessary to maintain effective and efficient power distribution and control at any time. An OPF controller is used to control switching between solar PV and the main grid. The switch is grid-connected whenever solar irradiance or solar power is below the load demand. A boost converter is used to increase the DC voltage to 430V to maintain a stable voltage supply for the microgrid system. The results showed that the OPF controller is able to control the switching in grid-connected and islanded modes. Future work is needed to make the microgrid system much better. Future studies might use solar irradiance from real data to analyze the performance of the OPF controller. Moreover, the users can implement energy storage systems to support the microgrid system whenever solar PV encounters challenges such as sudden drops in solar irradiance or other uncertainties. Therefore, this analysis may help the system to minimize its dependency on the main grid, consequently reducing power costs for the community.

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