An Intelligent Energy Management Framework for Enhancing Microgrid Stability Using Excess Power Storage and Adaptive Distributed Energy Resource Dispatch

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***Abstract*—The increasing penetration of renewable energy sources such as solar photovoltaic (PV) and wind power has introduced significant challenges in maintaining stable and reliable microgrid operation due to their intermittent nature. This study proposes an intelligent energy management framework for enhancing microgrid stability through excess renewable power storage and adaptive Distributed Energy Resource (DER) dispatch. The proposed framework is implemented in the MATLAB/Simulink environment by integrating photovoltaic systems, wind turbines, Battery Energy Storage Systems (BESS), distributed generators (DGs), and utility grid support under the supervision of an intelligent Energy Management Controller (EMC). The controller performs real-time renewable energy assessment, intelligent battery charging and discharging, adaptive DER dispatch, and coordinated power balancing to optimize energy utilization and improve system performance. Simulation results demonstrate that the proposed framework increases renewable energy utilization from 78.4% to 93.7%, reduces operational cost from $128.6/day to $101.8/day, decreases power loss from 8.4 kW to 4.1 kW, minimizes voltage deviation from 7.6 V to 2.9 V and frequency deviation from ±0.32 Hz to ±0.08 Hz, and improves the microgrid stability index from 90.8% to 98.1%, confirming its effectiveness in enhancing energy efficiency, operational reliability, and sustainable microgrid performance.**

***Index Terms*—Intelligent Energy Management; Microgrid Stability; Battery Energy Storage System (BESS); Distributed Energy Resource (DER) Dispatch; Renewable Energy Integration.**

I. INTRODUCTION

The modern electrical power grid has become more decentralized and sustainable, with the increased integration of renewable energy resources like solar photovoltaic (PV) systems, wind turbines, and distributed generation units [1]. Microgrids have become an attractive approach to efficiently incorporate these DERs and improving energy reliability, resilience and sustainability [2]. A micro-grid is a localized energy system that can be connected to the main energy grid or disconnected and operate with a local energy supply [3]. However, the major problems with microgrids are power instability, voltage instability, frequency deviation, and the unpredictability of renewable energy generation. These challenges require the emergence of intelligent energy management frameworks that can guarantee stable and reliable operations of microgrids [4,5].

One of the major problems in renewable energy microgrids is the intermittent nature of the energy sources [6]. If the solar radiation and wind power fluctuate, there is a possibility of operating instability and power quality degradation due to the mismatch between the power generation and the load demand [7]. However, at some time there may be more generation than is needed, or the renewable energy may not be used effectively, thus becoming a waste or curtailed. If the renewable energy is low, however, then the microgrid may experience power shortages, potentially causing the system to be less stable. It is therefore important to properly coordinate DERs, energy storages, and controllable loads for a balanced and resilient microgrid [8,9].

There has been significant interest in the possibilities of energy storage systems to solve the intermittency of renewable energy resources [10]. They are key components in regulating the frequency, providing support to the voltage, and balancing the energy levels by storing energy when renewable generation is high and releasing it when demand is high or renewable generation is low. However, intelligent control strategies are required to optimally operate the storage resources, which adaptively change the operating conditions to the maximum energy utilisation and the minimum operational cost [11].

In recent years, adaptive EMS has been developed using advancements in AI, optimization techniques, and smart grid technologies [12]. They are built with intelligent algorithms, predictive analytics and real-time monitoring to ensure optimal deployment of DERs. In adaptive DER dispatch, the controller of the microgrid continuously adjusts the dispatch of the energy generation and storage to optimize the dispatch based on the load demand and the renewable energy availability and network constraints [13,14]. This smart coordination enhances the performance of the system, reliability and reduces the dependence of the conventional fossil fuel-based generation [15]. As illustrated in figure 1, the energy management system coordinates the renewable energy, storage, generators, loads and interaction with power grid to ensure the efficient and stable operation of the microgrid.

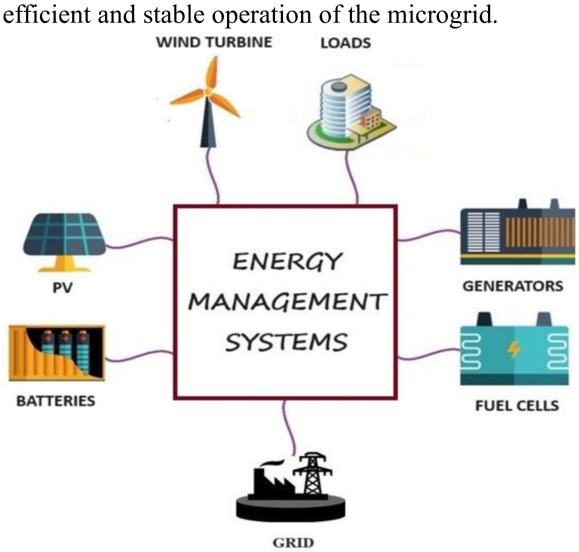

Figure 1. Intelligent EMS for Microgrid Stability Nsbf [16].

The present study investigates the development of an Intelligent Energy Management Framework for the enhancement of the stability of a micro grid employing excess power storage and dispatch of the DER system in an adaptive manner. This proposed framework intends to effectively store and use excess renewable energy by improving energy storage management and adaptive dispatch strategies for DERs. The framework aims to enhance voltage and frequency stability, minimize energy losses, and optimize overall microgrid performance by incorporating real-time control, predictive energy balancing, and intelligent resource allocation. The implementation of these smart energy management practices is anticipated to be critical to ensure a sustainable, resilient, and economically viable smart energy system for future energy needs.

Here are the research objectives as shown below:

- To develop an intelligent energy management framework for improving the stability and reliability of microgrid operation.
- To optimize the utilization of excess renewable energy through an efficient BESS charging and discharging strategy.
- To design an adaptive DER dispatch mechanism for balancing power generation and load demand under varying operating conditions.
- To evaluate the proposed framework in terms of renewable energy utilization, operational cost, battery performance, voltage and frequency stability, and power loss using MATLAB/Simulink.
- To compare the performance of the proposed intelligent energy management framework with a conventional Energy Management System (EMS) to demonstrate improvements in microgrid stability and overall energy efficiency.

II. LITERATURE OF REVIEW

Researchers have studied intelligent forecasting and energy management methods to optimize the use of renewables in microgrids. To achieve accurate solar and wind power predictions, Singh et al. (2024) [17] employed Support Vector Regression (SVR) models, minimizing prediction errors, cost of operation and enhancing the utilization of renewable energy. Arvind et al. (2025) [18] proposed the ORA-DL framework,

which combines deep learning, IoT sensing, and adaptive control to optimize energy demand forecasting, grid stability, and resource allocation while reducing energy waste. Similarly, Ramasamy et al. (2025) [19] used the LSTM model for forecasting and frequency-based distributed control to boost renewable energy penetration, minimize battery degradation, and enhance system responsiveness. Zheng et al. (2025) [20] presented a deep reinforcement learning-based energy management control strategy for hybrid hydrogen/battery storage systems to optimize the economic cost, battery lifetime, and system stability, while enhancing the system response and mitigating battery degradation.
Other studies have focused on optimization methods, integrated energy storage, and 'resilient' microgrid operation. To reduce voltage deviation, energy losses and carbon emissions and to avoid load curtailment, Hosseina et al. (2025) [21] presented a resilience-oriented optimization algorithm based on the Multi-objective Moth Flame Algorithm (MOMFA). Majeed et al. (2023) [22] proposed an energy management method based on optimization to optimize the utilization of the PV, Wind, Diesel Generator and Battery Storage systems for load scheduling and cost optimization. Ali et al. (2026) [23] proposed a stochastic energy management system to deal with renewable energy uncertainty and battery scheduling, while Taye et al. (2025) [24] used a droop control, adaptive filtering, and fuzzy logic to enhance voltage stability and reliability. Aghmadi et al. (2024) [25] showed that the cooperative multi-microgrid operation can be resilient, and Khani et al. (2024) [26] proposed a bi-level stochastic model to reduce the cost of renewable energy, demand-side management and energy storage. The present studies, however, have primarily concentrated on forecasting, optimization, or storage, and less on an integrated framework that leverages excess renewable energy storage and adaptive dispatching of DER resources to improve microgrid stability.

III. RESEARCH METHODOLOGY

The proposed methodology involves creating an intelligent management framework for microgrid stability, optimizing use of excess RE generation by battery energy storage and adjusting the dispatch of DERs. The framework is realized in a MATLAB/Simulink environment where the renewable energy resources, battery storage, DGs, and the utility grid are coordinated together and controlled by an intelligent EMC. The methodology includes the following steps:

3.1. Microgrid System Configuration

A microgrid is a power distribution system that combines electrical loads, BESS, renewable energy sources, and DERs into a localized power network to deliver reliable and efficient electricity. A microgrid is capable of grid-connected and islanded operation, ensuring power supply when the grid is disturbed, which is one advantage over traditional power systems. In the proposed approach, the major renewable energy sources include photovoltaic (PV) panels and wind turbines, and the BESS is designed to store excess energy from the PV and wind power systems when production exceeds demand, and to release the stored energy when demand is higher than supply. The DGs and the utility grid serve as auxiliary sources to ensure a continuous supply of power. An intelligent EMC continuously monitors power generation, battery status, and load demand to coordinate energy flow and enhance microgrid stability.

The total renewable power generated is expressed as

$$P_{RE} = P_{PV} + P_{WT}$$

where P_{PV} and P_{WT} denote the power generated by the photovoltaic and wind systems, respectively.

The overall power balance within the microgrid is represented as

$$P_{PV} + P_{WT} + P_{BESS} + P_{DG} + P_{Grid} = P_{Load} + P_{Loss}$$

where P_{BESS}, P_{DG}, and P_{Grid} represent the battery, DG, and utility grid power, respectively, while P_{Load} and P_{Loss} denote the load demand and system losses. This combination allows for effective use of renewable energy sources, reduced energy losses, and greater stability and reliability of the proposed microgrid.

3.2. System Initialization

The first phase in the proposed intelligent energy management framework is a system initialization phase, where all the components of the microgrid are set up and before the energy scheduling phase is to occur. The EMC gathers real-time data from the photovoltaic (PV) system, Wind Turbine (WT), BESS, DGs, utility grid, and load demand during this period. This initialisation sets the operating condition of the microgrid, allowing for precise monitoring, optimized power distribution, and informed decision-making across different renewable generation and load scenarios.

The total available generation is calculated as
$P_{Generation} = P_{PV} + P_{WT} + P_{DG}$
where P_{PV}, P_{WT}, and P_{DG} represent the output power of the photovoltaic system, wind turbine, and DGs, respectively.

The battery State of Charge (SOC) is determined by
$$SOC = \frac{E_B}{E_B^{max}} \times 100$$
where E_B is the current battery energy (kWh) and E_B^{max} is the maximum battery storage capacity (kWh).

The net available power within the microgrid is expressed as
$P_{Net} = P_{Generation} + P_{BESS} - P_{Load}$
where P_{BESS} is the battery charging/discharging power and P_{Load} is the total load demand. Positive P_{Net} means surplus energy for battery storage or export to the grid, while a negative number means energy is consumed via battery discharge, DG support or utility grid. The simulation parameters used for the simulation of the proposed intelligent microgrid energy management framework is summarized in Table 1.

Table 1. Simulation Parameters of the Proposed Microgrid

Parameter	Value
PV Capacity	100 kW
Wind Capacity	80 kW
Battery Capacity	250 kWh
DG Capacity	60 kW
Grid Voltage	415 V
Frequency	50 Hz
Battery SOC	20–90%
Simulation Time	24 h

3.3. Renewable Energy Generation Assessment
Renewable energy generation assessment is the process of estimating the power potential of PV panels and wind turbines for meeting load demands. This implies that renewable generation requires constant monitoring to keep the power balance in the microgrid and to assure its proper functioning, as its output depends on solar irradiance, temperatures, and wind speed. The EMC continually analyzes renewable energy generation to optimize energy use and reduce reliance on traditional energy resources.

The photovoltaic output power is calculated as
$P_{PV} = \eta_{PV} \times A_{PV} \times G$
where P_{PV} is the PV output power, η_{PV} is the PV efficiency, A_{PV} is the panel area, and G is the solar irradiance.

The wind turbine output power is expressed as
$$P_{WT} = \frac{1}{2}\rho A V^3 C_p$$

The total renewable power generated is
$P_{RE} = P_{PV} + P_{WT}$

The available renewable power is compared with the load demand using
$\Delta P = P_{RE} - P_{Load}$
where P_{Load} is the consumer demand. Energy utilization and microgrid stability are enhanced by a positive ΔP, which means that there is more renewable energy available to charge batteries or export to the grid, while a negative ΔP means battery discharge, DG support or utility grid assistance.

3.4. Excess Power Storage Strategy
The surplus renewable energy storage approach is an effective way to store renewable energy such as PV and wind sources that go to the BESS rather than being curtailed. The stored energy is released during times of low renewable generation or peak load demand to keep the power supply continuous and minimize reliance on DGs and the utility grid.

The EMC continually monitors the surplus power and battery SOC to optimize charging and discharging to maximize energy efficiency and microgrid stability.

The excess renewable power available for storage is calculated as
$P_{Excess} = P_{RE} - P_{Load}$

The battery charging power is determined by
$P_{Charge} = \min\left(P_{Excess}, P_{BESS}^{max}\right)$

The battery SOC is updated as

$$SOC_{t+1} = SOC_t + \frac{\eta_c P_{Charge} \Delta t}{E_B^{max}}$$

The battery discharge power during energy deficit is expressed as

$$P_{Discharge} = \min\left(P_{Load} - P_{RE}, P_{BESS}^{avail}\right)$$

where P_{BESS}^{max} and P_{BESS}^{avail} represent the maximum charging and available discharge capacities of the battery, respectively. Battery discharge is permitted only when $SOC > SOC_{min}$, ensuring safe battery operation while minimizing renewable energy curtailment and improving overall microgrid reliability.

3.5. Adaptive Distributed Energy Resource (DER) Dispatch

Adaptive DER dispatch optimally distributes power between renewable resources, BESS, DGs, and the utility grid to ensure stable microgrid operation and power balance. The EMC will continually monitor renewable energy production, battery SOC and load demand, and then make dispatch decisions. Renewable energy is used as the first source of power supply, followed by power stored in batteries, distributed generation, and utility grid power supply, thus providing a reliable power supply at minimal operation cost and better energy efficiency.

The total power supplied to the load is expressed as

$$P_{Generation} = P_{PV} + P_{WT} + P_{BESS} + P_{DG} + P_{Grid}$$

where P_{PV}, P_{WT}, P_{BESS}, P_{DG}, and P_{Grid} represent the power supplied by photovoltaic panels, wind turbines, battery storage, DGs, and the utility grid, respectively.

The power balance constraint is maintained as

$$P_{Generation} = P_{Load} + P_{Loss}$$

where P_{Load} is the consumer load demand and P_{Loss} denotes the system power losses.

The battery discharge condition is defined by

$$P_{BESS} = \begin{cases} P_{Discharge}, & SOC > SOC_{min} \\ 0, & SOC \leq SOC_{min} \end{cases}$$

where SOC_{min} is the minimum allowable battery SOC.

If renewables generation and battery output is not enough, then the output of the DGs is switched on:

$$P_{DG} = \max\left(0, P_{Load} - P_{PV} - P_{WT} - P_{BESS}\right)$$

Finally, the utility grid supplies the remaining unmet demand as

$$P_{Grid} = \max\left(0, P_{Load} - P_{PV} - P_{WT} - P_{BESS} - P_{DG}\right)$$

The adaptive dispatching strategy is designed to dynamically optimize all available energy resources to provide uninterrupted power service, minimize operational cost, reduce renewable energy curtailment, and enhance voltage stability and overall microgrid reliability under different operating conditions.

3.6. Intelligent Energy Management Controller (EMC)

The proposed framework's central decision-making unit is the Intelligent EMC, which coordinates all microgrid components. It is always monitoring renewable energy generation, battery SOC, load demand, DGs, and utility grid state, to make sure power is handled effectively. The EMC schedules charging/discharging of batteries based on real-time operating conditions, dispatches DERs, and manages power exchange with the utility grid. The controller operates by optimally balancing the power generation and consumption, which helps to lower the operating cost, decrease renewable energy curtailment, and improve the stability, reliability, and overall performance of the microgrid under dynamic operating conditions.

The power mismatch monitored by the controller is calculated as

$$\Delta P = P_{Generation} - P_{Load}$$

where $P_{Generation}$ is the total generated power from all available sources and P_{Load} is the total consumer demand.

The control decision for battery operation is expressed as

$$P_{BESS} = \begin{cases} P_{Charge}, & \Delta P > 0 \\ P_{Discharge}, & \Delta P < 0 \end{cases}$$

where positive power imbalance causes battery charging and negative causes battery discharging.

The EMC continually optimizes the power allocation to the renewable generation, the remaining battery SOC and load demand to maintain stable microgrid operation.

3.7. Microgrid Stability Enhancement

Microgrid stability enhancement is accomplished by keeping a constant power generation/load relationship under changing operating conditions. The proposed intelligent energy management framework plays a vital role in enhancing system stability by coordinating renewable energy sources, BESS, DGs, and utility grid support using adaptive dispatch.

The EMC helps to reduce voltage and frequency fluctuations, as it reacts to sudden shifts in renewable energy production and consumer demand. Renewables curtailment, battery cycling, and reliable power delivery can be reduced through proper coordination of energy resources available.

The power balance condition for stable operation is expressed as

$$P_{Generation} = P_{Load} + P_{Loss}$$

where $P_{Generation}$ is the total generated power, P_{Load} is the load demand, and P_{Loss} represents system losses.

The voltage deviation is calculated as

$$\Delta V = V_{ref} - V_{actual}$$

where V_{ref} is the reference voltage and V_{actual} is the measured bus voltage.

The frequency deviation is determined by

$$\Delta f = f_{ref} - f_{actual}$$

where f_{ref} is the nominal system frequency and f_{actual} is the measured operating frequency. Maintaining minimum voltage and frequency deviations ensures stable, reliable, and efficient microgrid operation.

3.8. Simulation and Performance Evaluation

The proposed intelligent energy management framework is tested and validated with MATLAB/Simulink with various operating cases such as normal load, peak demand, excess renewable generation, and deficiency of renewable generation. The system performance is evaluated with respect to utilization of renewable energy, operational cost, battery SOC, voltage stability and power losses.

A conventional energy management approach is compared to the effectiveness of the proposed framework.

The renewable energy utilization is calculated as

$$\eta_{RE} = \frac{P_{RE}}{P_{Load}} \times 100$$

where P_{RE} is the renewable power supplied to the load and P_{Load} is the total load demand.

The operational cost is determined by

$$C_{Total} = C_{Grid} + C_{DG} + C_{BESS}$$

where C_{Grid}, C_{DG}, and C_{BESS} represent the costs associated with utility grid power, DG operation, and battery energy storage, respectively.

The outcomes demonstrate the feasibility of the proposed framework to achieve the objectives of better utilization of renewable energy sources, lowering operational costs, and boosting the overall stability of the microgrid.

IV. RESULTS AND DISCUSSION

The proposed intelligent energy management scheme was tested in the MATLAB/Simulink environment with various operating conditions. The simulation results were contrasted to the results obtained from a conventional EMS in order to evaluate the enhancements in using renewable energy, battery performance, operational cost, voltage and frequency stability and power loss.

The results achieved show the efficiency of the proposed framework in improving the overall performance and stability of the microgrid. The simulation was conducted under the same operating conditions for the conventional EMS and the proposed framework for a fair performance comparison.

4.1. Renewable Energy Utilization Analysis

Table 2 shows the performance comparison between conventional Energy Management System (EMS) and proposed intelligent energy management framework. The proposed framework has the potential to increase the utilization of renewable energy from 78.4% to 93.7%, and operational cost reduction from $128.6/day to $101.8/day.

The battery utilization improves to 88.4% from 69.5% while the voltage deviation decreases to ±2.9 V from ±7.6 V and frequency deviation reduces to ±0.08 Hz from ±0.32 Hz.

Moreover, the power loss reduces from 8.4 kW to 4.1 kW, leading to a better microgrid stability index of 98.1%.

Table 2. Performance Comparison of the Proposed Energy Management Framework

Parameter	Conventional EMS	Proposed Framework
Renewable Energy Utilization (%)	78.4	93.7
Operational Cost ($/day)	128.6	101.8
Battery Utilization (%)	69.5	88.4
Voltage Deviation (V)	7.6	2.9
Frequency Deviation (Hz)	±0.32	±0.08
Power Loss (kW)	8.4	4.1
Microgrid Stability Index (%)	90.8	98.1

The utilization of renewable energies by the conventional EMS and the proposed intelligent energy management framework is shown in Figure 2. The traditional EMS can use 78.4% of the renewable energy, while the proposed EMS can utilize 93.7% of renewable energy by using intelligent energy storage and adaptive DER dispatch. The improvement highlights the framework's capability of optimising use of the renewable energy, reducing energy curtailment, and optimising the operational efficiency and stability of the microgrid. In general, the proposed framework shows the better performance than the traditional EMS.

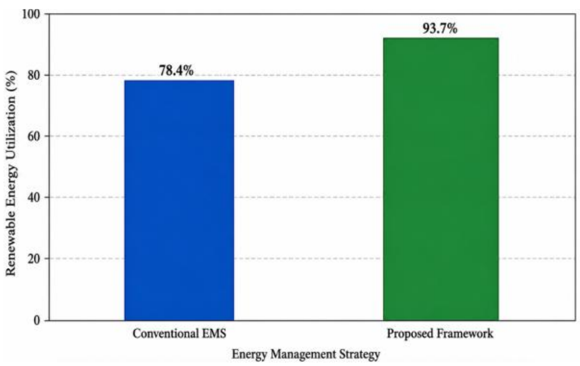

Figure 2. Renewable Energy Utilization Comparison between Conventional EMS and Proposed Framework

4.2. Battery Energy Storage Performance

The results of battery charging and discharging with various operating conditions are shown in Table 3. In low load mode, 118 kWh energy is stored in the battery and 26 kWh is discharged, resulting in a high SOC of 90%. The charging/discharging of 82 kWh/65 kWh, under normal load, gives an SOC of 74%. In peak load and renewable deficit condition, the battery discharge is 122 kWh and 146 kWh, respectively, which leads to the SOC getting down to 48% and 28% respectively, hence enabling uninterrupted power supply.

Table 3. Battery Charging and Discharging Performance

Operating Condition	Battery Charging (kWh)	Battery Discharging (kWh)	SOC (%)
Low Load	118	26	90
Normal Load	82	65	74
Peak Load	34	122	48
Renewable Deficit	12	146	28

The Battery SOC change is shown in different operating conditions that are shown in Figure 3. During the low-load condition, the charging rate is maximum and the SOC is the highest at 90%. With increased load demand, SOC drops to 74% under normal load and even more under peak load (48%) due to increased discharging of the battery. If the condition is renewable deficit, the SOC is 28%, which shows the strong use of the battery to handle the load. The results show that the proposed battery management strategy can provide stable and reliable power supply, optimize use of battery resources, and outperform the traditional method under various operating conditions.

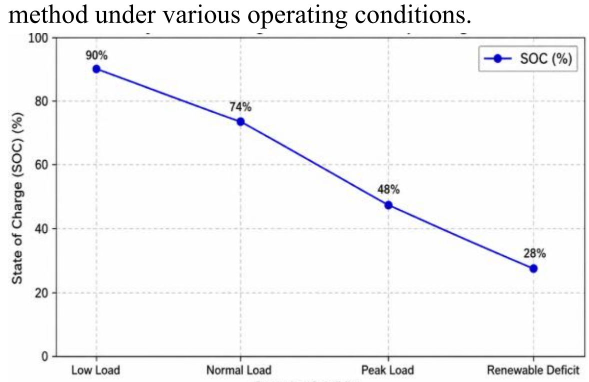

Figure 3. Battery SOC under Different Operating Conditions

4.3. Microgrid Stability and Economic Performance

Table 4 shows the performance of voltage and frequency stability for conventional EMS and the proposed intelligent energy management framework. The proposed framework results in a lower voltage deviation of 7.6V to 2.9V which shows better power quality and a lower frequency deviation of ±0.32Hz to ±0.08Hz. In addition, the response time is decreased by 178 ms to 142 ms, and the microgrid stability index is increased from 90.8% to 98.1%, indicating better system stability, quicker control response, and more stable microgrid operation under different load conditions.

Table 4. Voltage and Frequency Stability Analysis

Parameter	Conventional EMS	Proposed Framework
Voltage Deviation (V)	7.6	2.9
Frequency Deviation (Hz)	±0.32	±0.08
Response Time (ms)	310	142
Stability Index (%)	90.8	98.1

The operational cost of both the conventional EMS and proposed intelligent energy management framework is compared in Figure 4. The conventional EMS runs at $128.6/day, while the proposed framework lowers this cost to $101.8/day by implementing smart excess power management and adaptive dispatch of DERs. This cost-saving effect comes when renewable energy is used to its full potential, battery charging and discharging is optimized, and the need for DGs and utility grid energy is minimized.

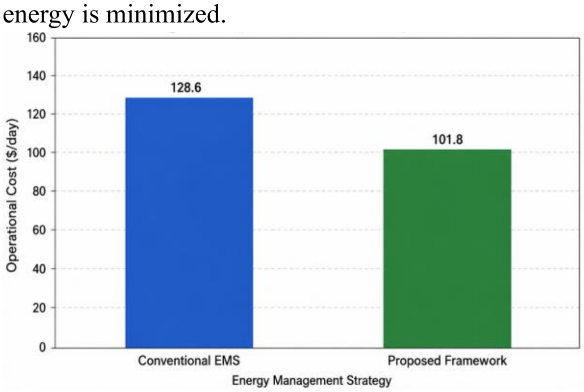

Figure 4. Operational Cost Comparison between Conventional EMS and Proposed Framework

The power loss comparison of conventional EMS with the proposed intelligent energy management framework is shown in Figure 5. It shows that the conventional EMS has a loss of 8.4kW while the proposed framework is 4.1kW that is a high energy efficiency gain. This is accomplished by optimizing battery usage, through intelligent excess power storage, and by optimized dispatch of DERs. The proposed framework can thus reduce the transmission losses, increase the power delivery efficiency, and increase the overall stability and reliability of the microgrid. The proposed framework always shows better stability, cost, and energy efficiency than the conventional EMS.

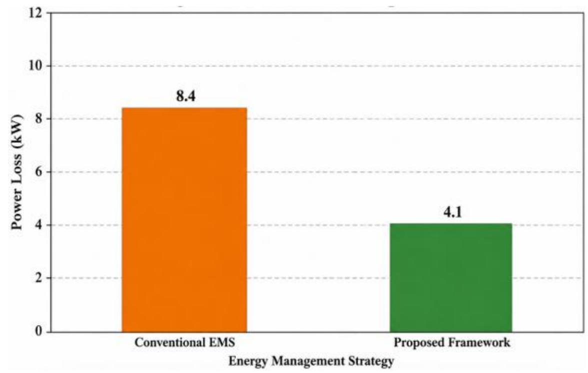

Figure 5. Power Loss Comparison between Conventional EMS and Proposed Framework

In summary, the simulation outcomes prove that the suggested intelligent energy management system is successful in increasing the use of renewable energy, optimizing battery operation, lowering the operational expenses and power losses, and boosting the voltage stability and reliability of microgrids. The improvements validate the superiority of the proposed framework over the conventional Energy Management System, operating under various conditions.

V. CONCLUSION AND FUTURE SCOPE

In this study, an intelligent EMS is proposed to improve the stability of the microgrid by strategically storing excess renewable generation and intelligently dispatching DERs. The proposed scheme is able to effectively combine PV systems, wind turbines, BESS, DG systems, and grid support under the control of an intelligent EMC. Through continuous monitoring of renewable generation, battery SOC and load demand, the controller intelligently controls power flow, optimises charging and discharging of the battery and effectively dispatches all available energy resources. The results from simulations performed in the MATLAB/Simulink environment show substantial gains over the traditional Energy Management System (EMS). The utilization of renewable energy was raised from 78.4% to 93.7%, the operational cost was reduced from $128.6/day to $101.8/day, and the power loss was reduced from 8.4 kW to 4.1 kW. Moreover, the voltage deviation was reduced from 7.6 V to 2.9 V, frequency deviation was improved from ±0.32 Hz to ±0.08 Hz, and the stability index of the microgrid was raised from 90.8% to 98.1%. The results demonstrate the framework's effectiveness in improving energy efficiency, operation reliability, and microgrid stability, and its support of sustainable integration of renewable energy.

Artificial intelligence-based predictive control, integration with electric vehicles and real-time hardware implementation could be explored in future work to enhance performance further.

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