Energy Science & Engineering

ORIGINAL ARTICLE OPEN ACCESS

Real-Time Energy Management System for a Hybrid Renewable Microgrid System

Christian Ndeke Bipongo | Marco Adonis | Ali Almaktoof

Department of Electrical, Electronic and Conputer Engineering, Cape Peninsula University of Technology, Cape Town, South Africa

Correspondence: Christian Ndeke Bipongo (ndekechristian@gmail.com; 219385017@mycput.ac.za)

Received: 21 May 2024 | **Revised:** 10 July 2024 | **Accepted:** 27 August 2024

Funding: The author acknowledges the financial assistance provided by the National Research Foundation (NRF).

Keywords: battery energy storage | distributed generation | hybrid renewable microgrid | real-time energy management system | renewable energy sources

ABSTRACT

This paper gives a detailed study for the design and implementation of an energy management system (EMS) for a hybrid renewable microgrid system using real-time software. Microgrids, with their ability to integrate renewable energy sources, face challenges in maintaining stability and reliability. The implemented EMS aimed to maximize the renewable energy sources utilization, including PV and wind power, in conjunction with a battery energy storage system. The objectives of this research included the implementation of an EMS that ensures a reliable and stable operation between the microgrid system and the main grid including the control of charge and discharge of the battery using Typhoon Hardware-in-the-Loop (HIL) software. The simulation results and case studies demonstrated the effectiveness and performance of the developed EMS in managing a hybrid renewable microgrid system. The results also demonstrated that the time of charging was maximized by utilizing a higher power. By doing so, the battery was fully charged in a shorter timeframe. The battery state of charge (SOC) was maintained between the fixed values (20% and 100%) as stated by the algorithm.

1 | Introduction

The use of renewable energy sources has significantly increased in recent years as a means to address environmental concerns and achieve energy sustainability [1]. Microgrid systems constituted by distributed generations and diverse energy sources, have become an effective remedy to incorporate renewable energy into the existing power infrastructure. However, renewable energy sources (RESs) such as solar and wind power are erratic, which makes microgrid systems less stable and reliable [2]. Real-time energy management becomes crucial to guarantee the effective use of RESs while maintaining grid stability [3].

The motivation behind this study stemmed from the augmentation of demand for sustainable energy solutions and the necessity to address the limitations of traditional power grids. Microgrid systems offer a decentralized approach to energy generation and distribution, allowing communities and industries to minimize emissions of greenhouse gas and decrease their dependence on fossil fuels [4]. By harnessing the potential of RESs, microgrids contribute to the energy transition infrastructure to a clean and more resilient. However, effective management of hybrid renewable microgrid systems requires sophisticated control algorithms and real-time monitoring capabilities [5].

The implemented energy management system (EMS) aimed to optimize the energy generation, storage, and distribution in real-time. This study had as primary objective the design and development of a real-time EMS adapted for hybrid renewable microgrid systems.

The implemented system was developed utilizing Typhoon Hardware-in-the-Loop (HIL) simulation package with HIL402 configuration in the virtual environment. The organization of the remaining parts of the paper include, Section 2, the architecture of microgrid systems is presented. Real-time energy management system is presented in Section 3. Section 4 presents the developed EMS control flowchart. The results of the simulation are provided in Section 5. The conclusion of the paper is provided in Section 6.

2 | Hybrid Renewable Microgrid System Architecture

Hybrid renewable microgrid systems have attracted a lot of interest lately because of their capacity to handle energy sustainability challenges while enhancing grid resilience and

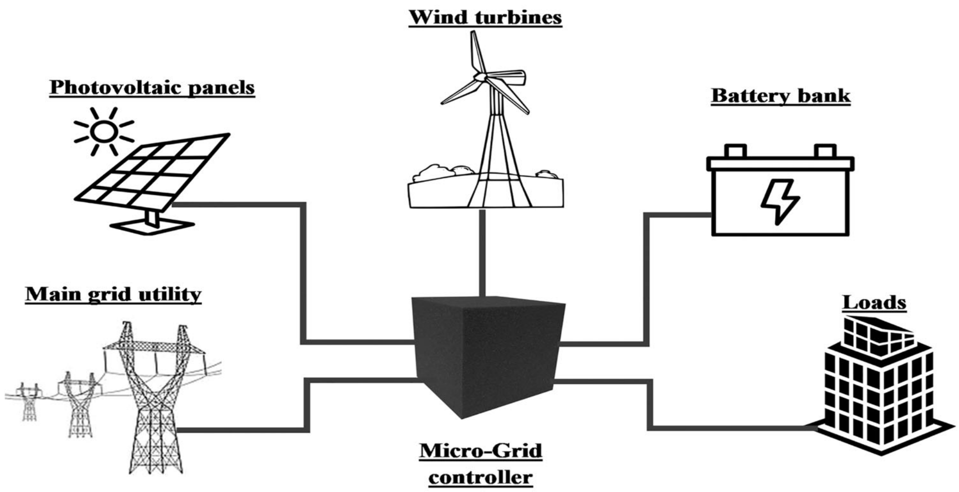

FIGURE 1 | Microgrid architecture [7].

TABLE 1 | Comparative analysis of renewable and conventional energy sources.

Metric	Renewable sources	Conventional sources
Efficiency	▪ Solar panels: up to 22% ▪ Wind turbines: up to 45% ▪ Hydropower: 90%+	▪ Coal plants: ~33% ▪ Natural gas plants: 50%–60% ▪ Nuclear: 33%
Cost	▪ Decreasing due to technological advancements and economies of scale ▪ Solar PV: \$0.06/kWh ▪ Wind: \$0.03–0.05/kWh	▪ Increasing due to fuel prices and regulatory costs ▪ Coal: \$0.06–0.15/kWh ▪ Natural gas: \$0.05–0.10/kWh
Environmental impact	▪ Low to zero emissions ▪ Minimal resource depletion ▪ Solar and wind have negligible emissions ▪ Hydropower can impact ecosystems, but no emissions	▪ High emissions (CO_2, SO_2, NO_x) ▪ **S**ignificant resource depletion ▪ Coal: High CO_2 and pollutant emissions ▪ Natural gas: Lower than coal, but still significant CO_2 emissions
Reliability	▪ Intermittent, but improving with storage solutions (e.g., batteries, pumped hydro) ▪ Solar and wind depend on weather and time of day ▪ Increasing grid integration and smart grid technologies enhance reliability	▪ Generally high reliability ▪ Dependable on fuel availability and supply chain ▪ Fossil fuels can be stored and used on demand ▪ Vulnerable to supply disruptions (e.g., geopolitical tensions)
Scalability	▪ Easily scalable with modular setups ▪ Solar panels can be installed on rooftops, small or large fields ▪ Wind farms can be scaled by adding more turbines ▪ Community-based renewable projects are possible	▪ Large-scale, less flexible in scaling down ▪ Requires significant infrastructure and investment ▪ Difficult to scale incrementally ▪ Centralized power plants require extensive planning and resources

reliability [6]. Figure 1 presents the illustration of the renewable microgrid architecture. Hybrid renewable microgrid systems incorporate RES like photovoltaic (PV) arrays and wind turbines, which are the primary RESs in hybrid microgrid configurations [8]. These sources provide clean and sustainable energy but are intermittent in nature, requiring effective management and integration strategies. Besides the RES, a hybrid microgrid also includes energy storage systems, inverters and power electronics, control and monitoring systems as well as grid interconnection. Hybrid microgrid systems may operate connected to the main grid utility or operate in isolation (i.e., islanded mode) [9]. Grid interconnection enables bidirectional power flow, allowing excess energy to be exported to the main grid or imported during periods of low generation.

Hybrid renewable microgrid systems offer a promising solution for enhancing energy sustainability and resilience in distributed power generation networks [10]. However, to fully utilize hybrid microgrid systems in the transition to a cleaner and more sustainable energy future, intermittency, system integration, and optimization issues must be resolved.

2.1 | The Difference Between a Conventional Power Grid and a Microgrid

Electricity in a conventional power grid flows from the power plants to the consummation point in a single direction [11]. The generated power is controlled to balance generation and consumption throughout the network by ensuring that supply and demand are met in real-time. Unlike traditional grids, microgrids can function in multiple modes based on the situation. They can function independently in islanded mode during grid disruptions or outages, or they can be connected to the main grid to facilitate the exchange of electricity [12].

The following characteristics of microgrid systems are commonly classified as the main ways in which they differ from the traditional power grid; however, the purposes and objectives of a microgrid vary across different countries [13].

- Enhance the functionality of intermittent renewable energy sources and enable the power grid to modify different energy source systems.

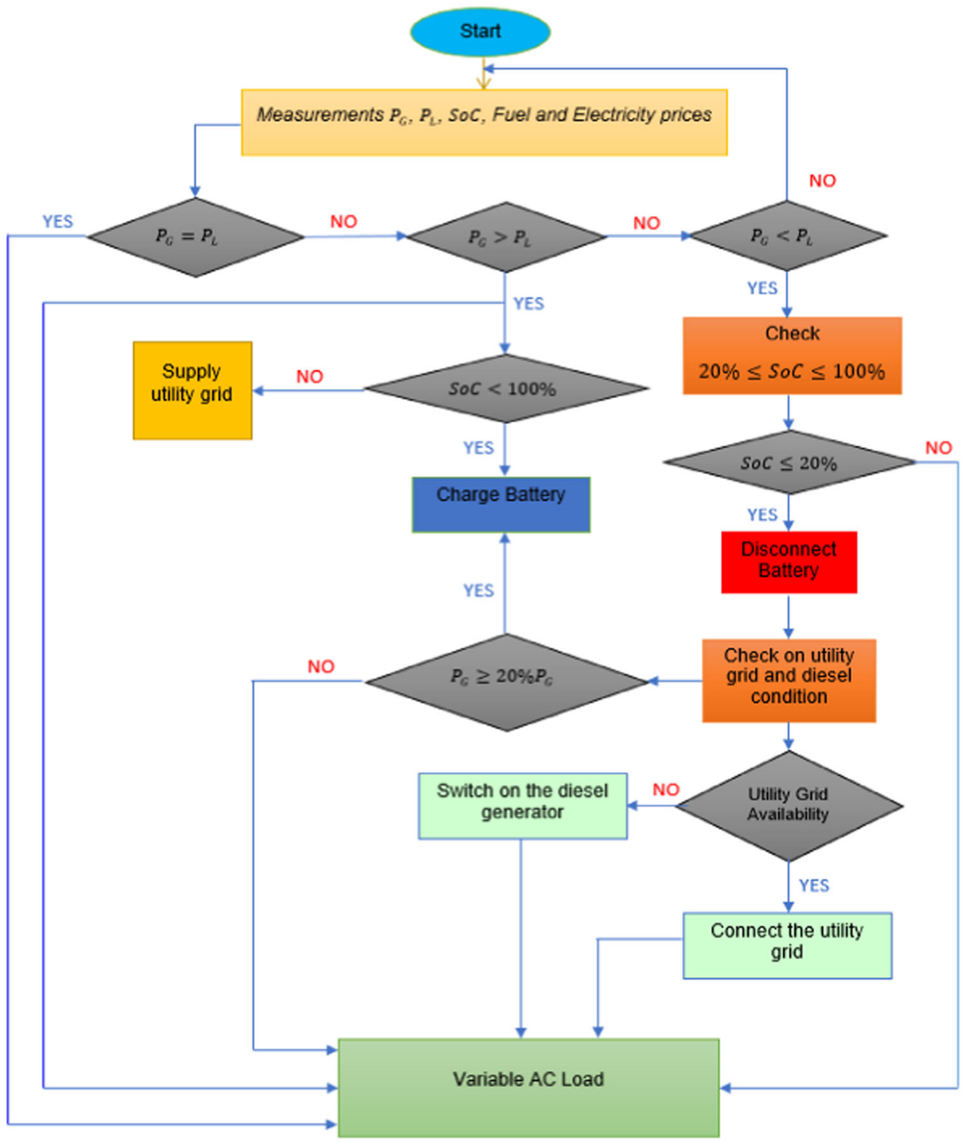

FIGURE 2 | Energy management algorithm flowchart.

- Almost completely removes the chance of extensive, prolonged blackouts, barring major physical harm.
- Increase the economy while reducing costs, emissions, and energy consumption.

The power grid distribution is an essential component of the electrical system that ensures safe, steady operation and optimal resource management. Due to distributed generation, widespread access, intermittent renewable energy sources, growing demand for energy production reliability, and economy, the conventional power grid is unable to meet the needs satisfied by the microgrid improvement [14]. The whole restore processing is much simpler in a microgrid structure because there are fewer factors that can be controlled, in accordance with its incorrect restoration procedure, which requires rapid action, usually human and in real-time [15].

2.1.1 | Some Benefits of Renewable Sources Compared to Conventional Source

To highlight the advancements and benefits of renewable energy sources over conventional ones, a comparative analysis is conducted using key metrics such as efficiency, cost, environmental impact, reliability, and scalability [16]. Table 1 presents a summary of this comparison based on data gathered from recent studies.

As shown in Table 1, renewable energy sources have several advantages over conventional sources.

1. Efficiency: Renewable sources such as solar and wind have seen significant improvements in efficiency. Modern solar panels can achieve efficiencies up to 22%, while advanced wind turbines can reach efficiencies up to 45%.

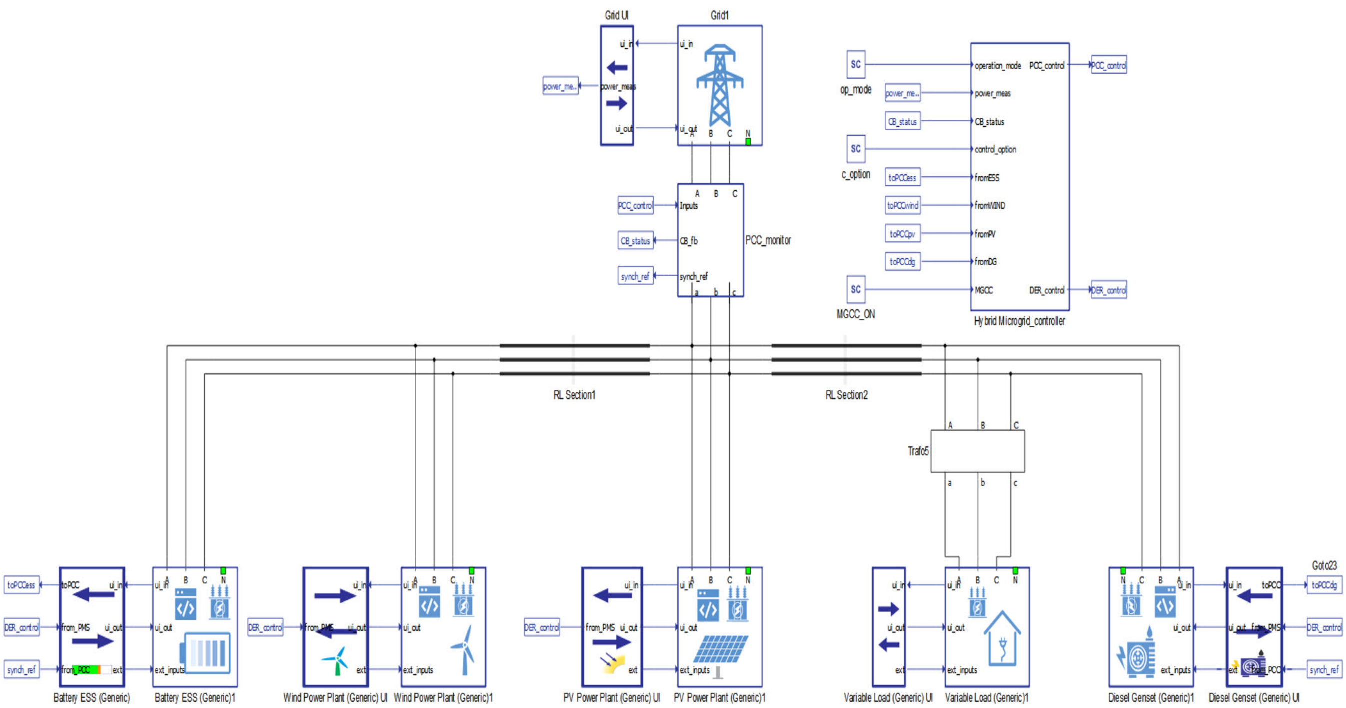

FIGURE 3 | Hybrid microgrid mode.

TABLE 2 | Energy management system table condition.

Conditions	Variable AC load	Battery	Utility grid	Generator
$P_G = P_L$	Supply load	—	—	—
$P_G > P_L$	Supply load	Charge battery	—	—
SOC < 100%	Supply load	Charge battery	—	—
SOC = 100%	Supply load	Disconnect batt	Connect grid	—
SOC ≥ 20%	Supply load	—	—	—
SOC ≤ 20%				
Grid available	Supply load	—	Connect grid	—
Grid unavailable	Supply load	—	—	Connect gen
$P_G \geq 20\% P_G$ Check grid availability, if yes	Supply load	Charge battery	Connect grid	—
$P_G \geq 20\% P_G$ Check grid availability, if no	Supply load	Charge battery	—	Connect generator

In contrast, conventional sources like coal plants have remained relatively stagnant at around 33% efficiency.

2. Cost: The cost of renewable energy has been decreasing rapidly due to technological advancements and economies of scale. For instance, the cost of solar photovoltaic energy has dropped to approximately $0.06/kWh, and wind energy costs between $0.03 and $0.05/kWh [17]. Conversely, the cost of conventional energy sources like coal and natural gas is either stable or increasing due to fuel prices and regulatory costs.
3. Environmental Impact: Renewable energy sources offer substantial environmental benefits by producing low to zero emissions. Solar and wind energy have negligible emissions during operation, while hydropower, despite potential ecosystem impacts, emits no pollutants [18]. Conventional sources, particularly coal, emit high levels of CO_2, SO_2, and other pollutants, contributing significantly to air pollution and climate change [19].
4. Reliability: While renewable energy sources can be intermittent, advancements in energy storage solutions, grid integration, and smart grid technologies are enhancing their reliability [20]. Conventional sources are generally reliable as they can produce energy on demand, but they are vulnerable to fuel supply disruptions.
5. Scalability: Renewable energy systems are highly scalable and can be implemented in modular setups, making them suitable for a wide range of applications from small-scale residential to large-scale industrial projects [21]. Conventional energy systems, however, require significant infrastructure and investment, making them less flexible and more challenging to scale incrementally.

This comparative analysis clearly demonstrates the improvements and advantages of renewable energy sources over conventional sources. Renewable energy not only offers higher efficiency and lower costs but also provides significant environmental benefits and scalability, making it a more sustainable and future-proof option for energy generation [22].

This research aims to optimize the utilization of renewable energy sources while ensuring stability, reliability, and efficiency of the hybrid microgrid operation. By implementing a sophisticated control algorithm, the aim is to seamlessly integrate various renewable energy sources, such as solar and wind, with a battery energy storage system and diesel generator. The primary goal is to minimize reliance on fossil fuels, reduce carbon emissions, and promote sustainability by maximizing the utilization of clean energy resources within the hybrid microgrid. This research offers several significant contributions such as developing an EMS control that optimizes energy usage within the hybrid microgrid, ensuring that energy is produced and consumed efficiently. By coordinating the operation of renewable energy sources, energy storage systems, and demand-side management strategies, it minimizes energy wastage and improves overall system efficiency. Implementing comprehensive control in real-time and management systems to adaptively respond to variation in renewable energy generation and load demands. By addressing these aspects, the research aims to promote wider adoption of sustainable energy practices by offering useful guidance for the design and hybrid microgrid systems operation.

Hardware and software solutions for real-time simulation from Typhoon HIL software are utilized to test, validate and optimize the developed energy management control performance. Through the development of an advanced EMS control for hybrid microgrid systems integrating RESs, this research contributes to the body of knowledge already in existence. To build

TABLE 3 | Test variables component.

Variable	Symbol	Value
Nominal grid line voltage	V_{PCC}	10 kV
Nominal converter line voltage	$V_{\mathrm{nom\_LL}}$	380 V
Nominal battery voltage	$V_{\mathrm{nom\_batt}}$	1000 V
Nominal capacity of the battery	BAh	900 Ah
Rated power	S_{B}	1 MW
Load active and reactive power	P_{L}, Q_{L}	800 kW, 0 VAR
Wind power	P_{wd}	500 kW
PV power	P_{pv}	500 kW
Rated power of the diesel generator	S_{G}	1.5 MVA
Nominal frequency	f_{B}	50 Hz
Current loop proportional gain	k_p	0.5
Current loop integral gain	k_i	3.0
Transformer equivalent series inductance1	Tr_{L1}	0.0034 H
Transformer equivalent series resistance1	Tr_{R1}	0.0862 Ω
Transformer equivalent series inductance2	Tr_{L2}	5.0817 µH
Transformer equivalent series resistance2	Tr_{R2}	$1.2272\ 10^{-4}$ Ω
Faster execution rate	T_{s1}	1 µs
Slower execution rate	T_{s2}	5 µs

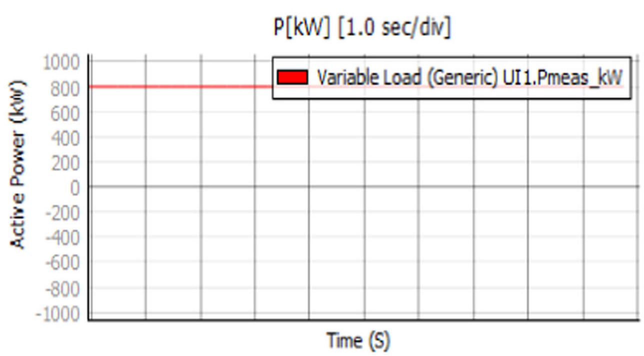

FIGURE 4 | Load demand power graph.

a robust and effective energy network, the study integrates solar, wind, and diesel generator with a battery. Intermittency related issues were the main focus, along with energy dispatch optimization and system stability.

3 | Real-Time Energy Management System

A real-time EMS is a critical component of modern power systems, enabling efficient utilization and optimization of energy resources in real-time [23]. Due to the expansion of the RESs incorporation into the grid, the need for effective energy management systems has become more pronounced [17]. Real-time EMS facilitates dynamic control and power production monitoring, distribution, including consumption, to finally ensure grid stability, reliability, and cost-effectiveness. There are different components of real-time energy management system, which include:

- Control algorithms and optimization techniques: Real-time EMS utilizes sophisticated control algorithms and optimization strategies to regulate energy flow and maintain supply and demand equilibrium [24]. These algorithms dynamically adjust generation schedules, dispatch power from renewable and conventional sources, and optimize energy storage usage to meet system requirements while minimizing operating costs and environmental impacts [25].
- Forecasting and predictive analytics: Real-time EMS integrates weather forecasting, load forecasting, and predictive analytics to anticipate changes in energy generation and consumption patterns [26]. By accurately predicting future conditions, EMS can proactively adjust system parameters and optimize energy management methods to mitigate the variability and uncertainty impact [27].
- Energy storage integration: Energy storage systems (ESSs), which include batteries, flywheels, and pumped hydro storage, have vital functions in real-time EMS as they provide flexibility and resilience to the grid [28]. EMS algorithms optimize the schedules of ESSs charge/discharge to mitigate variations in the production of renewable energy, stabilize grid frequency, and provide backup power during outages.
- Grid connectivity and communication: Real-time EMS relies on robust communication networks and grid connectivity to exchange data and control signals between various grid components [29]. Smart grid technologies like distributed energy resources management systems (DERMS) and

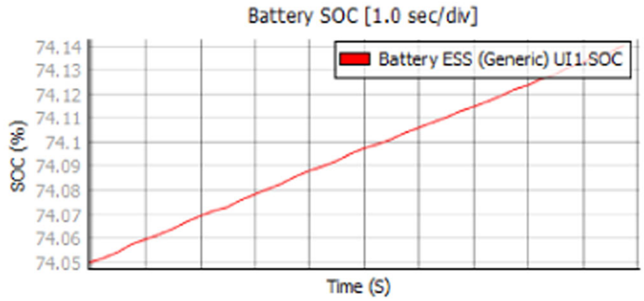

FIGURE 6 | Battery SOC on the charging mode.

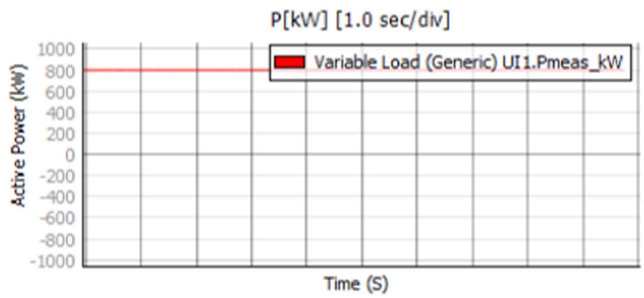

FIGURE 7 | Graph of the required power from the load.

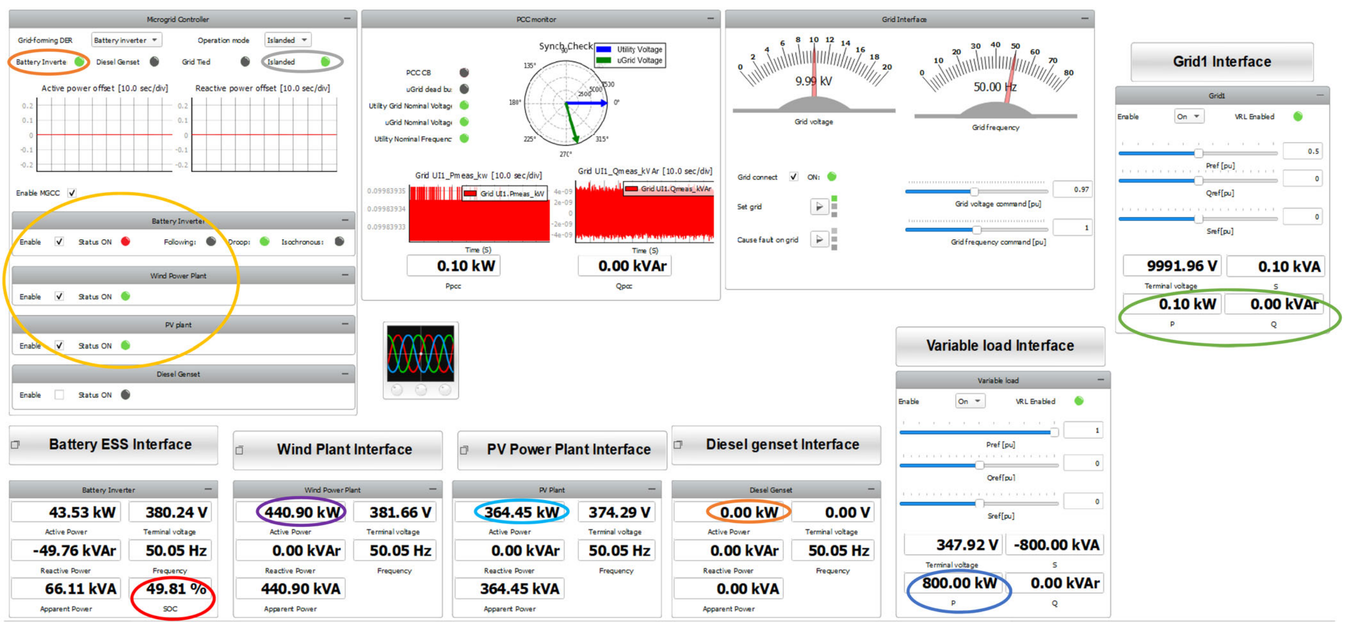

FIGURE 5 | HIL SCADA panel interface for scenario 1.

demand response systems, enable bidirectional communication and coordination among grid stakeholders, enhancing grid reliability and efficiency.

This study has a goal to accelerate the adoption of sustainable energy solutions by developing an algorithm to optimize the coordination of renewable energy sources and battery energy storage inside a hybrid microgrid. By developing dependable EMS control for hybrid microgrid systems, this work provides insightful information to engineers, policymakers, and stakeholders involved in the planning and implementation of renewable energy projects. Beyond merely theoretical advancements, the potential impact could actually aid in the future transition to cleaner and more sustainable energy sources. Furthermore, this research promotes a wider adoption of sustainable energy practices by providing helpful guidelines for the design and development of hybrid microgrid systems. Additionally, the implemented algorithm control is adaptable, allowing users to access and modify any control parameter.

4 | Energy Management Control for the Implemented System

The developed system included two supply power sources (PV and wind power systems), along with a battery and a diesel generator. The generator provided power to satisfy the demand of the load in the absence of the utility grid. The implemented hybrid microgrid and EMS were physically built using Typhoon HIL software, which was also utilized to test, validate, and improve its performance. Every component of the circuit is represented by matching model blocks that are included in the software. Figure 2 presents the developed energy management control flowchart.

Figure 3 presents the developed Typhoon HIL model.

The developed EMS ensured that the power supply provides the requirement of the load based on four scenarios, assisted by the battery, the diesel generator, and the utility grid.

Scenario 1: When the requirement of the load and the supplied power are equal.

Scenario 2: When the power generated become higher than the load requirement.

Scenario 3: When the supplied power is insufficient to satisfy the load requirement.

Scenario 4: When the battery attained its minimum limit (20%) and the requirement of the load still high than the power generated.

5 | Simulation Results and Discussion

This section presents the results of the simulation for the implemented EMS control and consider different scenarios. Using

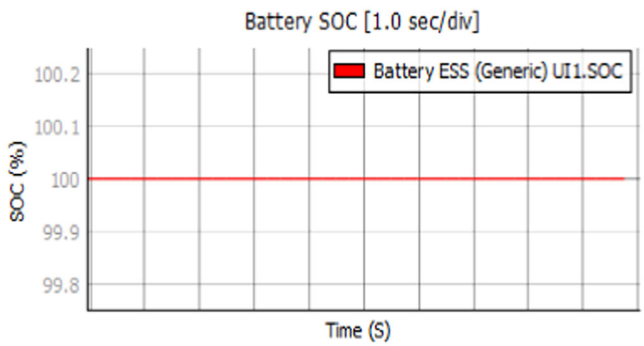

FIGURE 9 | Maximum charge of the battery.

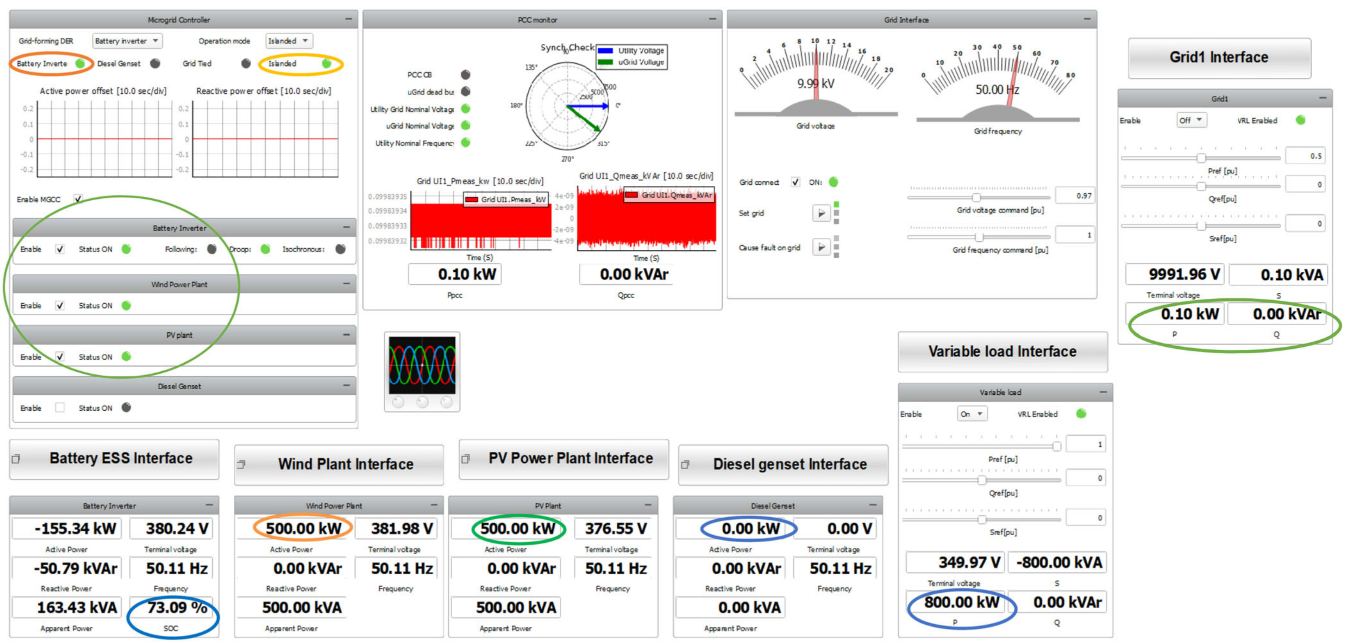

FIGURE 8 | HIL SCADA panel interface for scenario 2.

scenarios helps to understand the real world more fully. Using scenarios is essential since it can give a specific plan and method. Thus, it is a very useful guideline to use the situations in chronological order. Table 2 provides the summary of the diverse modes of operation for these scenarios.

Table 3 presents the component test variables for the simulation utilization.

Scenario 1: The load demand and the supplied power from the RESs in the first scenario are equal. Table 2 shows that an 800 kW load demand is assumed. As result, all of the generation power is supplied to the load directly and uninterrupted. Figure 4 illustrates the power graph from the load supplied by the generated power.

Figure 5 presents the HIL SCADA panel interface, as it can be seen, the utility grid, the diesel generator as well as the battery, are isolated. In this instance, the entire production power is continuously provided to the load, as the HIL interface shows. As can be seen on the HIL interface, the diesel generator and utility grid are off, the battery is in red, and the LED indicators for PV power and wind power are displayed in green to signify their functioning states. The highlighted circles illustrate different values and operation of the system on HIL SCADA panel

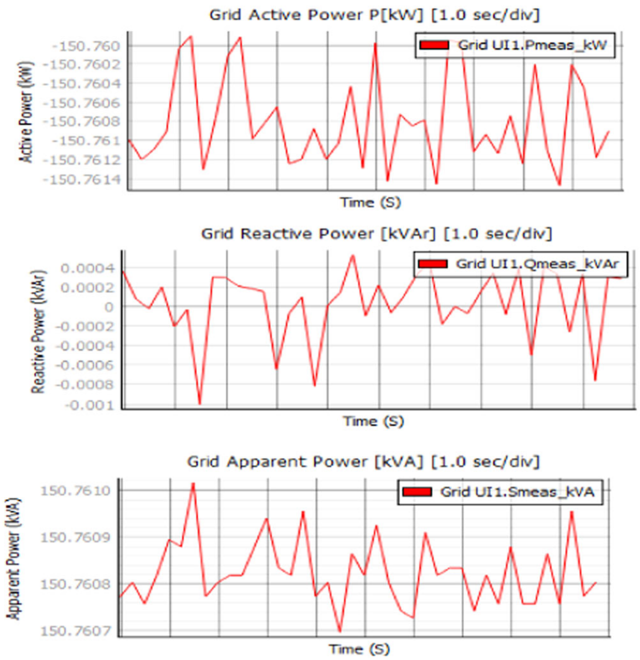

FIGURE 10 | Utility grid power (supplied by the production excess).

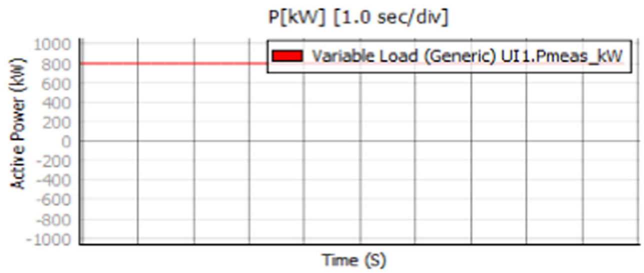

FIGURE 12 | Load demand power graph.

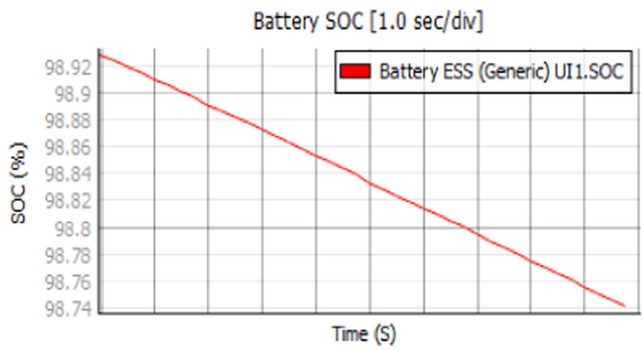

FIGURE 13 | Battery SOC on the discharging mode.

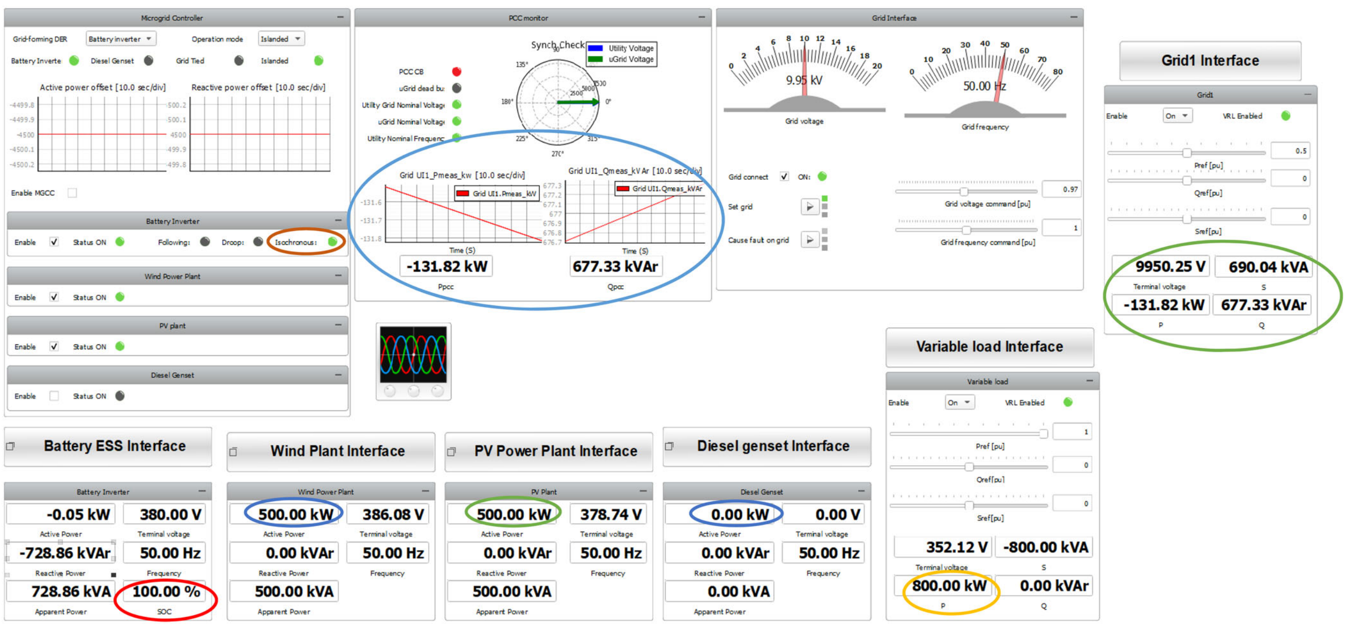

FIGURE 11 | HIL SCADA panel interface for grid-connected mode.

based on each scenario in which battery, wind plant, PV plant, diesel genset, variable load and utility grid interfaces and the microgrid controller are presented.

Scenario 2: The production power exceeds the load requirement. In this situation, the production surplus is either used to supply the utility grid or recharge the battery, based on the battery state of charge (SOC). The battery will be recharged if its SOC is in the minimal range (≤ 20%), and the excess of production will be fed into the utility grid if it is in the maximum range (100%). The charging mode of the battery is shown in Figure 6.

Figure 7 presents the load demand power. At this point, the production power supplied the load and charges the battery concurrently.

Figure 8 provides the HIL SCADA panel interface for this second case. The panel shows that the generated power exceeds the load demand power. The panel interface shows that the production surplus is utilized to recharge the battery because the battery SOC was below its maximum value. The battery will be recharged until it attained its maximum value (100%), and when this limit is attained then the production surplus will be supplied to the utility grid until the condition changed. At this time the diesel generator is turned off as shown in the HIL SCADA panel.

Looking at Figure 9, the battery has reached its maximum capacity and is now removed from the system to await the discharge mode when necessary.

Figure 10 shows how the excess production supplies the utility grid, as it can be seen, the utility grid is currently connected to receive supplies from the production excess.

Figure 11 provides the HIL SCADA panel interface when the maximum charge limit of the battery is attained.

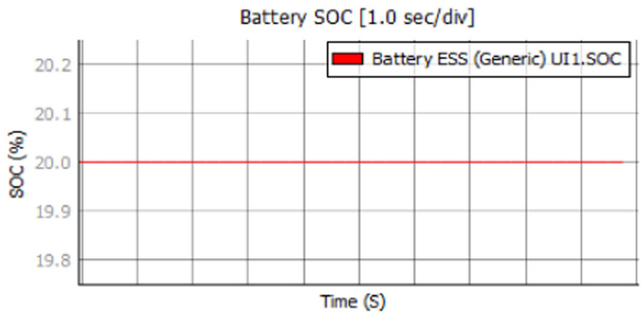

FIGURE 15 | Battery SOC on its minimum value.

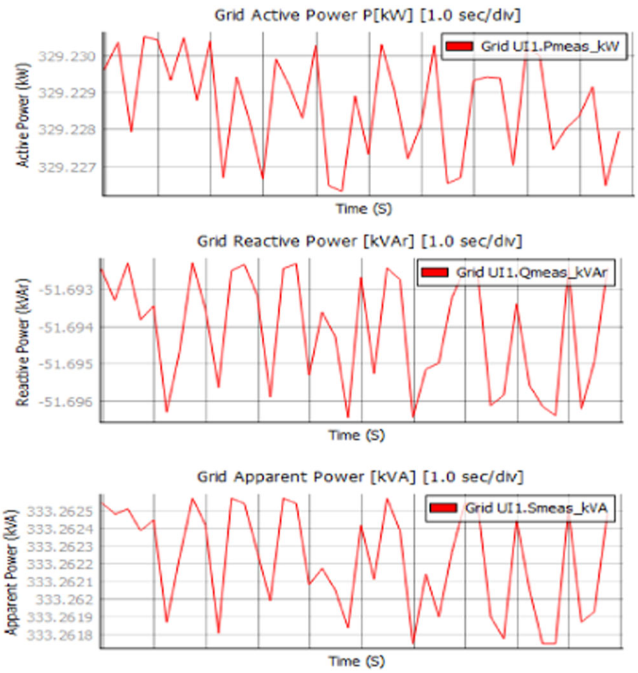

FIGURE 16 | Utility grid supplied power (grid connected mode).

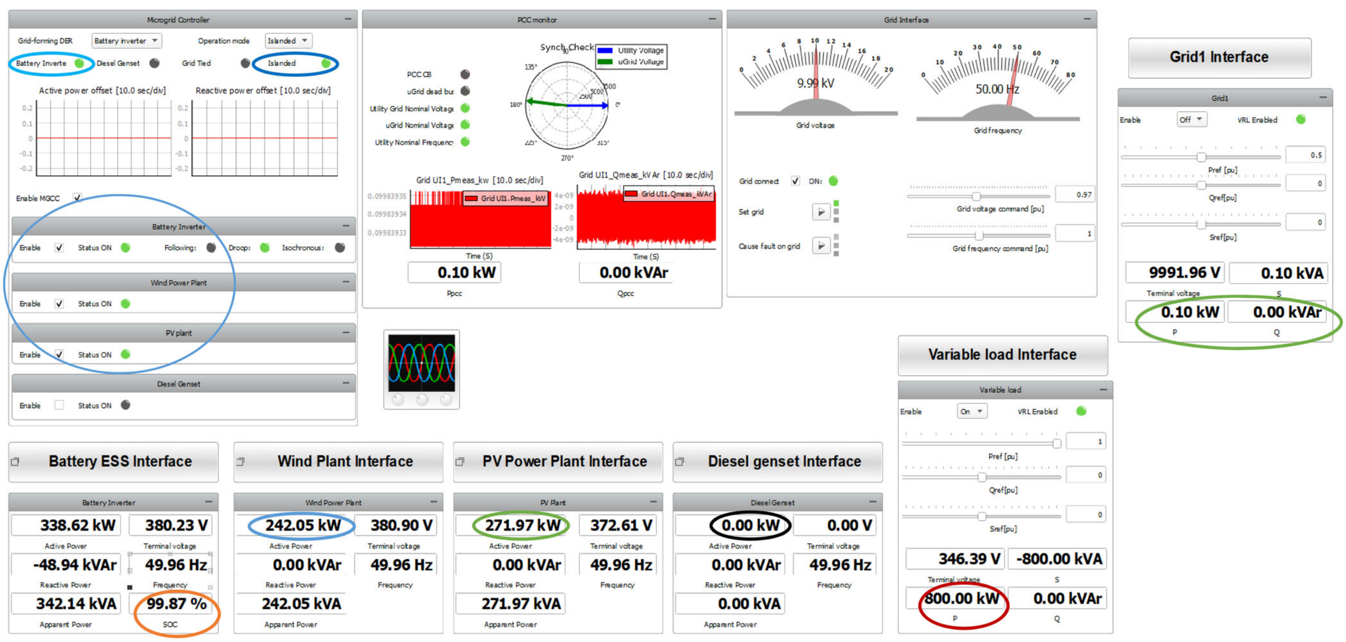

FIGURE 14 | HIL SCADA panel interface for the third scenario.

When the maximum battery charge limit is attained, the production excess is sent to the utility grid and the demand of the load is simultaneously satisfied as illustrated from Figure 11. The battery is immediately disconnected when its maximum value is reached, as indicated in the HIL panel interface. Figure 12 shows the load demand power graph.

Scenario 3: The requirement of the load exceeds the generation power in this case, thus, the battery will help to satisfy the load demand. The requirement is that the implemented EMS first verifies the maximum and lowest values of the battery storage to determine how much power is available. When the SOC exceeds 20%, the battery is connected for discharge; if the SOC falls below 20%, the battery is unplugged from the system. The battery was previously completely charged, as seen in Figure 13. In this case, the battery discharges in accordance with the given condition and keeps going until it hits 20% SOC, the minimum value, or the conditions change.

The HIL SCADA panel interface is displayed in Figure 14 when the generated power falls short of the load requirement. The results show that the battery is discharging and the utility grid as well as the diesel generator are isolated. Once the minimum limit value will be attained, the battery will stop to discharge and the demand of the load will be satisfied by the grid or the diesel generator.

When the minimum battery SOC limit is attained and the supplied power is below the amount required to meet load demands. In this instance, depending on the utility grid accessibility, the demand of the load is satisfied either by the utility grid or the diesel generator assistance. The battery is automatically unplugged to prevent a deep discharge when the minimum value is achieved, as shown by the battery SOC graph in Figure 15.

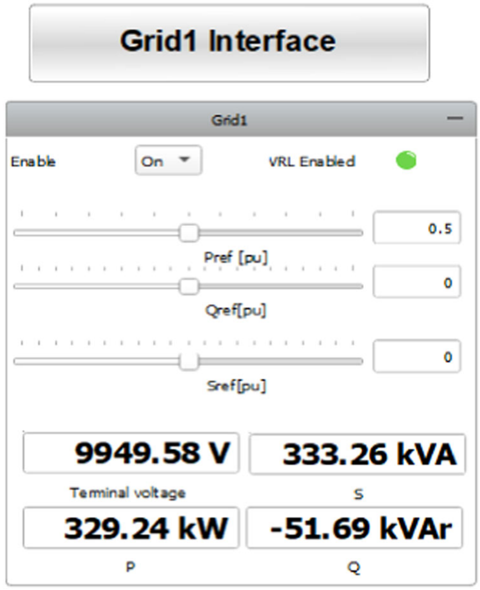

FIGURE 18 | Utility grid SCADA panel interface.

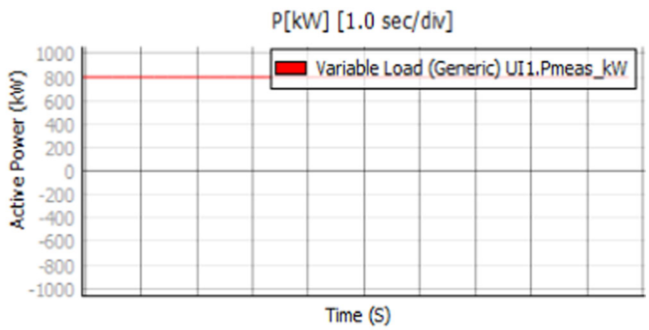

FIGURE 19 | Load demand power graph.

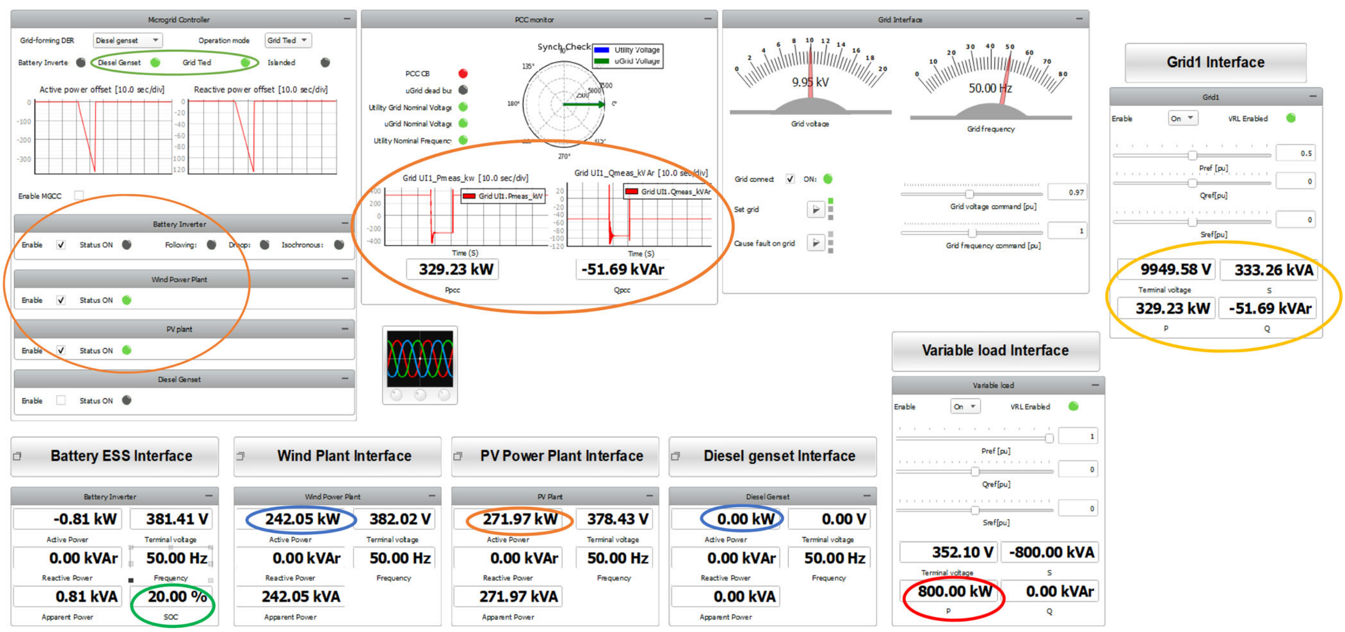

FIGURE 17 | HIL SCADA panel interface when the battery attained its minimum value.

Figure 16 shows the power supplied from the utility grid.

Figure 17 shows the HIL SCADA panel interface for the third scenario in which the battery reaches its minimal value.

Figure 18 presents the utility grid HIL SCADA panel interface, the remaining power is provided according to the accessibility of the utility grid. Here, the grid is providing power to the load.

Figure 19 shows the load demand power graph. The utility grid and RESs assist to satisfy the requirement of the load.

Figure 20 presents the HIL SCADA panel interface for the third scenario in which the utility grid is not operational. Thus, the diesel generator is activated to satisfy the requirement of the load. The diesel generator LED indicator is turned on, while the LED indicators of the utility grid and the battery are turned off, as shown on the HIL panel interface in Figure 20.

Figure 21 shows the diesel generator output power graphs. As it can be seen for this case, the diesel generator is activated to assist the demand by providing power to the load in the absence of the utility grid.

Figure 22 shows the load demand graph. The diesel generator and renewable energy sources help to meet the demand.

The Typhoon HIL software test shows how effective the implemented EMS is. The developed EMS facilitates the efficient use of RESs and enhances their incorporation within the electrical system. Additionally, it fulfils every scenario that is illustrated and regulates the energy flow between the load demand, and the microgrid as well as the utility grid. Furthermore, the developed EMS pacrevents the battery from rapid charge and deep discharge by keeping its SOC in admissible limits.

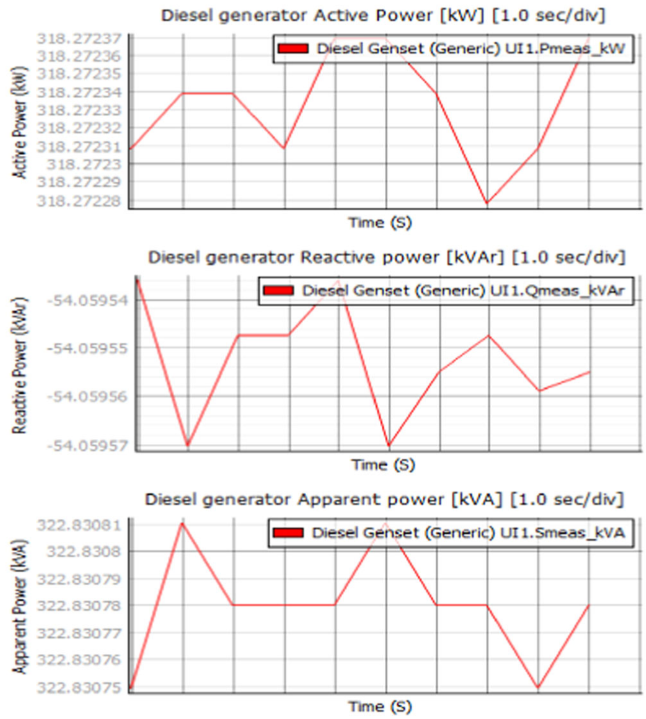

FIGURE 21 | Diesel generator output power graph.

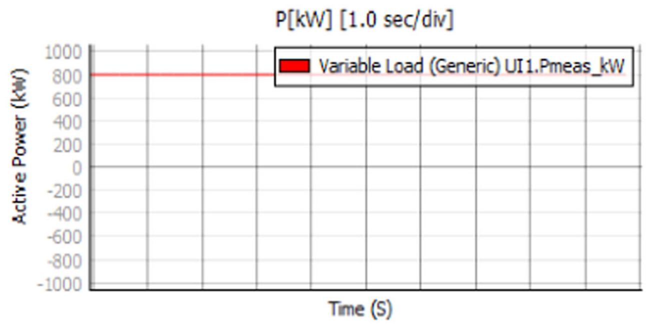

FIGURE 22 | Load demand power graph.

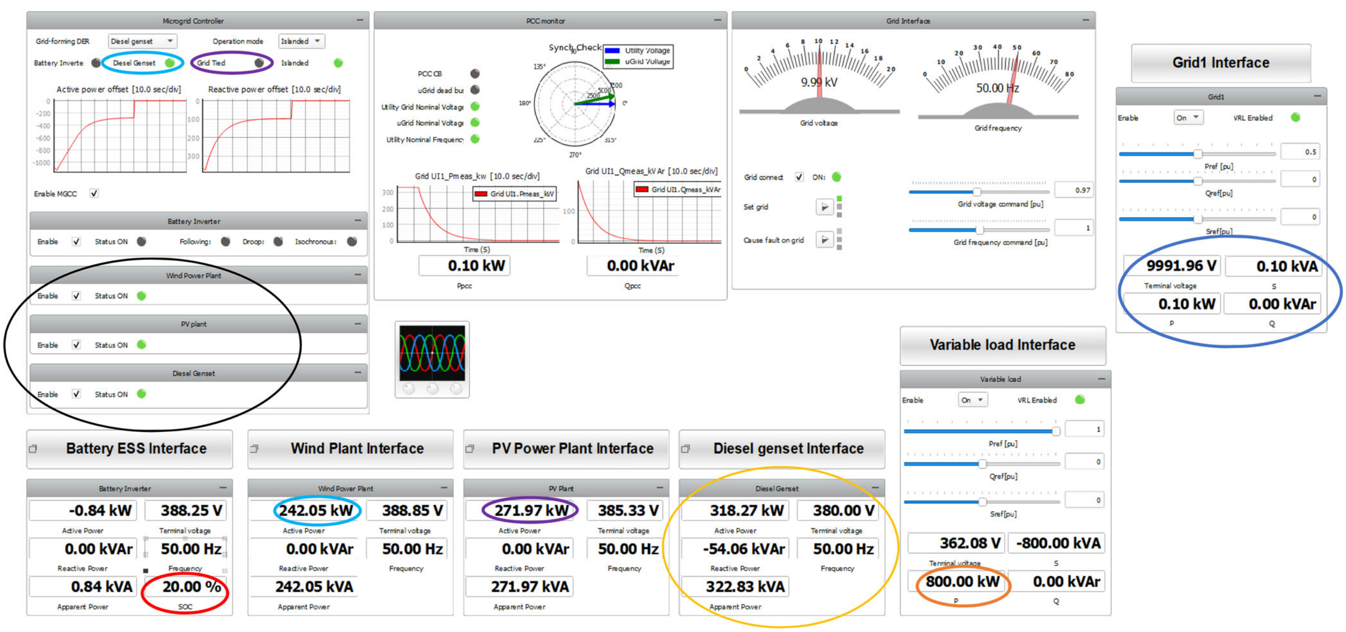

FIGURE 20 | HIL SCADA panel interface when diesel generator switched on.

6 | Conclusion

In this paper, a real-time EMS for hybrid renewable microgrid system was provided. During the simulation, a variety of scenarios were used to demonstrate the resilience and efficacy of the implemented algorithm to manage the load in both isolated and grid-connected modes and guarantee an optimal battery operation as intended. The hybrid microgrid system that was designed had a fixed variable AC load of 800 kW and a total generation power of 1 MW from renewable sources. The aim and objective of this research were achieved by implementing and developing a hybrid microgrid model utilizing the virtual environment of Typhoon Hardware-in-loop (HIL) simulation package with HIL402 configuration. The results demonstrate the ability of the implemented control to manage the energy flow between the RESs and the load, which are both operating in conjunction with the utility grid. It also ensures an optimal relationship between the battery charge and discharge rates. Additionally, the results showed that using a higher charging power rather than a reduced one maximized the charging time. As a result, the battery received a full charge faster than usual. The algorithm had defined the permissible limits between 20% and 100%, and it was discovered that the battery SOC remained within those ranges. To increase the entire system dependability, further research based on EMS of cost-effective for smart microgrids network is necessary.

Nomenclature

AC	alternative current
DC	direct current
DER	distributed energy resource
DG	distributed generation
EMS	energy management system
ESS	energy storage system
HIL	hardware-in-loop
Kv	kilo Volt
KWh	kilowatt hour
KWp	kilowatt peak
MW	mega Watt
PCC	point of common coupling
PV	photovoltaic
SOC	state of charge

Author Contributions

As the Corresponding Author, I attest that each of the listed authors reviewed the work and gave their submission approval. Christian Ndeke Bipongo is the first author named since it is anticipated that he contributed most to the analysis and conception of the implemented control, model testing as well as validation. Drs. Marco Adonis and Ali Almaktoof are the second and third authors of this work, respectively, as they played a crucial role in providing direction, editing, and quality assurance of this work, respectively, as they played a crucial role in providing direction, editing, and quality assurance.

Acknowledgments

As the Corresponding Author, I thus declare that this work was produced as a component of a PhD project, with the supervision, direction, and editorial support of Drs. Marco Adonis and Ali Almaktoof. They also edited and revised the text before the publication. I also acknowledge the financial assistance provided by the National Research Foundation (NRF).

Ethics Statement

Since neither humans nor animals are the focus of the study, participant consent was not required to collect data for this project.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data sets are available from the corresponding author on reasonable request.

References

1. C. Kalaivani, M. V. Subramanyam, G. Singaram, A. U. Kumar, K. Mohanraj, and R. Saravanakumar, "Review of Hybrid Microgrid Power Management Using Renewable Energy Sources," *2023 9th International Conference on Advanced Computing and Communication Systems (ICACCS)* 1 (2023), 1491–1496, https://doi.org/10.1109/ICACCS57279.2023.10112787.

2. F. Sayeed, S. Hanumanthakari, S. Oommen, et al., "A Novel and Comprehensive Mechanism for the Energy Management of a Hybrid Micro-Grid System," *Energy Reports* 8 (2022): 847–862, https://doi.org/10.1016/j.egyr.2022.09.207.

3. A. Satapathy, N. Nayak, and T. Parida, "Real-Time Power Quality Enhancement in a Hybrid Micro-Grid Using Nonlinear Autoregressive Neural Network," *Energies* 15, no. 23 (2022): 9081, https://doi.org/10.3390/en15239081.

4. R. G. Allwyn, A. Al-Hinai, and V. Margaret, "A Comprehensive Review on Energy Management Strategy of Microgrids," *Energy Reports* 9 (2023): 5565–5591, https://doi.org/10.1016/j.egyr.2023.04.360.

5. S. Ahmad, M. Shafiullah, C. B. Ahmed, and M. Alowaifeer, "A Review of Microgrid Energy Management and Control Strategies," *IEEE Access* 11 (2023): 21729–21757, https://doi.org/10.1109/ACCESS.2023.3248511.

6. M. M. Iqbal, S. Kumar, C. Lal, and C. Kumar, "Energy Management System for a Small-Scale Microgrid," *Journal of Electrical Systems and Information Technology* 9, no. 1 (2022): 1–17, https://doi.org/10.1186/s43067-022-00046-1.

7. D. El Bourakadi, A. Yahyaouy, and J. Boumhidi, "Multi-Agent System Based Sequential Energy Management Strategy for Micro-Grid Using Optimal Weighted Regularized Extreme Learning Machine and Decision Tree," *Intelligent Decision Technologies* 13, no. 4 (2019): 479–494, https://doi.org/10.3233/IDT-190003.

8. A. Aghmadi, H. Hussein, K. H. Polara, and O. Mohammed, "A Comprehensive Review of Architecture, Communication, and Cybersecurity in Networked Microgrid Systems," *Inventions* 8, no. 4 (2023): 84, https://doi.org/10.3390/inventions8040084.

9. F. Nejabatkhah, "Optimal Design and Operation of a Remote Hybrid Microgrid," *CPSS Transactions on Power Electronics and Applications* 3, no. 1 (2018): 3–13, https://doi.org/10.24295/cpsstpea.2018.00001.

10. A. Bandara, K. Hemapala, and N. C. Ekanayake, A Survey on Hybrid Renewable Energy Systems for Microgrid Application PIICON 2020—9th IEEE Power India International Conference (2020), https://doi.org/10.1109/PIICON49524.2020.9113033.

11. S. K. Salman, "Evolutionof Conventional Power Systems to Smart Grids," 54th International Universities Power Engineering Conference (UPEC) 2019 - Proceedings (July 2001), 1–6, https://doi.org/10.1109/UPEC.2019.8893444.

12. M. A. Islam, M. Hasanuzzaman, N. A. Rahim, A. Nahar, and M. Hosenuzzaman, "Global Renewable Energy-Based Electricity Generation and Smart Grid System for Energy Security," *The Scientific World Journal* 2014 (2014), https://doi.org/10.1155/2014/197136.

13. W. Feng, M. Jin, X. Liu, et al., "A Review of Microgrid Development in the United States – A Decade of Progress on Policies, Demonstrations, Controls, and Software Tools," *Applied Energy* 228, no. April (2018): 1656–1668, https://doi.org/10.1016/j.apenergy.2018.06.096.

14. F. R. Badal, S. K. Sarker, Z. Nayem, S. I. Moyeen, and S. K. Das, "Microgrid to Smart Grid's Evolution: Technical Challenges, Current Solutions, and Future Scopes," *Energy Science & Engineering* 11, no. 2 (2023): 874–928, https://doi.org/10.1002/ese3.1319.

15. N. Shaukat, M. R. Islam, M. M. Rahman, et al., "Decentralized, Democratized, and Decarbonized Future Electric Power Distribution Grids: A Survey on the Paradigm Shift From the Conventional Power System to Micro Grid Structures," *IEEE Access* 11, no. June (2023): 60957–60987, https://doi.org/10.1109/ACCESS.2023.3284031.

16. T. Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, and N. Prabaharan, "A Comprehensive Study of Renewable Energy Sources: Classifications, Challenges and Suggestions," *Energy Strategy Reviews* 43, no. August (2022): 100939, https://doi.org/10.1016/j.esr.2022.100939.

17. Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "A Review of Hybrid Renewable Energy Systems: Solar and Wind-Powered Solutions: Challenges, Opportunities, and Policy Implications," *Results in Engineering* 20, no. September (2023): 101621, https://doi.org/10.1016/j.rineng.2023.101621.

18. A. I. Osman, L. Chen, M. Yang, et al., "Cost, Environmental Impact, and Resilience of Renewable Energy Under a Changing Climate: A Review," *Environmental Chemistry Letters* 21, no. 2 (2023): 741–764, https://doi.org/10.1007/s10311-022-01532-8.

19. Y. Khan and F. Liu, "Consumption of Energy From Conventional Sources a Challenge to the Green Environment: Evaluating the Role of Energy Imports, and Energy Intensity in Australia," *Environmental Science and Pollution Research* 30, no. 9 (2023): 22712–22727, https://doi.org/10.1007/s11356-022-23750-x.

20. S. M. Pragash, *Smart Grid Technology and Its Impact on Renewable Energy Integration*. (IEEE, 2017), 1–11, https://doi.org/10.13140/RG.2.2.25508.14722.

21. L. Zemite, J. Kozadajevs, L. Jansons, I. Bode, E. Dzelzitis, and K. Palkova, "Integrating Renewable Energy Solutions in Small-Scale Industrial Facilities," *Energies* 17, no. 11 (2024): 2792, https://doi.org/10.3390/en17112792.

22. W. Strielkowski, E. Tarkhanova, M. Tvaronaviˇ, and Y. Petrenko, "Renewable Energy in the Sustainable Development of Electrical," *Energies* 14 (2021): 1–24.

23. S. Zeinal-Kheiri, S. Ghassem-Zadeh, A. M. Shotorbani, and B. Mohammadi-Ivatloo, "Real-Time Energy Management in a Microgrid With Renewable Generation, Energy Storages, Flexible Loads and Combined Heat and Power Units Using Lyapunov Optimisation," *IET Renewable Power Generation* 14, no. 4 (2020): 526–538, https://doi.org/10.1049/iet-rpg.2019.0297.

24. S. Yu, L. You, and S. Zhou, "A Review of Optimization Modeling and Solution Methods in Renewable Energy Systems," *Frontiers of Engineering Management* 10, no. 4 (2023): 640–671, https://doi.org/10.1007/s42524-023-0271-3.

25. S. Basnet, K. Deschinkel, L. Le Moyne, and M. Cécile Péra, "A Review on Recent Standalone and Grid Integrated Hybrid Renewable Energy Systems: System Optimization and Energy Management Strategies," *Renewable Energy Focus* 46 (2023): 103–125, https://doi.org/10.1016/j.ref.2023.06.001.

26. M. Amir, A. Zaheeruddin, and A. Haque, "Intelligent Based Hybrid Renewable Energy Resources Forecasting and Real Time Power Demand Management System for Resilient Energy Systems," *Science Progress* 105, no. 4 (2022): 1–33, https://doi.org/10.1177/00368504221132144.

27. A. Elmouatamid, R. Ouladsine, M. Bakhouya, N. El Kamoun, M. Khaidar, and K. Zine-Dine, "Review of Control and Energy Management Approaches in Micro-Grid Systems," *Energies* 14, no. 1 (2021): 168, https://doi.org/10.3390/en14010168.

28. S. Choudhury, "Review of Energy Storage System Technologies Integration to Microgrid: Types, Control Strategies, Issues, and Future Prospects," *Journal of Energy Storage* 48, no. July 2021 (2022): 103966, https://doi.org/10.1016/j.est.2022.103966.

29. J. Ugwu, K. C. Odo, C. P. Ohanu, J. García, and R. Georgious, "Comprehensive Review of Renewable Energy Communication Modeling for Smart Systems," *Energies* 16, no. 1 (2023): 1–28, https://doi.org/10.3390/en16010409.