JJEE Volume 9 | Number 4 | December 2023 | Pages 591-606

Jordan Journal of Electrical Engineering

ISSN (print): 2409-9600, ISSN (online): 2409-9619

Homepage: jjee.ttu.edu.jo

Enhancing Energy Reliability and Balance with Fuzzy Logic Controlled Microgrid System

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Received: April 04, 2023 *Revised: May 18, 2023* *Accepted: May 27, 2023*

***Abstract*—** This paper presents a microgrid energy management system that encompasses a combination of solar panels with maximum power point tracking (MPPT), a battery storage unit connected by a bidirectional converter and a wind turbine. The microgrid is designed to maintain a balance between energy supply and demand under varying weather conditions and loads. The system employs a fuzzy logic controller to regulate the power flow between the loads and sources, ensuring reliable and efficient operation. The microgrid is of the DC type, providing power to both DC and AC loads. The proposed system is designed and implemented using Matlab/Simulink and evaluated using simulation studies. The obtained results show the large extent to which the recommended approach ensures a steady energy supply under different load and weather scenarios, indicating that the proposed microgrid energy management system is a viable and efficient solution for small-scale renewable energy systems.

***Keywords*—** Fuzzy logic controller; Microgrid; Energy management; Energy supply reliability; Energy balance; Renewable energy system.

1. INTRODUCTION

Meeting increasing global energy demand while mitigating the environmental impact of power generation poses significant challenges. Conventional power sources that rely on fossil fuels have negative environmental consequences, including air pollution and carbon dioxide emissions that exacerbate environmental issues. Renewable energy sources, such as hydropower, wind, and solar, have emerged as viable alternatives that offer a sustainable and cleaner option to traditional power generation [1]. Renewable energy sources have already begun to play a significant role in the energy mix of many countries, with several nations setting ambitious targets to increase their share of renewable energy. In 2020, renewable energy will account for 72% of all new power generation capacity additions globally, with solar and wind power leading the way [2]. Renewable energy sources have the ability to lower electricity prices, provide energy security, and support regional economic growth, in addition to their environmental advantages. For instance, in many nations, the price of electricity produced by renewable energy sources is now more affordable than the price of electricity produced by conventional power sources such as coal- and gas-fired power plants [3]. This trend is expected to continue as renewable energy technologies continue to improve and become more cost-effective. However, renewable energy sources face several challenges

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Article's DOI: 10.5455/jjee.204-1680652201

that limit their widespread adoption. One of the most significant challenges is the intermittent nature of renewable energy sources [4]. Unlike traditional power generation sources, which can provide a steady and reliable output, renewable energy sources depend on weather conditions and can fluctuate in output. This variability can make it challenging to balance the supply and demand of power and maintain a stable power grid, particularly during times of peak demand or adverse weather conditions. The effectiveness of Renewable energy (RE) generation, however, is impacted by meteorological factors including wind speed, temperature, and solar irradiation, which can lead to a number of issues in an electrical system. Therefore, a hybrid grid strategy based on RE is required for the more effective and secure microgrid (MG) solution [5]. As a result, there is a need for effective energy management systems that can integrate and balance multiple distributed energy resources (DERs) to ensure a stable and reliable power supply [6].

Several methods have been proposed for integrating renewable energy sources into microgrids to address these challenges. One such method is model predictive control (MPC) [7]. MPC is a sophisticated control method that uses a mathematical model of the system to predict future decisions and optimize control actions accordingly. However, the main drawback of MPC is its high computational complexity and the requirement for accurate models, making it difficult to implement in real-time. A different approach is the utilization of linear programming (LP) control. This strategy involves using a linear optimization model to distribute the power generation and storage resources of the microgrid [8]. Nevertheless, the primary disadvantage of LP control is that it presumes a linear connection between the input and output variables, which may not always be the case. Another method is Proportional-Integral-Derivative (PID) control. This control method is a simple and widely used approach that adjusts control actions based on the error between the desired and actual output [9]. However, the main drawback of PID control is that it may struggle to handle complex and nonlinear systems. Furthermore, Artificial Neural Networks (ANNs) have been applied in microgrid energy management systems to predict future energy demands and optimize energy storage systems. ANNs can model complex, nonlinear systems and learn from past data to make accurate predictions [10]. However, the main disadvantage of ANNs is their high computational complexity and the requirement for significant amounts of training data.

Finally, fuzzy logic control has emerged as a promising solution for microgrid energy management. Fuzzy logic control uses a set of linguistic rules to determine control actions based on the input variables [11]. Fuzzy logic control can handle complex, nonlinear systems, uncertainties, and imprecise information. It has been successfully applied in several microgrid energy management systems and has shown superior performance compared to other control methods. In conclusion, microgrids offer a flexible and robust foundation for integrating renewable energy sources, ensuring a steady and reliable power supply. While various methods have been proposed for microgrid energy management, fuzzy logic control has emerged as the most suitable solution due to its ability to handle complex and nonlinear systems as well as uncertainties.

The microgrid energy management system presented in this paper employs a bidirectional converter to integrate multiple renewable energy sources, such as solar panels and wind turbines. To control the power flow between the sources and loads and ensure reliability and efficient functioning, the suggested system uses a fuzzy logic controller. The microgrid is designed to maintain a balance between energy supply and demand under varying weather conditions and loads, providing a sustainable and reliable solution for small-scale power generation. The proposed system in this study was created using Matlab/Simulink, and its effectiveness was evaluated through simulation studies. The findings demonstrate the effectiveness of the suggested approach in providing a consistent energy supply, even when faced with various load and weather conditions. This microgrid energy management system offers a practical and effective solution for small-scale renewable energy systems. Overall, this paper contributes to the ongoing efforts to develop reliable and efficient microgrid energy management systems that can effectively integrate renewable energy sources into the power grid. By addressing the challenges of renewable energy integration, microgrids offer a promising solution for promoting sustainable and cleaner power generation, reducing electricity prices, and mitigating the impact of climate change.

2. MICROGRID CONCEPT AND MODELLING

A microgrid is a small-scale energy system that can operate independently or in conjunction with the larger electrical grid. It typically includes distributed energy resources such as solar panels, wind turbines, batteries, and backup generators. The microgrid is designed to generate, store, and distribute electricity within a localized area [12]. Microgrids can be used to provide reliable, resilient and cost-effective energy to homes, businesses and communities, especially in remote or off-grid areas, as shown in Fig. 1.

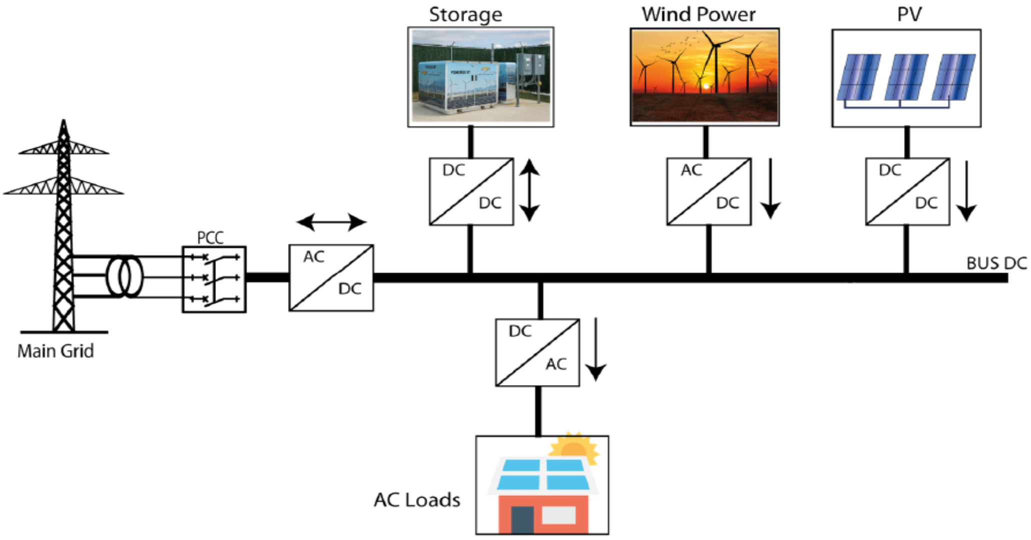


Fig. 1. Structure of the microgrid.

These systems facilitate the incorporation of renewable energy sources such as solar and wind power, which can help reduce greenhouse gas emissions and promote energy autonomy. A microgrid is an electrical system that combines various energy sources, primarily renewable resources, to provide reliable and efficient energy services to small clients in rural areas. This hybrid system operates at low or medium voltage and is designed to ensure that the energy supply is resilient and sustainable, even in the event of potential disruptions to the main grid [13]. The definition and concept of microgrids are evolving to offer customers sustainable energy options that incorporate renewable energy integration, grid stability, flexibility, and cost-effectiveness. As depicted in Fig. 1, a microgrid (MG) comprises circuit breakers (CBs) and inverters, along with power sources, a storage system, and controlled power requirements to maintain equilibrium.

However, in residential applications, the viability of microgrids can be affected by imbalances arising from the lower cost of electricity generation through renewable sources. Consequently, the implementation of a demand response mechanism and energy management system becomes crucial to uphold system stability and reduce electricity expenses, as suggested in [14].

2.1. Photovoltaic Structure

According to Fig. 2, the photovoltaic system is composed of one or more solar panels, and its purpose is to convert sunlight into electrical energy. Maximum power point tracking (MPPT) is a technique used to optimize the output of the solar panels by tracking the maximum power point and adjusting the load accordingly [15]. PV generators and the load are connected by a DC/DC power converter, also known as a static converter. The main function of the converter is to collect the maximum power generated by the PV generators and transfer it to the load. To ensure maximum power efficiency at all times, the boost converter is controlled by an MPPT controller. In our work, we utilize the perturb and observe (P&O) method [16].

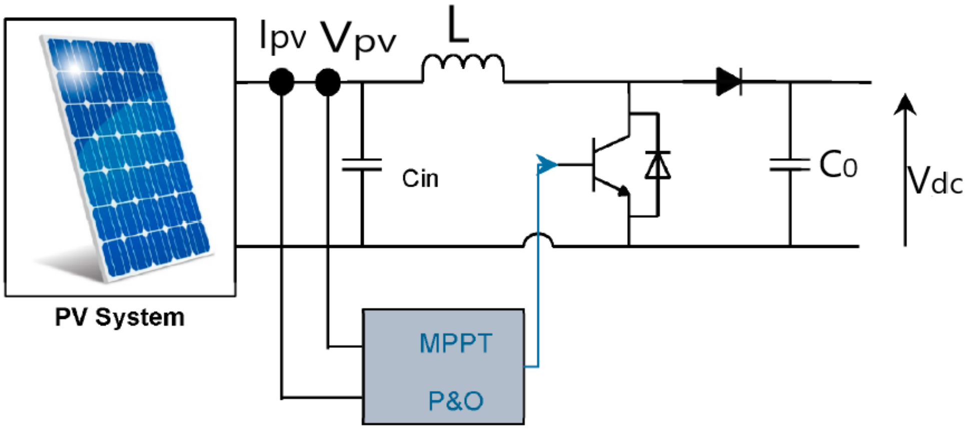


Fig. 2. Photovoltaic system.

The output voltage and current of the solar system can be calculated using the following equations:

$$V_{out} = V_{oc} - (I_{sc} \cdot R_s) \tag{1}$$

$$I_{out} = (P_{max} \cdot V_{mp})(I_{sc} + K.(T - T_{ref})) \tag{2}$$

where V_{out} is the output voltage, V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, R_s is the series resistance, I_{out} is the output current, P_{max} is the maximum power, V_{mp} is the voltage at the maximum power point, K is the temperature coefficient, T is the operating temperature and T_{ref} is the reference temperature.

2.2. Wind Energy System

Components of the wind generator are shown in Fig. 3. They include a synchronous permanent magnet generator, a wind turbine, and a power converter regulated by an MPPT system. By harnessing the kinetic energy of the wind, wind energy systems (WES) offer a promising and readily accessible source of electrical energy. This energy is utilized to rotate the turbines, converting it from mechanical to electrical energy. The amount of wind energy produced is inversely proportional to the wind speed. The MPPT control device tracks the peak power point for each wind speed [17]. The voltage output generated by the Permanent Magnet Synchronous Generator (PMSG), associated to the wind system, undergoes rectification through a three-phase diode bridge. To track the wind turbine's maximum power point, a Perturb and Observe (P&O) algorithm-based MPPT technique is employed. The feasibility of this approach is achieved through the implementation of a DC-DC boost converter.

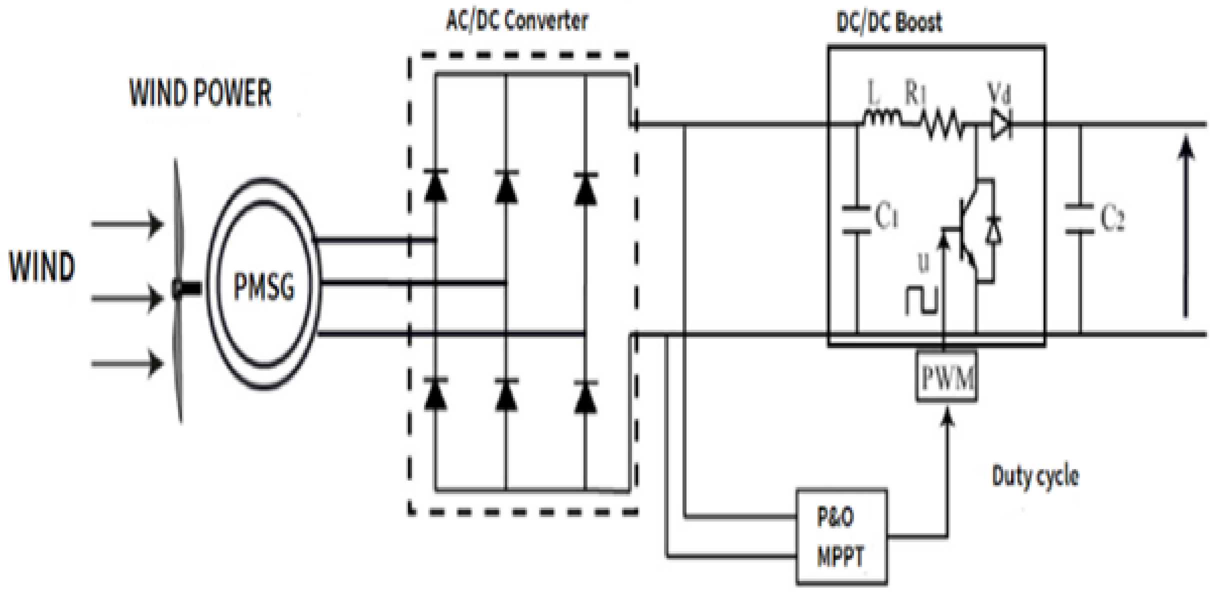


Fig. 3. Wind turbine system.

Wind energy is converted into electrical energy by the wind turbine. The output voltage and current of the wind turbine can be calculated using the following equations [18]:

$$V_{out} = \frac{(V_w \, . \, C_p \, . \, A \, . \, 0.5 \, . \, rho \, . \, V_w)}{\left(\frac{1}{3} . \, H.(R+H)\right)} \tag{3}$$

$$I_{out} = \frac{P_{out}}{V_{out}} \tag{4}$$

where V_{out} is the output voltage, V_w is the wind speed, C_p is the power coefficient, A is the swept area of the blades, rho is the air density, H is the height of the turbine, R is the radius of the blades, Pout is the output power and I_{out} is the output current.

2.3. Battery Storage System

The battery storage system (BSS) serves as a temporary supply of power when the flow of energy produced by solar sources is insufficient to meet load demand. The BSS, on the reverse side, operates as a load when there is an excess of electricity to maintain the system in balance. A bidirectional DC-DC converter, a Li-ion battery and a controller to regulate the cell's charging and discharging to maintain state of equilibrium on the microgrid bus, are shown as part of BESs components in Fig. 4.

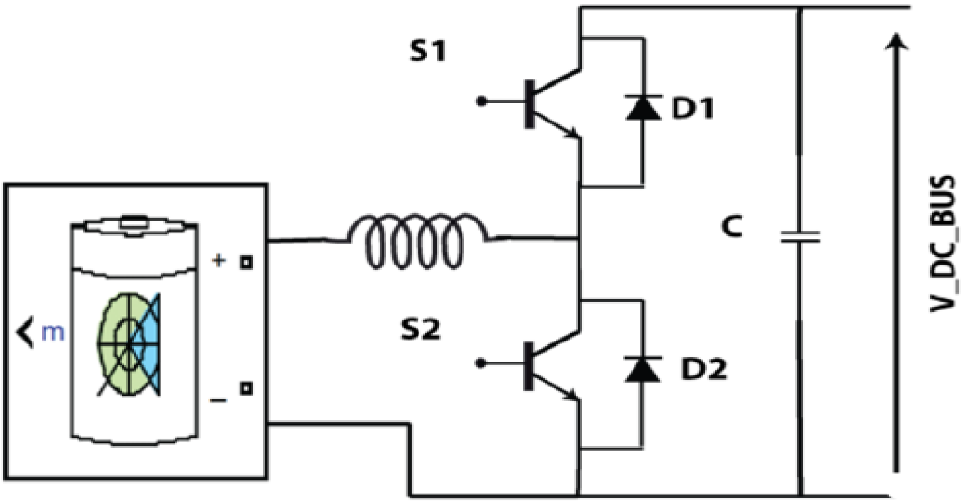


Fig. 4. Battery storage system.

For later usage, the battery storage system saves extra energy produced by the solar panel and wind turbine [19]. The voltage and current of the BSS can be calculated using the following equations:

$$V_{batt} = (n \,.\, N_s \,.\, V_{cell}) - (n \,.\, N_s \,.\, V_{out} \,.\, R_{batt}) \tag{5}$$

$$I_{batt} = \left(\frac{P_{out}}{V_{batt}}\right) + I_{loss} \tag{6}$$

where V_{batt} is the battery voltage, n is the number of cells in series, N_s is the number of series strings, V_{cell} is the voltage per cell, I_{batt} is the battery current, R_{batt} is the internal resistance of the battery, P_{out} is the output power, and I_{loss} is the power loss. The bidirectional DC-DC converter is employed to oversee the battery's charging and discharging processes, which involve converting the DC output from the solar system, wind turbine, and battery storage system. In addition, it has the capability to convert DC power from the battery into AC power that can be utilized by the loads [20]. The output voltage and current of the bidirectional converter can be calculated using the following equations:

$$V_{out} = \frac{(V_{dc} \,.\, D)}{\sqrt{2}} \tag{7}$$

$$I_{out} = \left(\frac{P_{out}}{V_{out}}\right) . \sqrt{2} \tag{8}$$

where V_{out} is the output voltage, V_{dc} is the DC voltage, D is the duty cycle, P_{out} is the output power and I_{out} is the output current.

3. ENERGY MANAGEMENT SYSTEM UNDER FUZZY LOGIC CONTROLLER

3.1. Fuzzy Logic Controller Design

Fuzzy logic control (FLC) has been applied in many challenging sectors. One of the most well-thought-out approaches to distributed power optimization problems is FLC. In-depth research has been done on FLC functions to increase their capacity for managing expert system problems. The MATLAB/Simulink Fuzzy Logic Toolbox served as the foundation for the creation of a FLC controller for grid control. Block diagram of the fuzzy logic controller is shown in Fig. 5 [20].

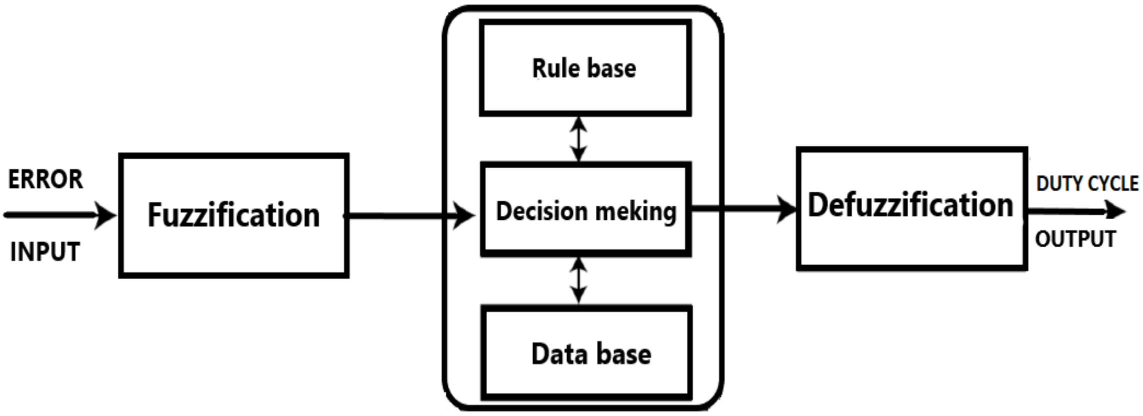


Fig. 5. Block diagram of the fuzzy logic controller.

The fuzzy logic controller (FLC) consists of three key components: fuzzification, a fuzzy inference system, and defuzzification. The procedure of fuzzification involves converting a precise input into a linguistic variable using membership functions. This process requires domain knowledge and often utilizes trapezoidal or triangular membership functions. The inference stage employs rule-based operations guided by trained awareness. Finally, the linguistic variable receives a clear value through defuzzification. Fig. 6 in this study displays the membership functions used for the microgrid energy management input.

plot points: 181

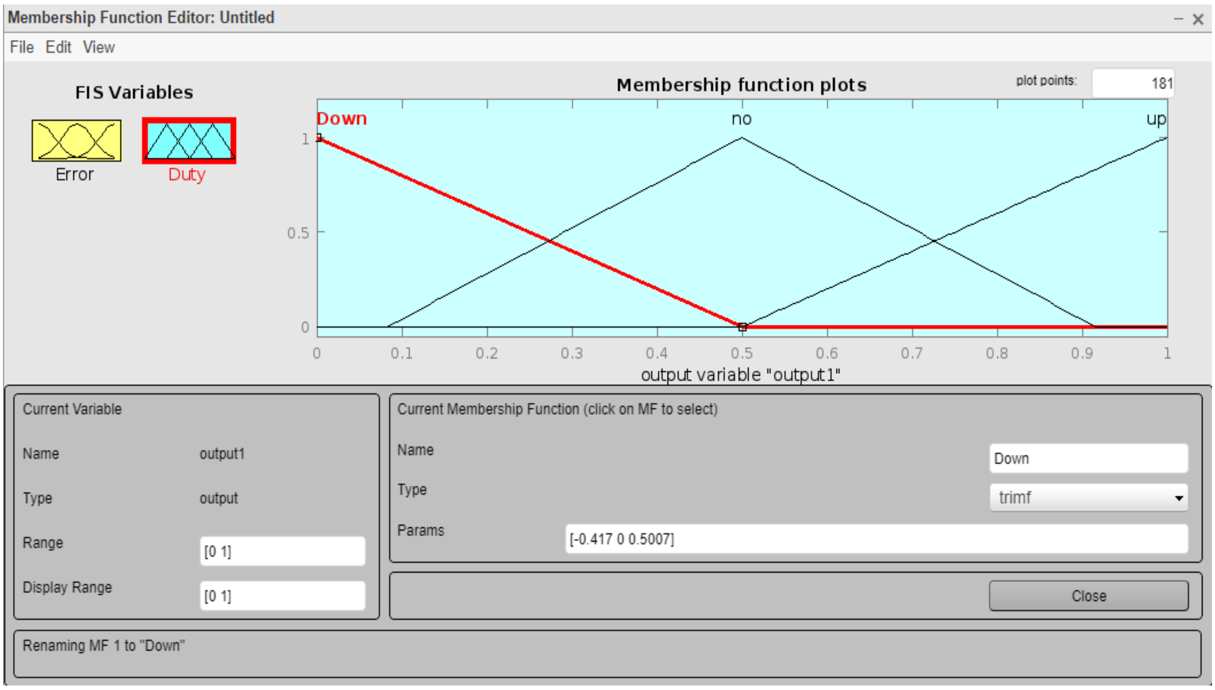
Name input1
Type input
Range [0 1]
Display Range [0 1]

Name Negative
Type trimf
Params [0 0 0.5]

Selected variable "input1"

Fig. 6. Membership function of the error signal.

By comparing the DC bus voltage with the voltage of reference, the method of control adopts an optimal switching pattern for the battery's charging and discharging. The fuzzy logic controller receives four inputs as a result of this comparison. The controller then provides the PWM block's duty cycle, as shown in Fig. 7, so that a signal can be sent to the buck/boost converter.



plot points: 181

Name output1

Type output

Range [0 1]

Display Range [0 1]

Name Down

Type trimf

Params [-0.417 0 0.5007]

Renaming MF 1 to "Down"

Fig. 7. Output function of membership.

If the energy produced from the renewable energy sources is greater than the power consumed by the loads in the microgrid, the FLC will control the charging rate of the battery to store the surplus energy. If the amount of energy consumed by the loads in the microgrid is greater than the amount of power generated from renewable sources, the FLC will control the discharging rate of the battery to supply the microgrid with the required energy. The FLC uses a set of fuzzy rules to determine the charging and discharging rates of the battery based on the battery voltage and the power generated from renewable energy sources.

3.2. Energy Management System

The discounted power generation from renewable sources, which causes microgrid surplus or deficit, affects the value of a microgrid for customers. For system stability and a decrease in electricity costs, the integration of a demand response mechanism and an energy management system is crucial based on the research in [14].

Fig. 1 depicts the various power sources that constituted the microgrid utilized in this study. The proposed microgrid management technique is based on a FLC controller. An MPPT controller is used to regulate a DC/DC converter connecting the photovoltaic solar system to the DC bus in order to maximize the generation of power. A wind turbine is also connected to the DC bus using multiple converters and an MPPT block to extract the maximum available power. An AC/DC converter connects the primary grid to the DC bus, but it is only utilized during emergencies when insufficient renewable energy is available and the BES charge falls below 20%. The battery system is linked to the microgrid via a bidirectional DC/DC converter, and its operation is controlled by a FLC controller. The provided system for managing energy attempts to satisfy the energy need by controlling the voltage at 300 V. The objective is to maintain the frequency of the AC bus at 50 Hz, ensuring the battery is neither overcharged nor undercharged. The EMS method sends a control signal to each microgrid component, which makes each part a decentralized controller that is independent of other sources. The flowchart of Fig. 8 illustrates the energy management technique used in this project. The energy management system of the microgrid is composed of different operational modes, as illustrated in Fig. 8, that consider the various power production modes, load consumption, and battery state of charge (SOC). According to the battery's level of charge, the structure's power flow can be divided into three operational settings. It is crucial to maintain the battery's state of charge within a specified range (20% < SOC < 80%) to improve its lifespan. When using renewable energy sources to meet demand for consumption (PLoad) and charge the battery, the MPPT technique is applied.

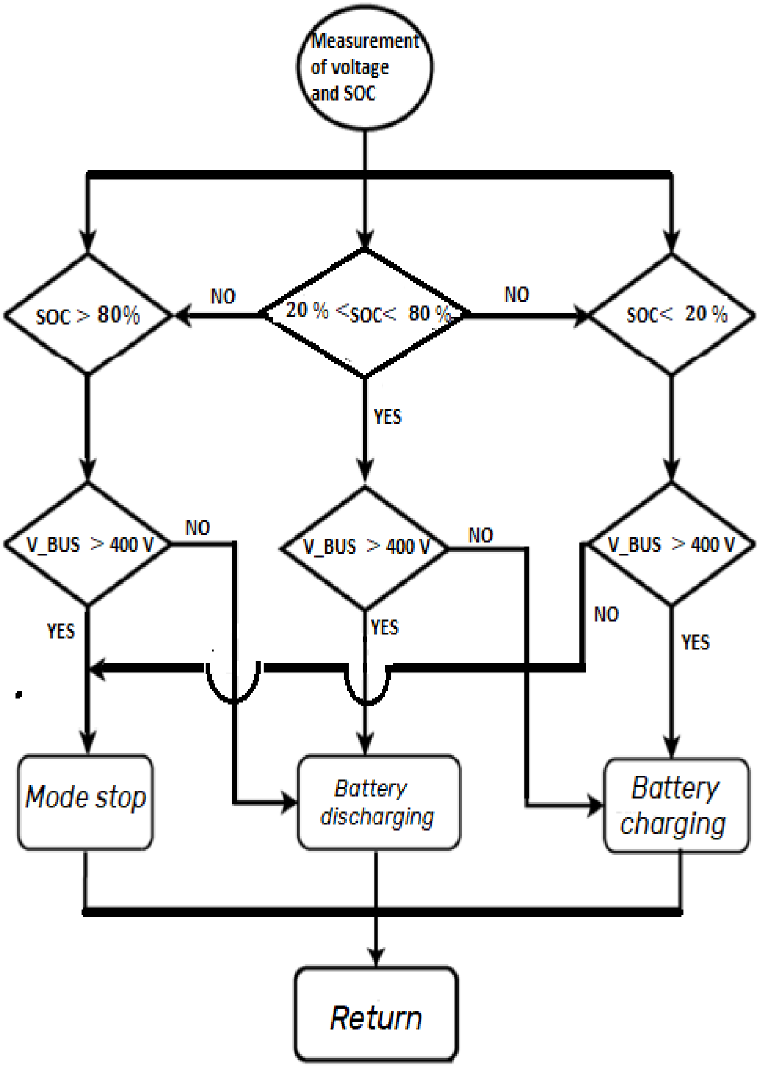


Fig. 8. Flowchart of the energy management plan.

4. SUMULATION RESULTS AND DISCUSSION

As depicted in Fig. 9, this study suggests a smart DC microgrid that is combined with a hybrid energy system. The system's primary elements are the hybrid energy sources, like wind and solar energy, and the battery system storage (BSS), each of which presents its own converters and is connected to the DC-link. The power converters try to get the most electricity possible out of each renewable resource. The second component represents the loads, which include a smart university with AC loads such as laboratory experimentation benches, fans, and lights. The energy control unit calculates energy consumption and production to select the appropriate control modes. The simulation of the proposed system is carried out using Matlab/Simulink.

The PV system has a maximum power output of 50 KW, while the PMSG wind turbine provides up to 45 KW. The reference voltage for the DC link is set at 300 V. When the starting point of charge (SOC) of the battery storage system is 80%. The load demand for the AC bus varies between 20 KW and 60 KW for one second, whereas the load demand for the DC bus is 10 KW at 300 V.

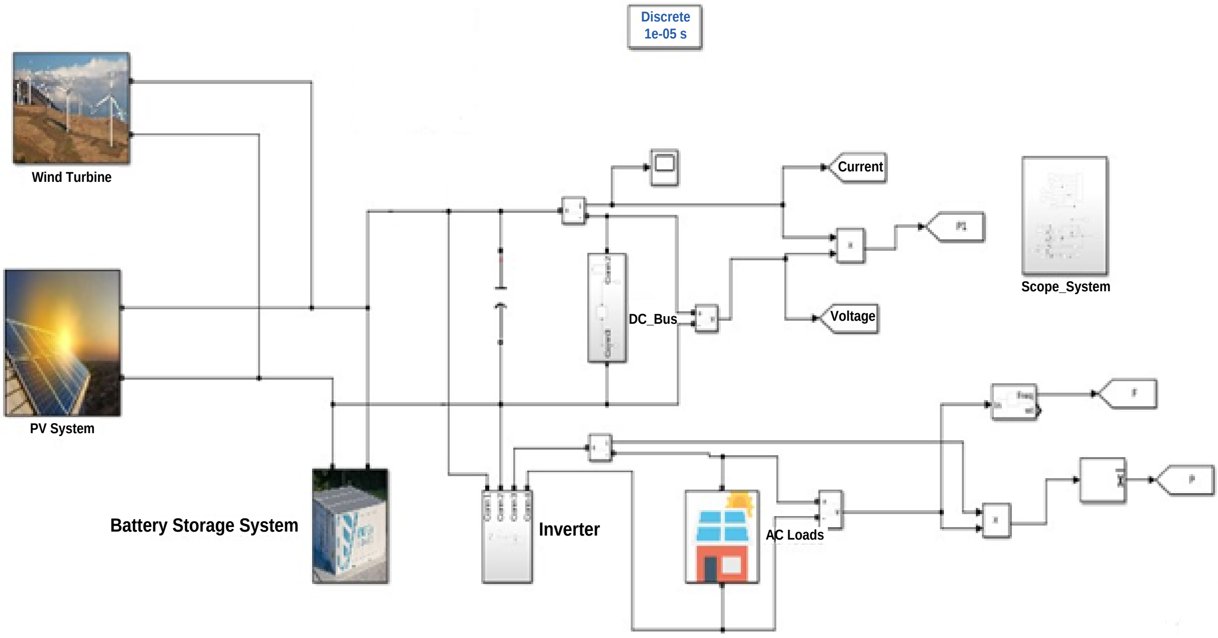


Fig. 9. Simulink model of the proposed hybrid microgrid.

To compare each controller's performance in preserving balance in the microgrid under adverse conditions to the advised energy management strategy, the simulation was ran for one second at an 0.00001 second sampling rate. To assess how each component responded to the various changes, interface monitoring was done. The variations in power output from the solar panels and wind turbines under the suggested weather scenario are shown in Figs. 10 and 11.

During the initial period of the simulation, from t = 0 s to t = 0.2 s, the total power generated by the renewable sources was not sufficient to meet the demand of the DC and AC loads, which was 30 KW. Specifically, the PV panels generated approximately 5 KW, and the wind turbines produced around 12 KW. As a result, the battery had to discharge its stored energy to supply power to the microgrid to maintain balance and meet load demands. The battery was programmed to maintain a state of charge between 20% and 80%. The charge state incline showed a decrease, and the battery supplied 20 KW of power to the system, as shown in Figs. 12 and 13. Consequently, the issue of power deficiencies in the DC bus and AC loads was resolved. The solar energy input increased by more than 60 KW between t = 0.2 s and t = 0.5 s, and the wind power increased to 30 KW, resulting in a system imbalance and a shortage of energy. As previously mentioned, the battery plays a critical role in balancing the system. As the battery's state of charge was within the safe zone, to maintain an equilibrium between power generation and consumption, it stored the excess energy.

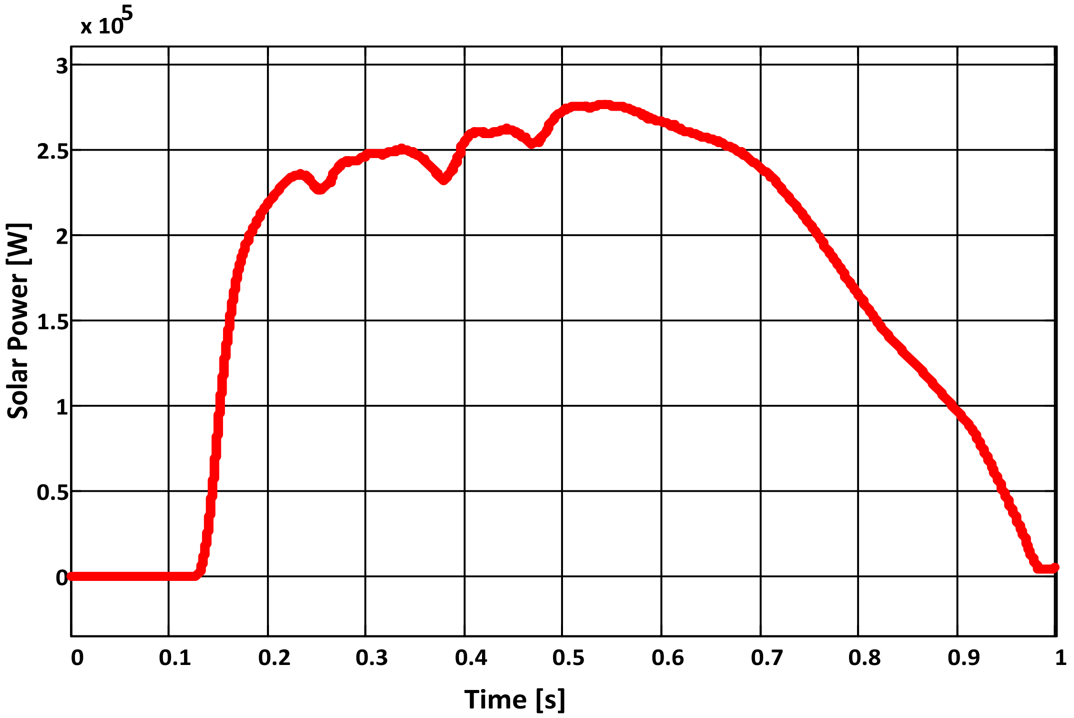


Fig. 10. Measured solar power.

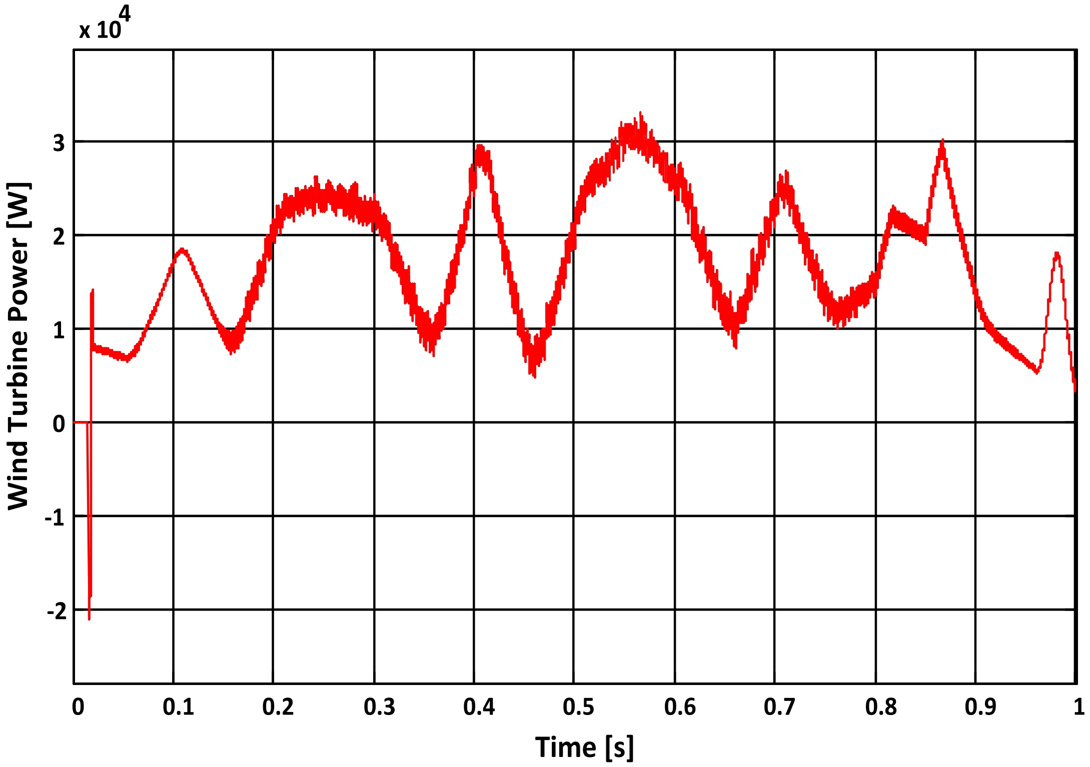


Fig. 11. Measured wind turbine power.

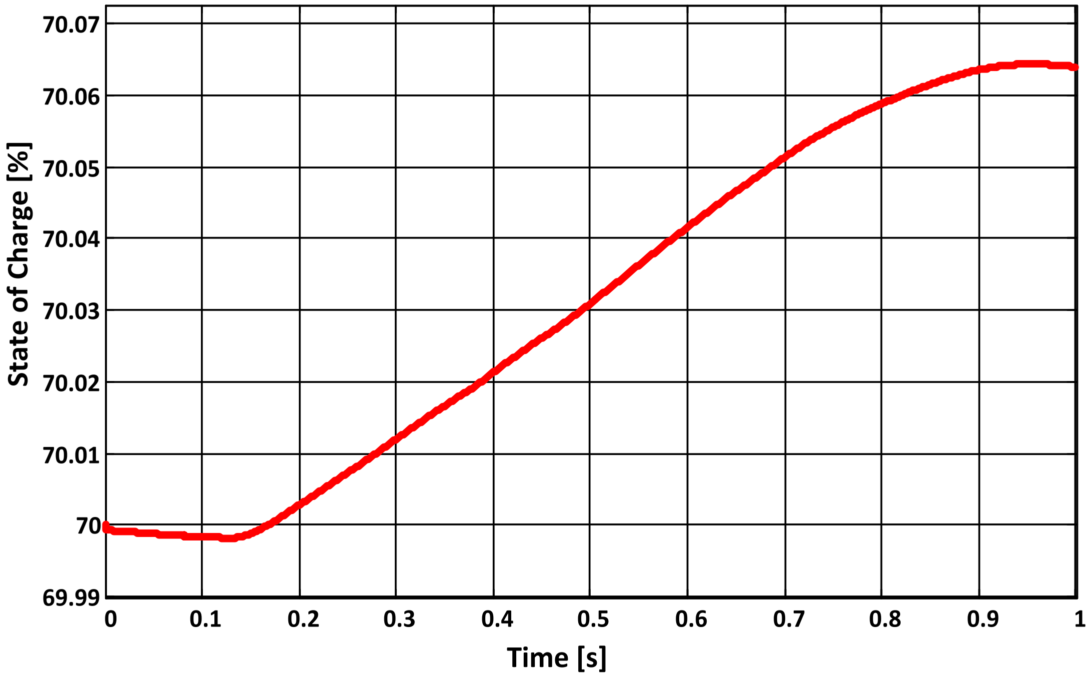


Fig. 12. BES state of charge variants.

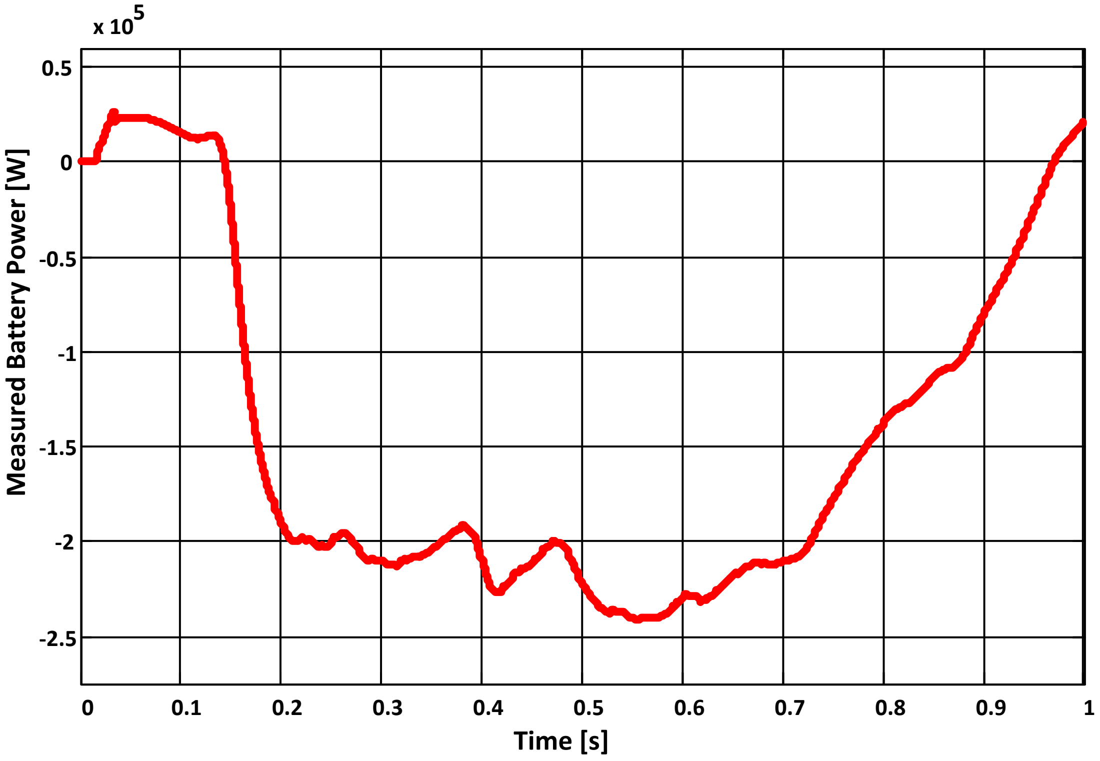


Fig. 13. BES power variants.

During the time interval from t = 0 s to t = 1 s, both the AC and DC buses' consumption of energy was gauged. During the time interval from t = 0 s to t = 0.3 s, while the AC load used 20 KW, the DC load was limited to 10 KW. The DC load stayed constant while the AC load rose to 50 KW between t = 0.3 s and t = 0.5 s. Finally, the AC load rose to 60 KW from t = 0.5 s to t = 1 s. Throughout this entire duration, the DC bus voltage has remained at a constant 300 V, as initially requested for simulation purposes. By examining Figs. 14 to 16, it can be inferred that the FLC method has significant advantages in maintaining both voltage and power at their desired reference values.

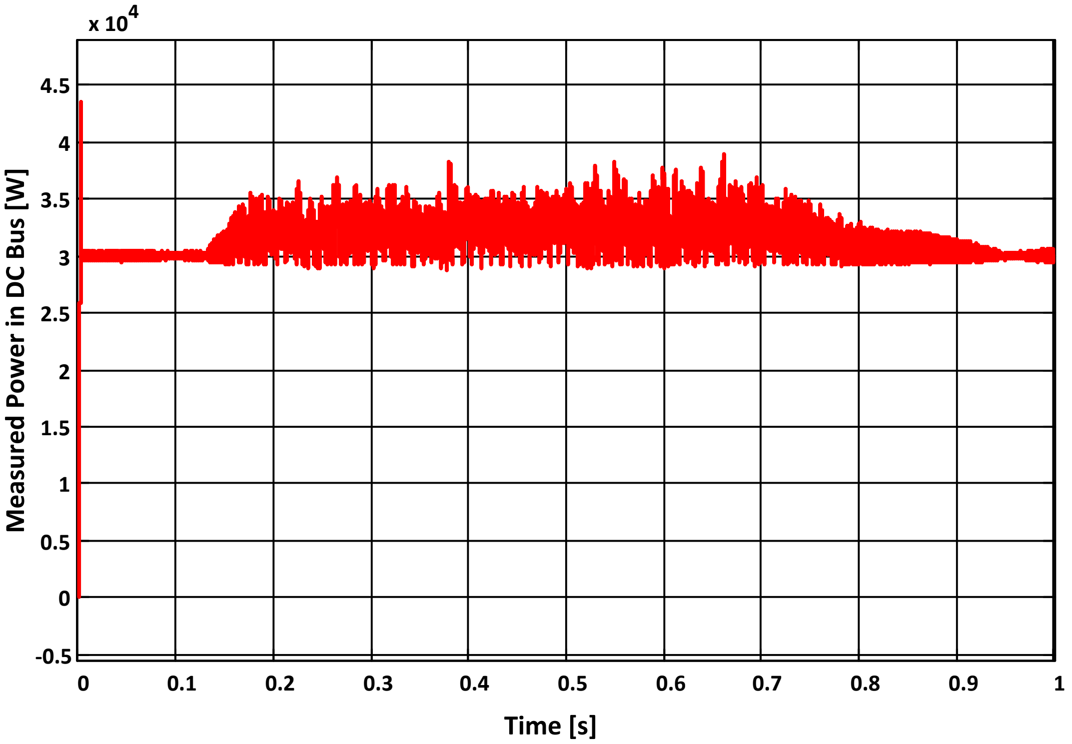


Fig. 14. Measured power in DC bus.

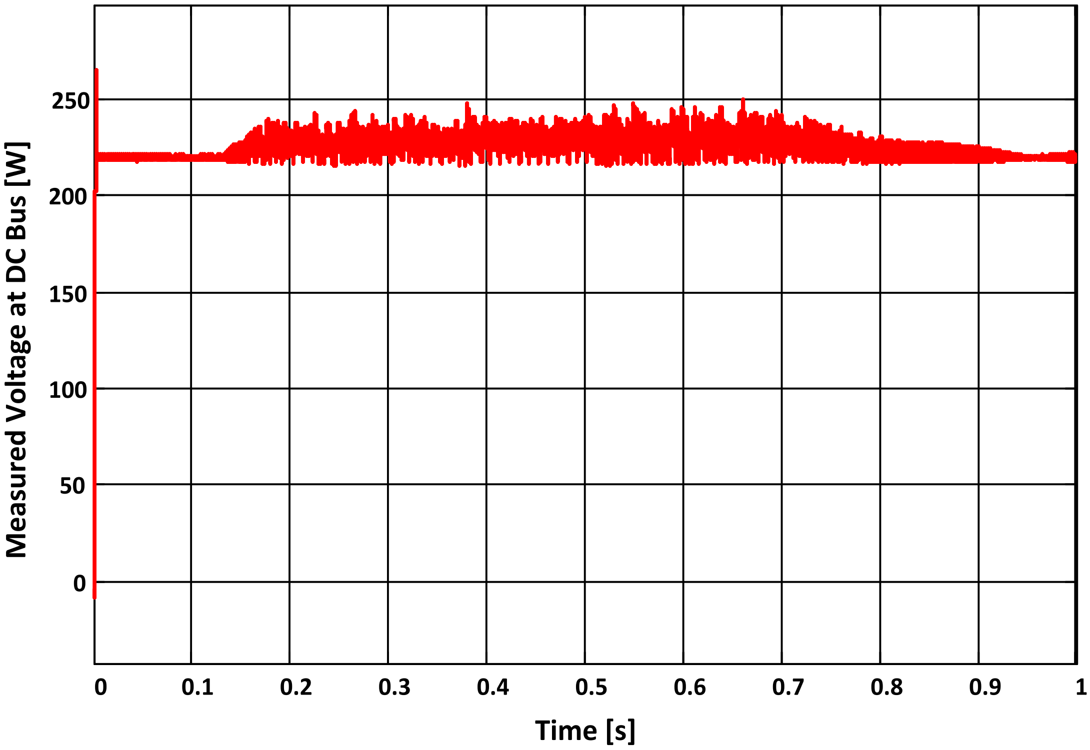


Fig. 15. DC bus measured voltage.

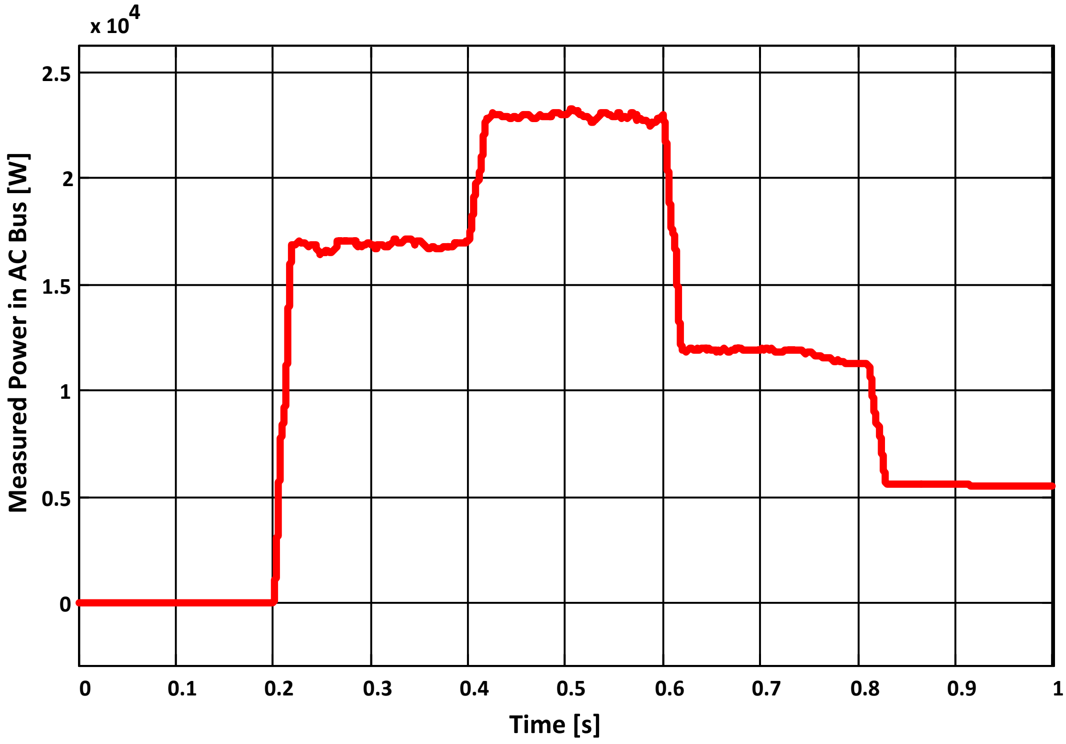


Fig. 16. Measured power in AC bus.

According to Fig. 17, the method exhibited a frequency variation within the range of -0.02 to +0.02, except for the initial phase of the test, used to describe the temporary/initial regime.

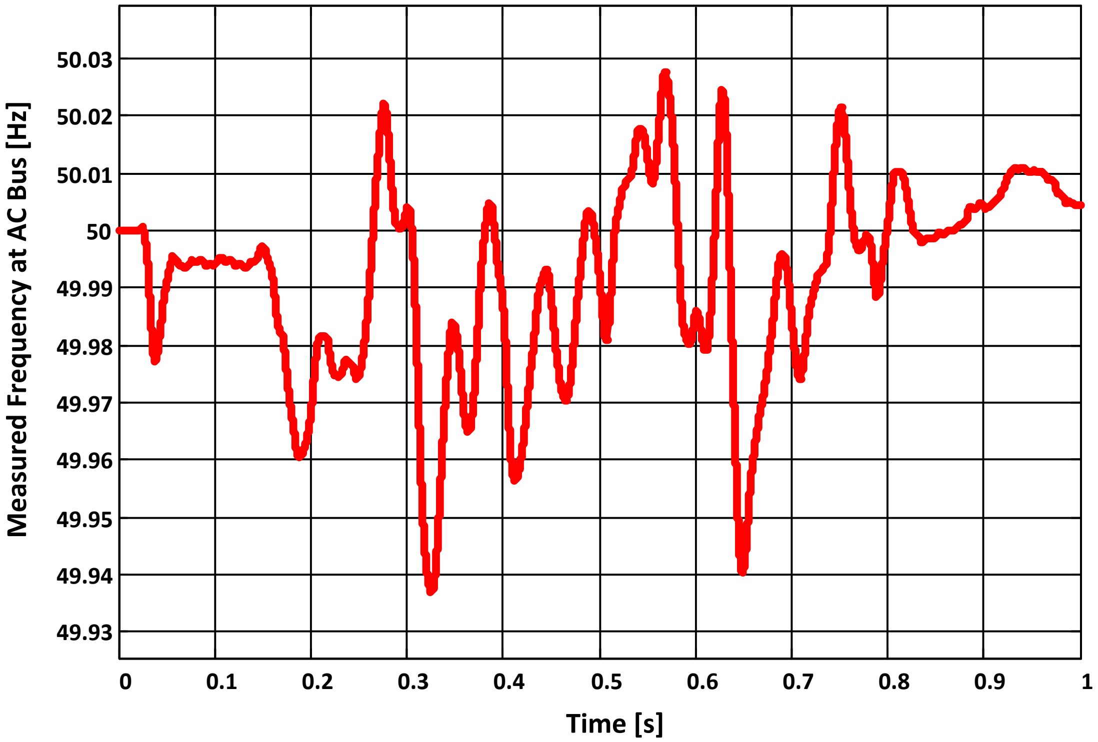


Fig. 17. Measured frequency at AC bus.

The simulation results show that the proposed energy management strategy based on the FLC controller successfully maximizes and maintains the microgrid's balance using renewable energy sources. The fuzzy logic controller was able to make intelligent decisions regarding the charging and discharging of the battery in response to the varying energy demands of the loads and the availability of renewable energy sources. As a result, the microgrid was able to maintain a stable power supply throughout the simulation period. Moreover, the fuzzy logic controller was able to adapt to changing conditions, such as changes in weather patterns and load demands, demonstrating its flexibility and robustness. The simulation results also showed that the battery was able to store excess energy during periods of high renewable energy generation and discharge it during periods of low renewable energy generation, thus reducing the dependence on the utility grid. Overall, the proposed energy management strategy based on the fuzzy logic controller proved to be an effective solution for maximizing the utilization of renewable energy sources and ensuring the stability of the microgrid.

5. CONCLUSIONS

This paper introduced an energy management system that focuses on maximizing power generation from renewable sources and effectively managing battery charging and discharging. The system was implemented and simulated using Matlab/Simulink. The obtained results showed the effectiveness of the proposed system in balancing the microgrid and providing stable power supply to the load. The measured power of the solar system and the wind turbines was found to closely match the required loads demand, and the battery state of charge and power were well managed. The DC bus voltage was stable and the frequency variation was less than 0.02. The proposed controller was found to effectively control charging and discharging of the battery. In conclusion, the proposed energy management system proved to be an effective solution for microgrid energy management, as it maximizes the utilization of renewable energy sources and ensures reliable power supply to the loads. Future work could focus on implementing the proposed system in a real microgrid system and testing its performance under different scenarios and conditions.

Acknowledgement: I would like to express my gratitude to all the individuals with whom I have collaborated on this and other associated works. I would like to extend a special acknowledgment and offer my sincerest appreciation to my PhD project supervisor, M. Tarik Jarou, and members of the Advanced Systems Engineering Laboratory.

REFERENCES

[1] A. Al-Shetwi, "Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges," *Science of the Total Environment*, vol. 822, pp. 153645, 2022.

[2] E. Dogan, M. Madaleno, D. Taskin, P. Tzeremes, "Investigating the spillovers and connectedness between green finance and renewable energy sources," *Renewable Energy*, vol. 197, pp. 709–722, 2022.

[3] M. Bilgili, A. Ozbek, B. Sahin, A. Kahraman, "An overview of renewable electric power capacity and progress in new technologies in the world," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 323–334, 2015.

[4] G. Notton, M. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte, A. Fouilloy, "Intermittent and stochastic character of renewable energy sources: consequences, cost of intermittence and benefit of forecasting," *Renewable and Sustainable Energy Reviews*, vol. 87, no. C, pp. 96–105, 2018.

[5] A. Albarakati, Y. Boujoudar, M. Azeroual, R. Jabeur, A. Aljarbouh, H. El Moussaoui, T. Lamhamdi, N. Ouaaline, "Real-time energy management for DC microgrids using artificial intelligence," *Energies*, vol. 14, no. 17, 2021.

[6] P. Basak, S. Chowdhury, S. Halder nee Dey, S. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5545–5556, 2012.

[7] J. Hu, Y. Shan, J. Guerrero, A. Ioinovici, K. Chan, J. Rodriguez, "Model predictive control of microgrids – an overview," *Renewable and Sustainable Energy Reviews*, vol. 136, pp. 110422, 2021.

[8] R. Bourbon, S. Ngueveu, X. Roboam, B. Sareni, C. Turpin, D. Torres, "Energy management optimization of a smart wind power plant comparing heuristic and linear programming methods," *Mathematics and Computers in Simulation*, vol. 158, no. C, pp. 418–431, 2019.

[9] V. Dubey, H. Goud, P. Sharma, "Role of PID control techniques in process control system: a review," *Proceedings of SSIC 2021*, vol. 238, pp. 659–670, 2022.

[10] Y. Boujoudar, M. Azeroual, H. El Moussaoui, T. Lamhamdi, "Intelligent controller based energy management for stand-alone power system using artificial neural network," *International Transactions on Electrical Energy Systems*, vol. 30, no. 11, pp. e12579, 2020.

[11] E. Mohammadi, M. Alizadeh, M. Asgarimoghaddam, X. Wang, M. Simões, "A review on application of artificial intelligence techniques in microgrids," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics,* vol. 3, no. 4, pp. 878–890, 2022.

[12] Y. Boujoudar, M. Azeroual, H. Elmoussaoui, T. Lamhamdi, "Intelligent control of battery energy storage for microgrid energy management using ANN," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 4, 2021.

[13] M. Mahmoud, S. Azher Hussain, M. Abido, "Modeling and control of microgrid: an overview," *Journal of the Franklin Institute*, vol. 351, no. 5, pp. 2822–2859, 2014.

[14] M. Tostado-Véliz, P. Arévalo, S. Kamel, H. Zawbaa, F. Jurado, "Home energy management system considering effective demand response strategies and uncertainties," *Energy Reports*, vol. 8, pp. 5256–5271, 2022.

[15] M. Hayat, D. Ali, K. Monyake, L. Alagha, N. Ahmed, "Solar energy—a look into power generation, challenges, and a solar-powered future," *International Journal of Energy Research*, vol. 43, no. 3, pp. 1049-1067, 2019.

[16] H. Mousa, A. Youssef, E. Mohamed, "State of the art perturb and observe MPPT algorithms based wind energy conversion systems: a technology review," *International Journal of Electrical Power and Energy Systems*, vol. 126, pp. 106598, 2021.

[17] A. Kushwaha, M. Gopal, B. Singh, "Q-learning based maximum power extraction for wind energy conversion system with variable wind speed," *IEEE Transactions on Energy Conversion*, vol. 35, no. 3, pp. 1160–1170, 2020.

[18] P. Gajewski, K. Pieńkowski, "Control of the hybrid renewable energy system with wind turbine, photovoltaic panels and battery energy storage," *Energies*, vol. 14, no. 6, 2021.

[19] Y. Boujoudar, H. Elmoussaoui, T. Lamhamdi, "Lithium-Ion batteries modeling and state of charge estimation using artificial neural network," *International Journal of Electrical and Computer Engineering*, vol. 9, no. 5, 2019.

[20] F. Eroğlu, M. Kurtoğlu, A. Vural, "Bidirectional DC–DC converter based multilevel battery storage systems for electric vehicle and large-scale grid applications: a critical review considering different topologies, state-of-charge balancing and future trends," *IET Renewable Power Generation*, vol. 15, no. 5, pp. 915–938, 2021.