International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Effective Energy Management and Voltage Stabilization of Hybrid Standalone Microgrid System Under Transient Load Condition

Mehulsinh G. Jadeja*[1], Pulinkumar J. Purohit[2], Parin H. Chauhan[3], Vishal G. Jotangiya[4], Divyesh J. Vaghela[5], Jayanti A. Jadav[6]

Submitted:01/05/2024 **Revised:** 15/06/2024 **Accepted:** 23/06/2024

Abstract: The global community is actively seeking ways to harness renewable energy sources to combat global warming and reduce reliance on fossil fuels. Solar and wind energy have gained popularity worldwide. However, the availability of solar irradiance and wind speed is unpredictable and beyond human control. Therefore, integrating an energy storage system is essential to maximize the utilization of these energy sources by converting them into electricity. Batteries are a prominent choice for medium power applications, but they require regular maintenance and are prone to self-discharge, leading to a gradual decline in storage capacity over time. For high power applications, hydrogen storage emerges as a cost-effective alternative to batteries. Stored hydrogen can be utilized for various purposes, such as transportation and electricity generation. An electrolyzer can efficiently split water into oxygen and hydrogen using electricity. Nonetheless, the slow heat transfer dynamics impede rapid hydrogen production, necessitating a new control technique to enhance production quality during fluctuations in solar irradiance and wind speed. Boost, buck, and DC to DC bidirectional converters are utilized to maintain a constant voltage at the DC-link under diverse operating conditions. A novel control algorithm has been devised to ensure power quality at the 3-phase AC load bus and effectively manage energy in the hybrid standalone system. The outcomes of this research, conducted using MATLAB/Simulink, are presented to assess performance under various scenarios.

Keywords: *Wind power conversion, Photo Voltaic, Electrolyzer, Flying Capacitor, Renewable Energy Sources, Microgrid*

1. Introduction

Providing electricity to consumers in regions without utility grids remains a challenging task. One effective solution to this issue is the establishment of small-scale independent microgrids at a local level [1]. These microgrids utilize renewable energy sources, making them environmentally friendly. By integrating various renewable energy sources such as solar power with Photovoltaic (PV) technology and wind power with Permanent Magnet Synchronous Generator (PMSG) technology, these systems can ensure reliable and high-quality electricity supply to consumers in remote areas [2].

Solar irradiance and wind velocity undergo continuous fluctuations, leading to variations in power generation [3]. To maintain a stable power balance in a standalone microgrid, it is essential to utilize an energy storage device [4]. Although batteries are commonly used for energy storage, they may not be suitable for high power applications over extended periods. Moreover, batteries have a limited lifespan and require frequent maintenance and replacements, resulting in increased expenses [18]. To address these challenges, the system combines a Fuel Cell (FC)-Electrolyzer with a small battery bank. The battery bank can quickly respond to sudden fluctuations, while the FC-Electrolyzer operates at a slower pace to maintain power equilibrium in a stable condition [5]. During times of surplus generation compared to the load, the FC-Electrolyzer produces hydrogen through electrolysis, which is then stored in tanks for future use to generate electricity through the FC and meet the load requirements. By utilizing the battery bank for short-term power provision and hydrogen for long-term storage, the system becomes more financially viable [6]. However, efficient energy management is crucial to ensure power quality in standalone systems. Additionally, this paper introduces the development of an inverter control mechanism to maintain a consistent voltage at the load bus even during unbalanced voltage conditions, thereby enhancing power quality.

1,2,5Electrical Engineering Department, Vishwakarma Government Engineering College, Chandkheda, Ahmedabad, Gujarat-India.
ORCID ID: 10009-0003-3945-8182, 20009-0006-0336-5357, 50000-0001-5144-8997
3,4,6Electrical Engineering Department, Lukhdhirji Engineering College, Morbi, Gujarat-India..
ORCID ID: 30009-0000-1345-435X, 40009-0001-0050-6015, 60009-0002-2892-1517
** Corresponding Author Email: jadejamehulsinh74@gmail.com*

2. Standalone Microgrid

The diagram in Figure 1 depicts the standalone microgrid that relies on renewable energy sources as discussed in this paper.

Previous research studies have examined the hybrid microgrid with similar standalone characteristics [7-13]. The authors proposed a power management strategy to regulate the various components within the microgrid [7]. In [8], the authors demonstrated the production of hydrogen using renewable energy-based power conversion units. However, [9] established a greenhouse powered by renewable energy sources, but the system was specifically designed for single-phase applications. [10] showcased the generation of hydrogen using renewable energy sources [24], but did not address power quality concerns. [11] introduced a DC microgrid that utilizes renewable energy sources for hydrogen production. Furthermore, [12] developed an energy management algorithm for a microgrid, but did not consider power quality concerns or unbalanced scenarios. Lastly, [13] conducted a comparative evaluation of different energy management systems for standalone wind, PV, wind, and hydrogen units [22]. This research article considers the objectives in its development.

a) An efficient control coordination has been established for wind, PV, Electrolyzer, FC, and battery systems.
b) A new control method has been developed for a bidirectional DC to DC circuit used between the battery and DC-link to efficiently manage power distribution among various devices.
c) Different version: Efficient regulators have been implemented to oversee the voltage control at the load terminal amidst fluctuations in wind or PV power production and alterations in the electrical demand.
d) To ensure stable voltage levels at the load bus in a three-phase system, it is crucial to maintain balanced voltages even when unbalanced currents are present.

The DC-ink battery bank is equipped with a built-in DC to DC bidirectional circuit. The circuit utilizes a control method to monitor the discharging/charging process of the battery in order to maintain a stable voltage at the DC link [25], as shown in Figure 2. The controller's output acts as the reference battery line current, and a hysteresis loop is established to generate the necessary switching pulses for switches Q1 & Q2 of the converter (Figure 1). To prevent overcharging or discharging of the battery bank, the State of Charge (SoC) is integrated into the controller of the DC to DC bidirectional circuit, as illustrated in Figure 2.

Once the state of charge (SoC) of the battery bank reaches its maximum level, any surplus power will be utilized by the electrolyzer to produce hydrogen. Similarly, during steady state operation, when the SoC reaches its minimum level, the fuel cell (FC) will generate the necessary power to meet the load demand. However, due to the slow dynamics of the FC, it is unable to provide power instantaneously, resulting in a voltage drop at the DC-link during transient situations [26]. To ensure a stable voltage at the DC-link, regardless of any system changes, it is essential to implement proper control coordination among all components in a standalone system [23]. Figure 3 and Figure 4 illustrate the appropriate control mechanisms for the buck circuit (used for the Electrolyzer) and the boost circuit (used for the FC), respectively. The designed controllers for the buck, boost, and DC to DC converters are configured in a way that enables the battery bank to promptly respond to sudden load changes, while maintaining steady operation for the Electrolyzer-FC set [18]. When the SoC reaches 20.0% and switch Q2 of the DC to DC circuit is turned on (while Q1 is turned off), the FC begin generating the required load power [18], with the battery maintaining its state across the dc-link. Figure 5 provides an illustration of the system's energy management. To optimize the extraction of power from a wind turbine, the control strategy is derived from [1]. In order to eliminate the need for an additional converter that functions as a maximum power point tracking (MPPT) circuit, the PV system is directly connected to the DC-bus.

The PV system incorporates an MPPT mechanism that is integrated with a DC to DC circuit and a buck circuit for the electrolyzer. This integration allows the MPPT circuit to function effectively within the PV system. In a distribution power system, there are various single-phase loads that operate simultaneously, resulting in uneven currents flowing through the three phases. When these imbalanced loads are present, the DC-link voltage will contain a second harmonic oscillating component. This second harmonic component has the potential to induce oscillations on the turbine shaft, which could impact the fatigue life of the shaft [18]. To address this issue, the dc-side active filter [14] is integrated with the controllers of the DC to DC converter for the battery, the buck converter for the electrolyzer, and the boost converter for the fuel cell (FC). The dc component is extracted through a low pass filter from, while the oscillating component is obtained. The first PI controller considers as an error and generates a reference signal to regulate the voltage. On the other hand, the second PI controller uses as its error and utilizes a reference signal of '0' to effectively eliminate the oscillating component in the DC voltage. By combining the outputs of both PI controllers, the ultimate reference current is achieved.

Unbalanced voltages across the three phases occur when there is an uneven load at the point of common coupling (PCC). This imbalance is caused by unequal voltage drops across the filter circuit in each phase. To tackle this issue, a specialized inverter controller has been created. This controller produces distinct modulation indexes for each phase, guaranteeing balanced voltages at PCC. The utilization of the control technique, which relies on dq0 of the inverter, is illustrated in Figure 6.

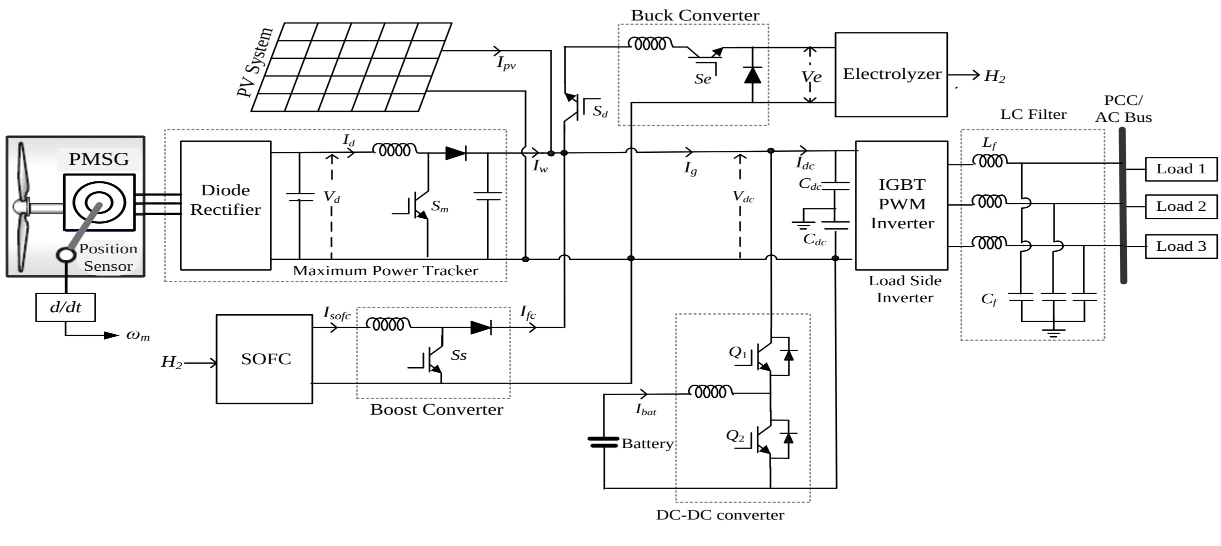

Fig. 1. Hybrid standalone microgrid [18].

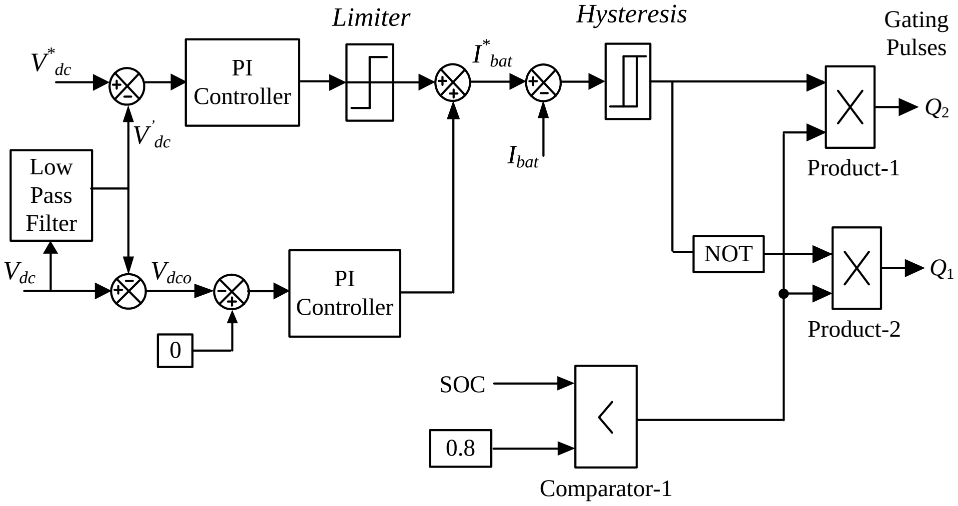

Fig. 2. The management of the bidirectional DC to DC circuit linked to the battery is under control [18].

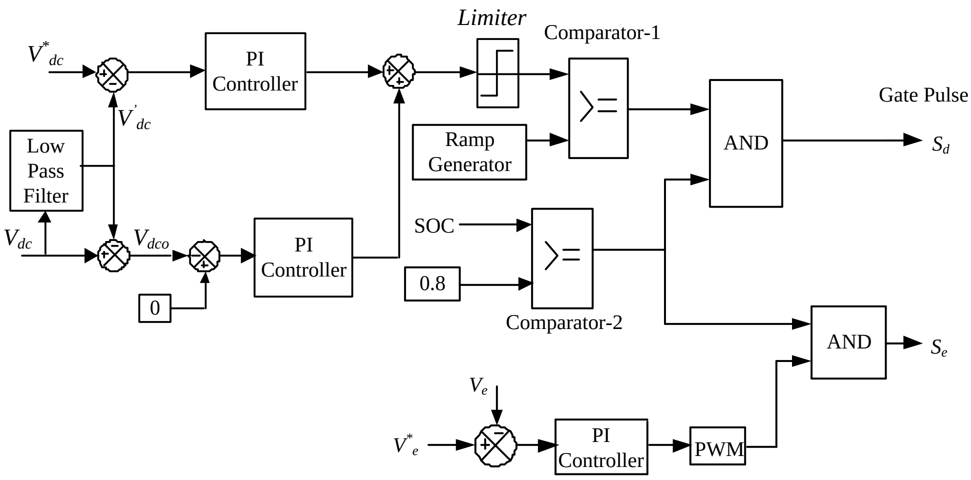

Fig. 3. Control of buck converter for Electrolyzer [18].

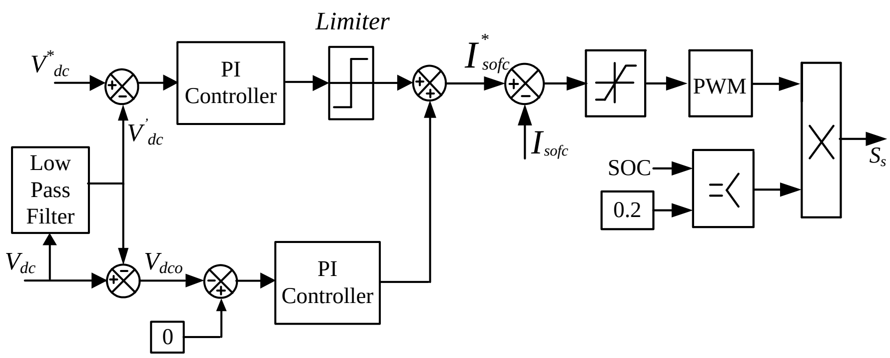

Fig. 4. Control of boost converter for FC [18].

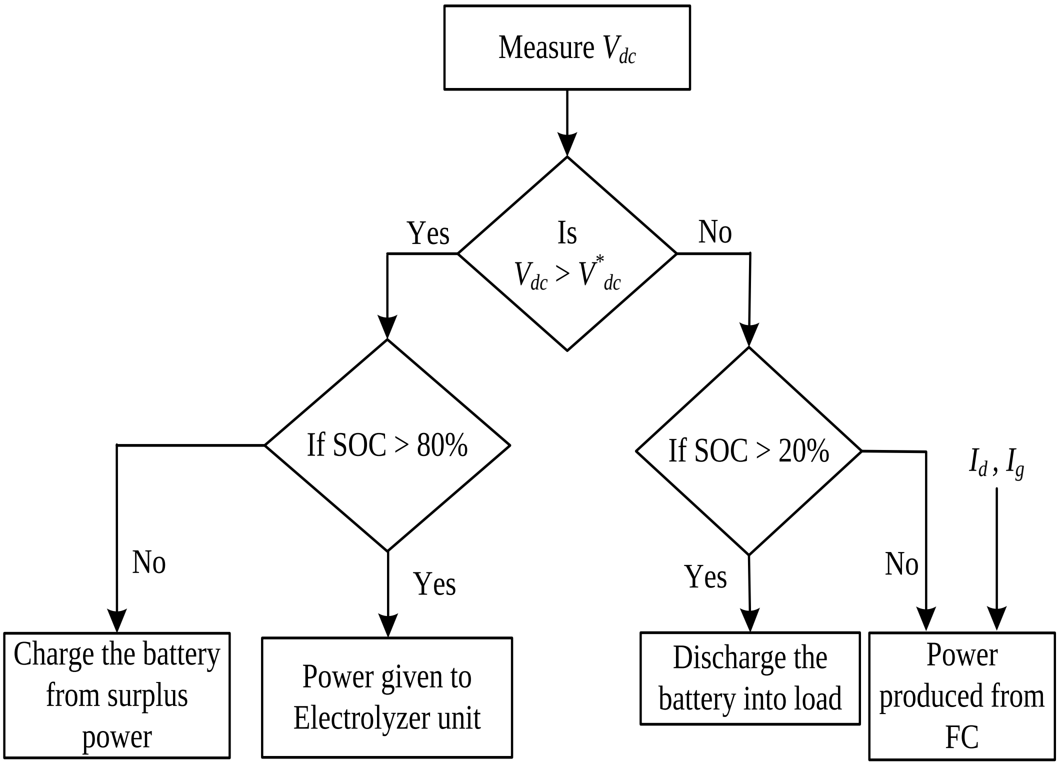

Fig. 5. Energy management algorithm [18].

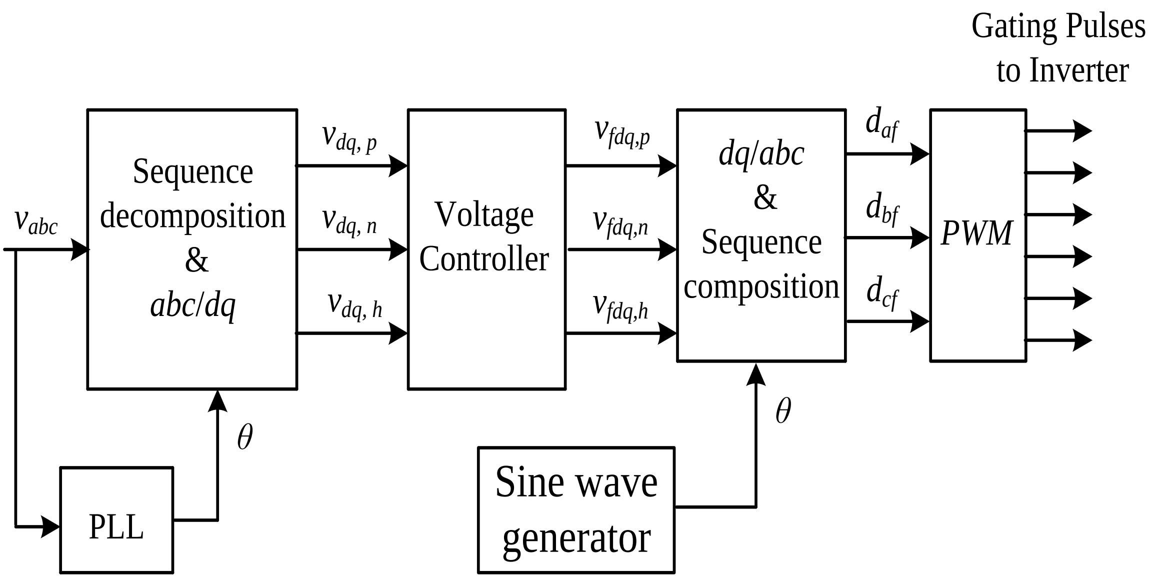

Fig. 6. Control of the inverter.

3. Unit management

Determining the appropriate unit sizing is a critical aspect in a microgrid, especially one that relies on renewable energy sources. This is essential as it helps minimize the overall cost of the system while ensuring a consistent and reliable power supply to consumers [15-16]. To achieve this, the HOMER software is employed to determine the optimal size of the components based on the load profile [7,18], as shown in Figure 7. The technical and economic data of the system is obtained from [7, 15, 17,18]. By utilizing the HOMER software, the optimal sizes for the wind and PV components are determined to be 15.0kW and 20.4kW respectively. As a result, this study considers the use of two PV arrays, each with a capacity of 7.50kW, and three wind turbines, each with a capacity of 6.80kW.

This study anticipates that the fuel cell (FC) will efficiently manage the highest demand without relying on wind and PV power. As a result, the required capacity of the FC is determined to be 18kW, with an additional 20% capacity for optimal performance. Similarly, the rating of the electrolyzer is determined by taking into account the surplus power available. By considering 60.0% of the maximum surplus power from different sources, the rating of the electrolyzer is calculated as follows:

Electrolyzer Rating = (Total generation – Minimum load demand) 60.0/100.

= (15.0+20.40-5.85) 0.60 = 17.73kW.

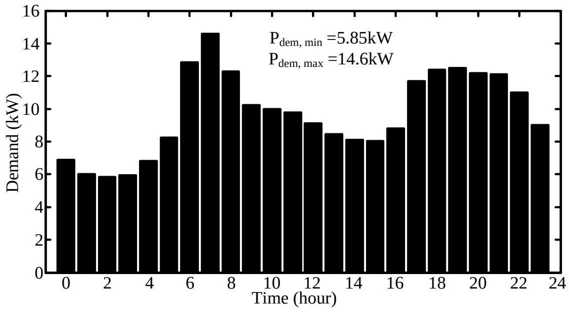

Fig. 7. Load demand [7].

4. Results

To optimize visualization, the MATLAB/Simulink platform displays outcomes utilizing a single PV array and one wind turbine. The assessment of controller effectiveness includes examining various microgrid scenarios as depicted in Figure 1 [1, 6, 18-21].

Case-A: Unbalanced operation

The system has been tested considering the unbalanced scenario illustrated in Figure 8.

Current (RMS) of:

Phase-A (ila)= 3.52A; Phase-B (ilb) = 9.45A; Phase-C (ilc) = 8.32A.

The torque response of the PMSG in an imbalanced state is shown in Figure 9 both with and without the suggested regulation of the DC-to-DC converter. Torque fluctuations can be lessened with the recommended controller and voltage regulation at the DC-link. However, the voltages at the PCC may fall out of balance because of uneven dips at the LC filter in each phase. Nevertheless, by producing the necessary modulation indexes for every phase, the suggested inverter controller can keep balanced voltages. The matching balanced line voltages at the PCC are shown in Figure 10. For a better understanding, Figure 11 displays the RMS values of the phase voltages and their corresponding Modulation Indexes.

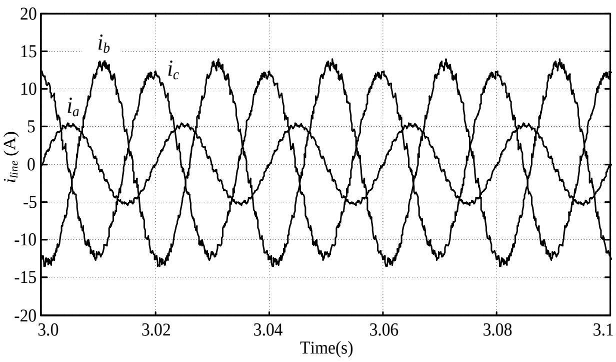

Fig. 8. Currents of three-phase system {Case-A}.

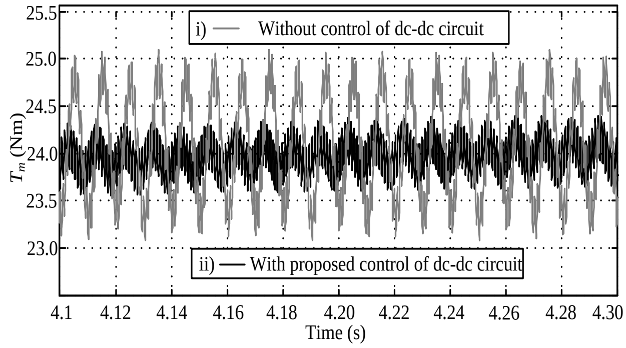

Fig. 9. Torque response {Case-A}.

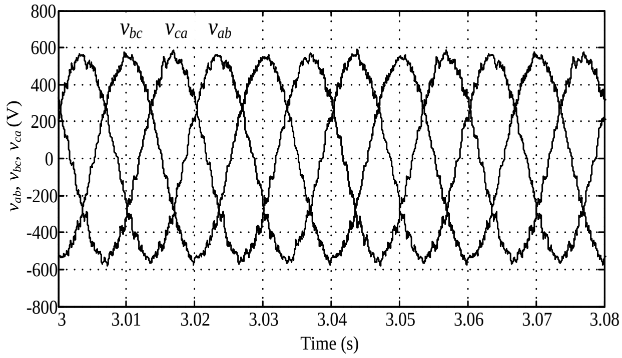

Fig. 10. Voltages {Case-A}.

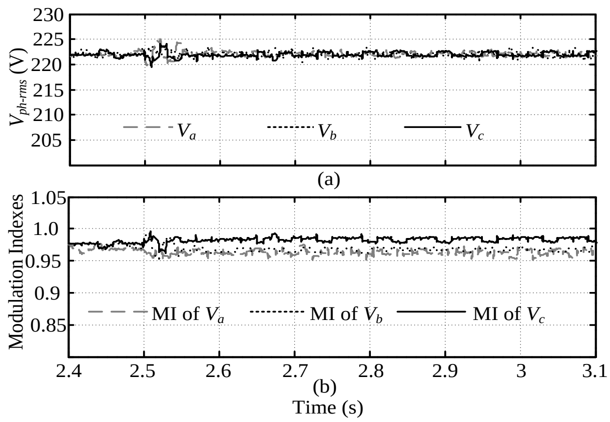

Fig. 11. (a) Voltage; (b) MI{Case-A}.

Case- B: Operation under battery and electrolyzer

The system's effectiveness relies on the proper functioning of the electrolyzer. This is accomplished by maintaining the State of Charge (SoC) of the batteries at approximately 80% and utilizing any excess power available from alternative sources. According to the energy management method described in this study, Figure 12 illustrates how the electrolyzer would start using the excess power once the battery bank's SoC surpasses 80.0%. Figure 13 shows that at about t=1.94sec, the SoC reaches 80.0%. The voltage behavior at the DC bus, now managed by the electrolyzer's buck converter, is displayed in Figure 13.

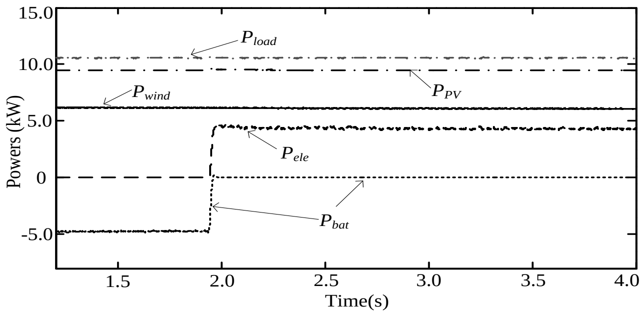

Fig. 12. Powers involved in microgrid during operation of electrolyzer {Case-B}.

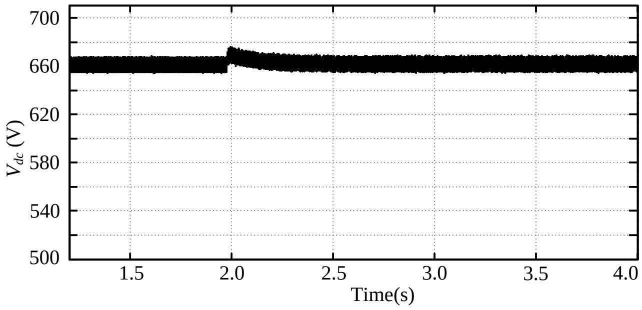

Fig. 13. Voltages {Case-B}.

Case- C: Operation with battery and FC

In order to evaluate the microgrid's effectiveness during FC operation, the effects of an abrupt load rise from 7.5 to 15.0 kW at t=10.0sec were examined. As per the suggested energy management system, the battery acted quickly to fulfil the increased demand, however the FC took longer to start producing power because of its slower dynamics. As a result, at roughly t=10.94sec, the battery bank's State of Charge (SoC) dropped to 20.0% (Figure 14). The FC commenced power provision at t=11.16sec and successfully met the load demand by around t=12.80sec. This effective coordination between the FC and battery led to the battery power diminishing to zero as the FC consistently supplied the required power. The microgrid's control scheme demonstrated its efficiency in achieving this coordination, as depicted in Figure 15.

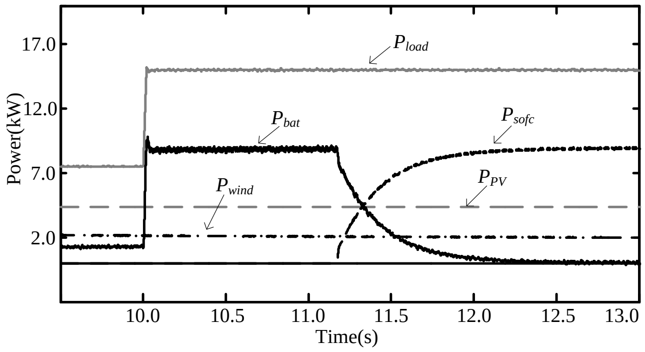

Fig. 14. Powers {Case-C}.

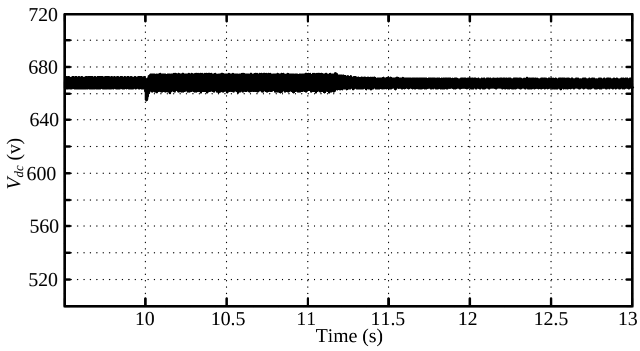

Fig. 15. Voltages {Case-C}.

Case- D: Operation with meteorological changes

The efficacy of the microgrid is evaluated while accounting for meteorological variations in weather. Analysing variations in load, temperature, wind speed, and irradiance is part of the assessment, as shown in Figure 16. Figure 17 presents the various power components examined in this study, namely the battery bank, fuel cell (FC), and electrolyzers, which collaborate to maintain a balance between generation and load. The detailed response of the root mean square (RMS) line voltage at the point of common coupling (PCC) is outlined in Figure 18. While the RMS voltage at the PCC may not provide a clear indication, the instantaneous line-to-line voltages and currents are elucidated in Figure 19 and Figure 20, respectively.

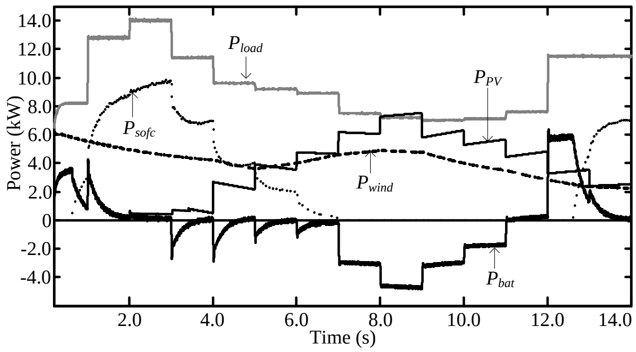

Fig. 16. Powers involved in microgrid {Case-D}.

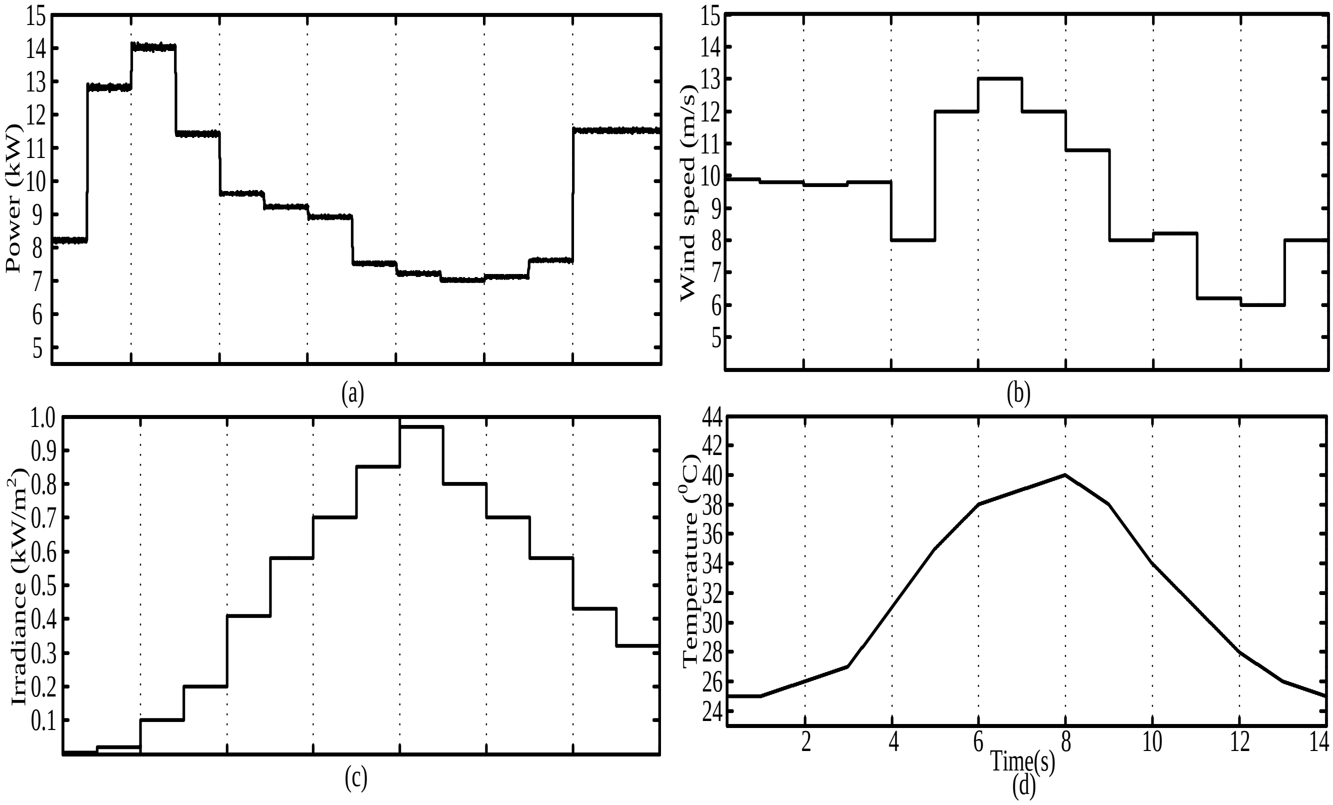

Fig. 17. Changes of (a) load current, (b) wind speed, (c) irradiance and (d) temperature {Case-D}.

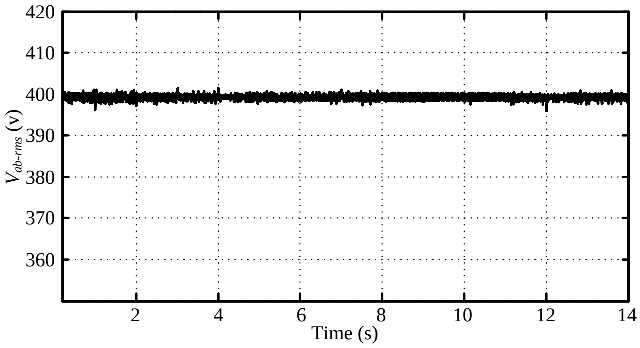

Fig. 18. Voltages {Case-D}.

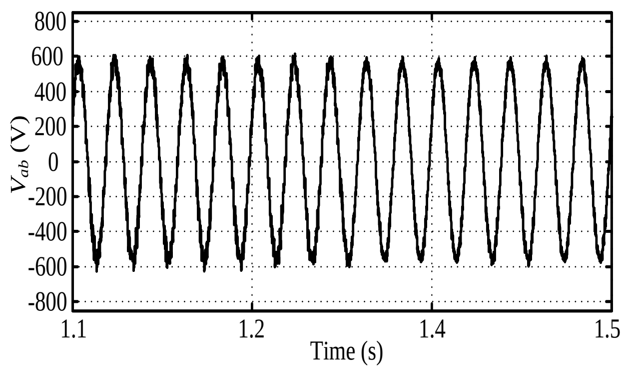

Fig. 19. Voltages {Case-D}.

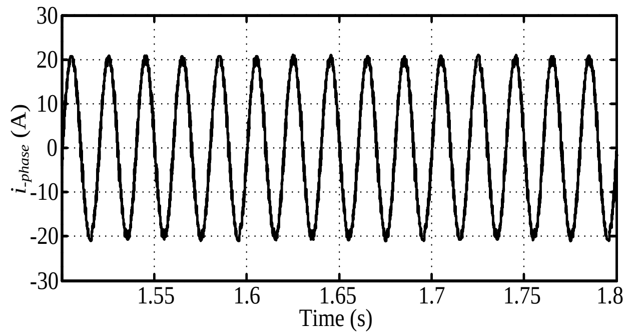

Fig. 20. Currents {Case-D}.

5. Conclusion

A highly effective energy management system has been deployed for microgrids that depend on renewable energy sources. This system employs synchronized control to enhance power quality and optimize hydrogen generation efficiency, while simultaneously minimizing operational costs. The control techniques proposed in this system aim to mitigate second harmonic distortions caused by imbalanced loads and ensure stable voltages at the point of common coupling (PCC). Extensive simulations conducted on Simulink have conclusively demonstrated that the suggested controllers can proficiently regulate load voltages even in the presence of fluctuating loads, wind speeds, and solar radiation levels. The results have been thoroughly analyzed and presented across various scenarios for comprehensive evaluation.

References

[1] C. N. Bhende, S. Mishra and S. G. Malla, “Permanent Magnet Synchronous Generator-Based Standalone Wind Energy

Supply System," IEEE Transactions on Sustainable Energy, vol. 2, no. 4, pp. 361-373, Oct. 2011, doi: 10.1109/TSTE.2011.2159253.
[2] H. U. R. Habib et al., "Optimal Planning and EMS Design of PV Based Standalone Rural Microgrids," in IEEE Access, vol. 9, pp. 32908-32930, 2021, doi: 10.1109/ACCESS.2021.3060031.
[3] M. H. Saeed, W. Fangzong, B. A. Kalwar and S. Iqbal, "A Review on Microgrids' Challenges & Perspectives," in IEEE Access, vol. 9, pp. 166502-166517, 2021, doi: 10.1109/ACCESS.2021.3135083.
[4] D. Steward, G. Saur, M. Penev and T. Ramsden, "Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage", Technical Report, National Renewable Energy Laboratory (NREL), Nov. 2009.
[5] W. Jiang and B. Fahimi, "Active Current Sharing and Source Management in Fuel Cell–Battery Hybrid Power System", IEEE Transactions on Industrial Electronics, Vol. 57, No. 2, pp. 752-761, Feb. 2010.
[6] Chimere Victor Ochiegbu, Samuel Gyamfi, and Eric Ofosu, "Modeling, Simulation and Design of Hydro-Solar Isolated Micro-grid without a Battery Storage System: A Case Study for Aba Business Cluster, Nigeria," International Journal of Engineering Trends and Technology, vol. 70, no. 2, pp. 125–136, 2022.
[7] C. Wang and M. H. Nehrir, "Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System", IEEE Transactions on Energy Conversion, Vol. 23, No. 3, pp. 957-967, Sep. 2008.
[8] Kodjo Agbossou, Mohanlal Kolhe, Jean Hamelin and Tapan K. Bose, "Performance of a Stand-Alone Renewable Energy System Based on Energy Storage as Hydrogen", IEEE Transactions on Energy Conversion, Vol. 19, No. 3, pp. 633-640, Sept. 2004.
[9] H. Caliskan, I. Dincer and A. Hepbasli, "Energy, Exergy and Sustainability Analyses of Hybrid Renewable Energy Based Hydrogen and Electricity Production and Storage Systems: Modeling and Case Study", Applied Thermal Engineering, In press (available online 21 April 2012).
[10] W. Gao, V. Zheglov, G. Wang and S. M. Mahajan, "PV - Wind - Fuel Cell - Electrolyzer Micro-grid Modeling and Control in Real Time Digital Simulator", International Conference on Clean Electrical Power, USA, pp. 29-34, June 2009.
[11] D. Ipsakis, S. Voutetakis, P. Seferlis, F. Stergiopoulos and C. Elmasides, "Power Management Strategies for a Stand-Alone Power System using Renewable Energy Sources and Hydrogen Storage", International Journal of Hydrogen Energy, Vol. 34, No. 16, pp. 7081-7095, Aug. 2009.
[12] O. Erdinc and M. Uzunoglu, "The Importance of Detailed Data Utilization on the Performance Evaluation of a Grid-Independent Hybrid Renewable Energy System", International Journal of Hydrogen Energy, Vol. 36, No. 20, pp. 12664-12677, Oct. 2011.
[13] E. Dursun and O. Kilic, "Comparative Evaluation of Different Power Management Strategies of a Stand-Alone PV/Wind/PEMFC Hybrid Power System", International Journal of Electrical Power and Energy Systems, Vol. 34, No. 1, pp. 81–89, Jan. 2012.
[14] P. Enjeti and S. Kim, "A new DC-side active filter for inverter power supplies compensates for unbalanced and nonlinear loads," Proceedings of IEEE Industry Applications Society Annual Meeting, Vol. 1, pp. 1023-1031, 1991.
[15] Z. W. Geem, "Size Optimization for a Hybrid Photovoltaic–Wind Energy System", International Journal of Electrical Power and Energy Systems, Vol. 42, No. 1, pp. 448-451, Nov. 2012. doi: 10.1016/j.ijepes.2012.04.051.
[16] Phommixay, Sengthavy, et al. "Review on the cost optimization of microgrids via particle swarm optimization", International Journal of Energy and Environmental Engineering, vol. 11, no. 1, Mar. 2020.
[17] R. Robichaud, G. Mosey and D. Olis, "Renewable Energy Optimization Report for Naval Station Newport", Technical Report NREL, Feb. 2012.
[18] V. Balu, K. Krishnaveni, P. Malla, and S. G. Malla, "Improving the power quality and hydrogen production from renewable energy sources based microgrid," Engineering Research Express, vol. 5, no. 3. IOP Publishing, p. 035037, Aug. 21, 2023.
[19] O. Bamisile, Q. Huang, P. Ayambire, P. O. K. Anane, S. Abbasoglu and W. Hu, "Analysis of Solar PV and Wind Power Penetration into Nigeria Electricity System," 2020 IEEE/IAS 56th Industrial and Commercial Power Systems Technical Conference (I&CPS), Las Vegas, NV, USA, 2020, pp. 1-5, doi: 10.1109/ICPS48389.2020.9176822.
[20] Malla, Priyanka, Malla, Siva Ganesh and Calay, Rajnish Kaur. "Voltage control of standalone photovoltaic – electrolyzer-fuel cell-battery energy system" International Journal of Emerging Electric Power Systems, vol. 24, no. 5, 2023, pp. 649-658. https://doi.org/10.1515/ijeeps-2022-0047.
[21] Y. Yang, C. Menictas, S. Bremner and M. Kay, "A Comparison Study of Dispatching Various Battery Technologies in a Hybrid PV and Wind Power Plant," 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 2018, pp. 1-5, doi: 10.1109/PESGM.2018.8585803.
[22] O. K. Ajiboye, E. A. Ofosu, S. Gyamfi, and O. Oki, "Hybrid Renewable Energy System Optimization via Slime Mould Algorithm," International Journal of Engineering Trends and Technology, vol. 7, no. 6. Seventh Sense Research Group Journals, pp. 83–95, Jun. 25, 2023. doi: 10.14445/22315381/IJETT-V71I6P210.
[23] E. N. Odonkor, P. M. Moses, and A. O. Akumu, "Evaluate Power Sharing Coordination Performance of Grid-Connected Microgrids Operation in Radial Distribution System using ANFIS Controller," International Journal of Engineering Trends and Technology, vol. 71, no. 12. Seventh Sense Research Group Journals, pp. 119–132, Dec. 06, 2023. doi: 10.14445/22315381/IJETT-V71I12P213.
[24] H. Eluri and G. N. M, "Fractional Order Fuzzy Logic Controller based Energy Management System for Grid Integrated Microgrid," International Journal of Engineering Trends and Technology, vol. 70, no. 5. Seventh Sense Research Group Journals, pp. 227–239, May 25, 2022. doi: 10.14445/22315381/ijett-v70i5p225.
[25] Nayab Mohsin Ali Tunio, Muhammad Rafique Naich, and Irfan Ahmed, "Experimental Study on Power Quality Analysis of Hybrid Energy System," SSRG International Journal of Electrical and Electronics Engineering, vol. 9, no. 4, pp. 7-18, 2022.
[26] F. Tanvir, "Design and Analysis of Hybrid Energy System," International Journal of Electrical and Electronics Engineering, vol. 4, no. 5. Seventh Sense Research Group Journals, pp. 1–5, May 25, 2017. doi: 10.14445/23488379/ijeee-v4i5p101.