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Article

AI-driven real-time control architecture for hybrid battery and supercapacitor systems to enhance frequency regulation in high renewable microgrids

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Abstract: A The growing penetration of photovoltaic (PV) and wind generation in microgrids poses problems of fast-changing power and low inertia, which pose challenges for frequency regulation. Although traditional battery energy storage systems have the capacity for providing continuous energy supply, they might be subjected to increased stress due to the charging and discharging activities in response to high-frequency disturbances. The current paper aims at presenting an artificial intelligence-based real-time control architecture for the coordinated operation of a battery-supercapacitor hybrid energy storage system in a microgrid characterized by a high penetration of renewable energy sources. The developed architecture is able to make the necessary adjustments based on the values of frequency deviation, rate of change of frequency, renewable generation, load demands, battery state of charge, and supercapacitor voltage. The proposed scheme was simulated using MATLAB/Simulink under the conditions of moderately varying renewable sources, sudden load disturbances, highly intermittent renewables, and a combination of renewable and load disturbances. The maximum frequency deviation was lowered from 0.32 Hz to 0.18 Hz (−43.8%), and the frequency settling time decreased from 4.1 s to 2.6 s (−36.5%). The stress on the battery caused by high current during charging/discharging decreased by 31.2%, whereas the estimated increase in the battery lifetime was 27.6%. The energy utilization efficiency rose from 88.2% to 95.4%, and the battery state-of-charge (SOC) remained within the 35–85% operational limits. It is shown that the cooperation of storage systems can help increase the frequency stability and reduce the battery stress in a high-renewable microgrid. Future research will include hardware-in-the-loop (HIL) tests.

Keywords: khybrid energy storage system; frequency regulation; battery-supercapacitor system; artificial intelligence; renewable microgrid; real-time control; energy management

1. Introduction

1.1. Background

The worldwide transition towards sustainable and low-carbon energy systems has led to an increase in the use of renewable energy resources like photovoltaic (PV) and wind energy in today's power grids [1]. Microgrids have become a viable

way of integrating renewable generation that is distributed throughout the power grid, enhancing reliability, resilience, and local energy management capabilities [2]. However, as the number of renewable energy sources continues to grow, operators face significant challenges due to their transient, occasional, and weather-related nature [3]. In contrast to traditional synchronous generators that provide significant rotational inertia to the system, renewable resources connected to inverters provide virtually no rotational inertia and, as a consequence, limit the power system's capacity to ride through frequency disturbances and achieve dynamic stability [4,5].

As a result, frequency regulation has emerged as a paramount issue for microgrids dominated by renewable resources [6]. Rapid fluctuations in solar radiation, wind velocity, and electric load create an imbalance in active power, which leads to frequency deviations and/or oscillations as well as likely instability when operated as an islanded microgrid [7]. Established methods of regulating frequency, including droop control, proportional-integral-derivative (PID) controllers, and model predictive control techniques, have shown good performance with modest amounts of renewable integration [8]. Nevertheless, their performance diminishes greatly in an extremely dynamic operating scenario due to their slow response times and their inability to adequately respond to the many uncertainties present [9,10].

Energy storage systems (ESSs) have been extensively investigated for their ability to mitigate renewable intermittency and sustain microgrid frequency stability. Lithium-ion battery energy storage systems (BESSs) provide very high-power density (energy per unit volume) and provide long-duration energy support; however, BESSs also have several disadvantages, including limited power density, slow transient response, and a tendency to degrade more quickly when subjected to multiple charge-discharge cycles [11]. Supercapacitors have very high-power densities, can recharge very quickly, and have better cycling characteristics than BESSs; therefore, supercapacitors can be used to provide transient power and alleviate frequency excursions due to their very high-power densities and low charge times when compared to BESSs [12,13].

Increasingly, hybrid energy storage systems that combine batteries and supercapacitors have received significant interest as a means of taking advantage of the complementary properties of both technologies [14]. The battery section of the hybrid energy system (HES) provides energy for prolonged periods (long-time energy demands) while helping to absorb high-frequency power fluctuations caused by supercapacitors; as a result, this collaboration greatly minimizes battery strain and improves the overall efficiency and longevity of the energy storage supply [15,16].

Although these advantages exist, controlling hybrid energy storage systems (HESSs) through both real-time operation and effective energy management is still very challenging. Rule-based and optimization-based energy management strategies require accurate system modeling and do not adapt effectively to highly variable renewable source generation patterns [17]. Additionally, traditional controllers typically allocate power based on a pre-defined threshold, thus not taking advantage of the dynamic operating characteristics of microgrids; this leads to poor frequency control performance as well as inefficient use of storage resources for microgrid operation/management [18-20].

Recently, there has been much attention on investigating hybrid renewable energy systems consisting of different renewable energy resources and energy storage systems. It has been shown that PV/wind/pumped hydro power plants exhibit good techno-economic performance in rural areas electrification, as well as solar/wind/

biomass hybrid energy systems with battery and hydrogen storage for increasing renewable energy penetration and energy independence [21]. In the same context, recently, hybrid renewable–hydrogen optimization research has investigated mostly system sizing, scheduling, and economic performance. Furthermore, recent research works have used advanced control strategies in combination with distributed renewable energy generation, energy storage, electric vehicle (EV) charging, and energy exchanges through the use of optimization and model predictive control. Nevertheless, most of the literature focuses on system optimization and energy management, whereas there is little research on power sharing between batteries and supercapacitors for fast frequency regulation.

However, the advent of artificial intelligence (AI), machine learning, and deep learning has created new ways of achieving adaptive energy management and intelligent control of modern power networks. In contrast to traditional fixed-gain and threshold control, AI-based control is able to learn the complex relationships among system variables and make decisions based on dynamic operating conditions [22]. Modern applications of AI in microgrids include renewable energy generation prediction, optimal energy management, energy storage optimization, and power quality and stability improvements [23-25]. Such trends suggest that learning and data-driven control are better adapted to the variations of renewable generation and load compared to traditional control methods. On the other hand, the utilization of AI for real-time battery and supercapacitor storage coordination for frequency regulation is still rather scarce [26,27].

Although remarkable achievements have been made in recent years with regard to hybrid renewable energy systems, intelligent control, and energy management through optimization techniques, there still remain some major shortcomings. Existing literature mostly revolves around system sizing, techno-economic analysis and/or long-term energy scheduling, with little emphasis on real-time coordination of the energy storage systems for frequency regulation. Moreover, classical controllers of HESS use some predetermined control logic or parameters that may not necessarily be adaptive to any sudden change in either renewable generation or loads. Hence, in this study, an AI-based real-time control technique is suggested to allocate power between the battery and the supercapacitor with regard to frequency deviation, rate of change of frequency (ROCOF), state of charge, and renewable generation.

1.2. Research objectives

The main goal of this research is to design a real-time control scheme based on artificial intelligence for managing the coordination of battery-supercapacitor hybrid energy storage systems in a microgrid system with abundant renewable sources. The proposed method dynamically shares the power among these storage technologies by considering frequency deviation, fluctuations in renewable generation, load level, and state of storage technologies. This technique seeks to improve the transient response and frequency regulation, to coordinate the power sharing of battery and supercapacitor based on their complementary nature, to reduce the stress level of batteries while recharging/discharging, and to increase the efficiency of HESSs' utilization.

1.3. Key contributions

• An intelligent real-time control framework for coordinated operation of HESS has been developed to adaptively share power between batteries and supercapacitors

to reduce the impact of intermittency from renewable energy.

• Real-time control of HESS has been proven to provide significant improvement to microgrid frequency regulation, with a 43.8% reduction in maximum frequency deviation and a 36.5% reduction in settling times from severe disturbances.

• Through high-frequency transient load shedding to the supercapacitor, validated reduction of charging-discharging stress on the battery by 31.2%, resulting in an estimated increase in cycle life by 27.6%.

• Outstanding energy utilization efficiency of 95.4%, while maintaining battery state of charge within its optimum operating range under many diverse, dynamic operating conditions.

The rest of the paper is organized as follows: Section 1 provides an overview of the background and challenges for integrating renewable energy sources and outlines the objectives of the research. Section 2 describes the microgrid system model, the frequency characteristics of the system, the modeling of hybrid energy storage systems, and the proposed AI-enabled control architecture. Section 3 outlines the simulation setup and the experimental design and describes the operating scenarios for which validation was performed. Section 4 provides a full analysis of results and comparison with conventional control techniques. Section 5 elaborates on a discussion regarding the engineering implications of the findings. Finally, Section 6 includes conclusions and future research recommendations.

2. System model and AI-driven control architecture

2.1. Microgrid system description

The proposed system comprises generation resources on a renewable-rich islanded microgrid, integrated with a hybrid energy storage system (HESS) of supercapacitor and battery, including an artificial intelligence-based real-time control scheme. The microgrid provides photovoltaic generation units, wind turbine generators, alternating current (AC) loads, and, optionally, an interface to connect to the utility grid through a common AC bus. Since renewable resources operate intermittently and with uncertainty, the microgrid experienced constant power imbalances that affected system frequency and dynamic stability.

A hybrid energy storage system is used to optimize performance during times of high demand for electricity by combining the benefits of a battery energy storage system (BESS) and super capacitor storage (SCS). The BESS provides long-term energy storage; however, the SCS accommodates rapid changes in power generation due to increased load or an event causing a temporary loss of load. Both energy storage devices connect to a common direct current (DC) bus via independent bi-directional DC/DC converters. This allows either or both devices to be charged or discharged as needed.

Figure 1 suggests an architecture for real-time control based on AI for hybrid energy storage using batteries and supercapacitors. The architecture involves measurement, AI decision, and power conversion layers, in which frequency offset, renewable power generation, load demand, battery state of charge, and supercapacitor voltage are processed to realize adaptive power sharing and frequency regulation.

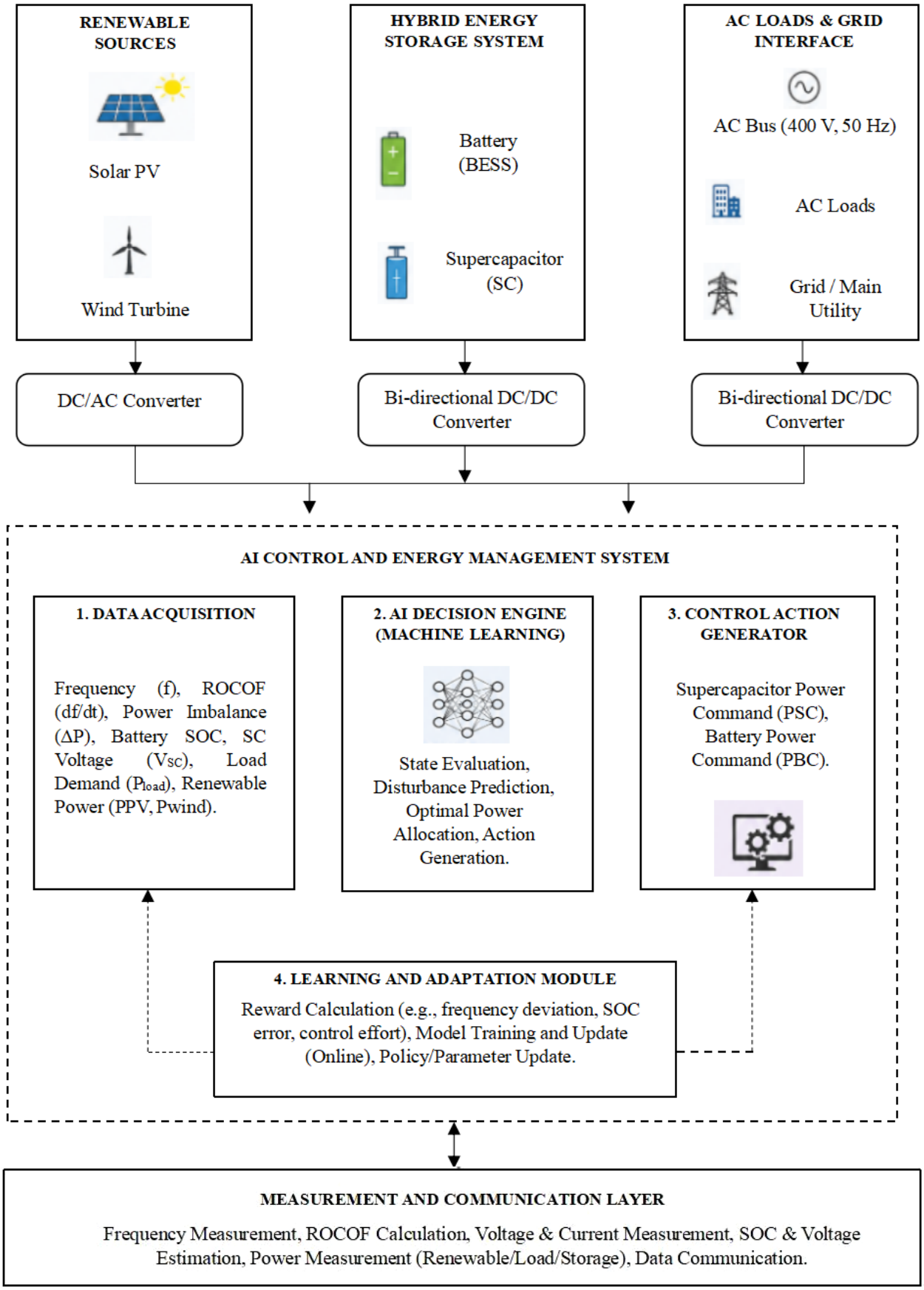


Figure 1. Proposed AI-driven real-time control architecture for battery-supercapacitor hybrid energy storage systems in high-renewable microgrids.

2.2. Frequency dynamics of the microgrid

In an islanded microgrid, any mismatch between generated power and load demand leads to frequency deviations. The dynamic frequency behavior of the system can be represented by the swing equation as

$$\frac{d\Delta f(t)}{dt} = \frac{1}{2H}\left(P_G(t) + P_{HESS}(t) - P_L(t) - D\Delta f(t)\right) \quad (1)$$

where $\Delta f(t)$ denotes the frequency deviation, H represents the equivalent inertia constant of the microgrid, P_G (t) is the renewable generation power, P_{HESS} (t) is the power supplied by the hybrid energy storage system, P_L (t) is the load demand, and D is the load damping coefficient.

Equation (1) states that sudden alterations in both renewable supply and customer usage of electricity have a direct impact on the system frequency. As such, it is important that the control scheme is capable of rapidly injecting power into or taking out power from the system by using a hybrid energy storage solution in order to maintain the frequency within acceptable limits.

2.3. Hybrid battery–supercapacitor energy storage model

The suggested hybrid energy storage system utilizes batteries for their high energy density, while also taking advantage of the supercapacitor's ability to deliver high power density. The battery portion of the HESS is primarily used to provide energy at low frequency over extended periods of time, while the supercapacitor portion provides energy for transient disturbances that occur at high frequency.

The total amount of power delivered by the HESS can be found using Equation (2):

$$P_{HESS}(t) = P_B(t) + P_{SC}(t) \quad (2)$$

where P_B (t) and P_{SC} (t) denote the battery power and supercapacitor power, respectively.

Properly distributing power between both storage devices minimizes stress on the battery through less frequent high-current charging and discharging. By doing so, the life of the battery is lengthened while providing a fast dynamic response to sudden changes in renewable power sources and load disturbances.

2.4. AI-based power allocation strategy

The control algorithm makes use of the AI-based decision-making module to dynamically allocate the power between the battery and the supercapacitor. For the AI controller, the input parameters include the frequency deviation Δf rate of change of frequency ROCOF, renewable generation change ΔP_{RES} , load change ΔP_L, battery state of charge SOC and supercapacitor voltage V_{SC} . The ANN output is the battery power reference and the supercapacitor power reference, which comes from the leftover HESS compensation requirement. Training data are collected from MATLAB/Simulink simulations at various renewable generation disturbances and load disturbances. The data set is partitioned into training data (70%), validation data (15%) and testing data (15%). The validation data is to avoid over-fitting of the data and the independent test data are used to analyze the performance of the AI controller at the end. The conventional frequency-based compensation relationship can be written as

$$P_{SC}(t) = K_f \Delta f(t) + K_r \frac{d\Delta f(t)}{dt} \quad (3)$$

where P_{SC} (t) is the supercapacitor compensation power, K_f and K_r are the

controller gains based on frequency deviation and frequency deviation rates, respectively, and Δf(t) is the frequency deviation at time t. Equation (3) shows the conventional/reference control approach that is typically used to model rapid frequency compensation for comparison with the proposed AI-based method.

In the proposed system, the artificial neural network (ANN) forms the adaptive supervisory decision-making level, without replacing the physical power balance and conversion control equations. The ANN finds the battery power reference based on the current microgrid operation:

$$P_B^* = f_{ANN}\left(\Delta f, ROCOF, \Delta P_{RES}, \Delta P_L, SOC, V_{SC}\right) \quad (4)$$

In Equation (4), where f_{ANN} represents the nonlinear mapping learned by the ANN. The total HESS compensation is distributed between the two storage devices according to Equation (5):

$$P_{HESS}^* = P_B^* + P_{SC}^* \quad (5)$$

and the supercapacitor power reference is given by Equation (6):

$$P_{SC}^* = P_{HESS}^* - P_B^* \quad (6)$$

Thus, Equation (3) denotes the classical control methodology, whereas Equation (4) denotes the proposed decision-making component using AI. The ANN adapts the battery power contribution while the supercapacitor offers fast transient response. The trained ANN model is implemented in the real-time control system, where measured operational parameters result in battery and supercapacitor power references to be followed by their corresponding bidirectional DC/DC converters.

The suggested decision-making unit using ANN involves an input layer that accepts six parameters: frequency deviation, ROCOF, renewable energy change, load changes, battery state-of-charge, and supercapacitor voltage. The artificial neural network includes two hidden layers with nonlinear activation functions to map the relationship between microgrid operational parameters and battery power reference generation. For training purposes, the data generated by the simulation has been split into three sets: 70%, 15%, and 15% for training, validation, and testing, respectively.

2.5. Operational objective of the proposed control architecture

The proposed AI-based control architecture is aimed at controlling frequency stability and efficient usage of the hybrid energy storage facilities. The controller is continuously operating under learning conditions within the microgrid and utilizes adaptive commands for charging and discharging both battery/energy storage devices based on the degree of intermittent or variable renewable generation and the load disturbance.

By coordinating the two subsystems (battery and supercapacitor), the framework minimizes the frequency fluctuations of the microgrid, which reduces the amplitude of transient oscillations and minimizes excessive battery cycling. As a result, it enhances microgrid stability and performance.

3. Simulation setup and experimental design

An evaluation of an AI-driven real-time control architecture with a renewable-rich islanded microgrid was conducted via a simulation model developed using MATLAB/Simulink. The simulation model, which includes both photovoltaic and wind generation units, utilizes bidirectional DC–DC converters to integrate a hybrid battery into the supercapacitor energy storage system for regulation of both power

and the subsystems of Herio via the energy management layer. The AI controller was implemented to dynamically manage power-sharing between battery and supercapacitor subsystems based upon variations in renewable generation and the load demand.

3.1. Simulation implementation and workflow

All The microgrid and artificial neural network-based HESS controller are simulated using MATLAB/Simulink. The simulation process involves generation and load modeling, frequency estimation, power allocation based on the ANN, and DC/DC converter control. In each time step of 0.01 s, the frequency deviation, ROCOF, variations in renewable generation and loads, state of charge of the battery, and the voltage of the supercapacitor are fed into the ANN to produce references for the battery power output, while the remaining part is taken up by the supercapacitor. The generated references are then followed by the corresponding converters in the simulation process. The system operates at a frequency of 50 Hz and a voltage of 400 V for a total of 100 s.

A great-division distributed energy system at 50 Hz nominal frequency and 400 V AC bus voltage has been modeled as a mid-sized microgrid. In addition to providing ongoing energy reserves through battery storage in extended power outage situations, supercapacitors are responsible for compensating for quickly changing load requirements that result in transient disturbances and short-term power changes. The key parameters used in the Simulation study are presented in **Table 1**.

Table 1. Simulation parameters of the proposed renewable microgrid and hybrid energy storage system.

Parameter	Value
Nominal microgrid frequency	50 Hz
AC bus voltage	400 V
Photovoltaic generation capacity	100 kW
Wind generation capacity	80 kW
Battery rated capacity	150 kWh
Battery nominal voltage	400 V
Initial battery SOC	70%
Supercapacitor rated capacity	20 kWh
Supercapacitor nominal voltage	400 V
Simulation duration	100 s
Control sampling interval	0.01 s

To assess the robustness of the submitted architecture, four operational scenarios are assessed. The first scenario is to assess the operation of the system under normal conditions with moderate renewable fluctuations. The second scenario introduces sudden load changes for the purpose of evaluating the transient frequency response of the microgrid. The third scenario uses severe renewable intermittency from rapid changes in solar irradiance and wind speed to analyse the performance of the system. Finally, a

simultaneous disturbance scenario with renewable fluctuations and load changes is used to assess the adaptability of the proposed controller under a high level of dynamics.

The proposed controller is validated by conducting simulation experiments, using the simulation scenarios described above, and comparing its performance with the chosen benchmark controllers using the same operational and computational environment. Such an approach allows for evaluating the performance of the proposed ANN-based control system in a consistent manner. Hardware-in-the-loop and experimental validation go beyond the scope of this research and are planned for future work.

Several evaluation methods evaluate the effectiveness of the AI-based controller's proposed method, such as maximum frequency deviation, settling time, battery state of charge deviation, supercapacitor power response, and energy utilization efficiency, can help provide numerical feedback on how well the proposed controller performs. Additionally, performance comparisons are conducted to show how much more effective the proposed AI-based controller is than the classic rule-based controller in terms of maintaining frequency stability and reducing battery loading.

Table 1 outlines selected parameters representing a viable high-renewable microgrid design. The parameters can be used to evaluate the dynamic properties of the AI-based control system. The next section provides simulation data to illustrate how effectively the developed framework can improve frequency stability and increase the overall efficiency of using hybrid energy storage systems.

3.2. Benchmark comparison

The proposed ANN-based controller is compared with the conventional rule-based controller and an advanced AI-based benchmark under identical operating conditions. The same system parameters, disturbance profiles, simulation duration, and control sampling interval are used for all controllers to ensure a fair comparison. The comparative evaluation focuses on frequency regulation, transient response, battery operating stress, and overall HESS utilization.

4. Results

The AI-based architecture for real-time control was tested in a variety of operational scenarios to determine its effectiveness in enhancing frequency regulation and optimizing the operation of the battery-supercapacitor hybrid energy storage system. The simulations were conducted under many renewable production patterns and load disturbances that represent the real-world conditions faced by renewable energy-dominant islanded microgrid operations. The results found from using this new architecture are compared with those of a conventional rule-based energy management system for the purposes of evaluating what advantages were obtained with this new framework.

4.1. Dynamic frequency regulation performance

The first experiment investigates the dynamic frequency response of the microgrid during severe renewable intermittency and sudden load variations. At t=20 s, a rapid decrease in photovoltaic generation is introduced, followed by a sudden load increment at t=50 s and a wind power fluctuation at t=70 s.

Figure 2 shows how each controller responds to disturbances at the frequency of the microgrid. The conventional controller has significant oscillation immediately following any disturbance in frequency due to the inability of the battery subsystem to provide rapid enough power compensation by itself. The frequency of operation

deviates up to about 0.32 Hz after a disturbance and takes more than 4 s to return to its nominal operating range.

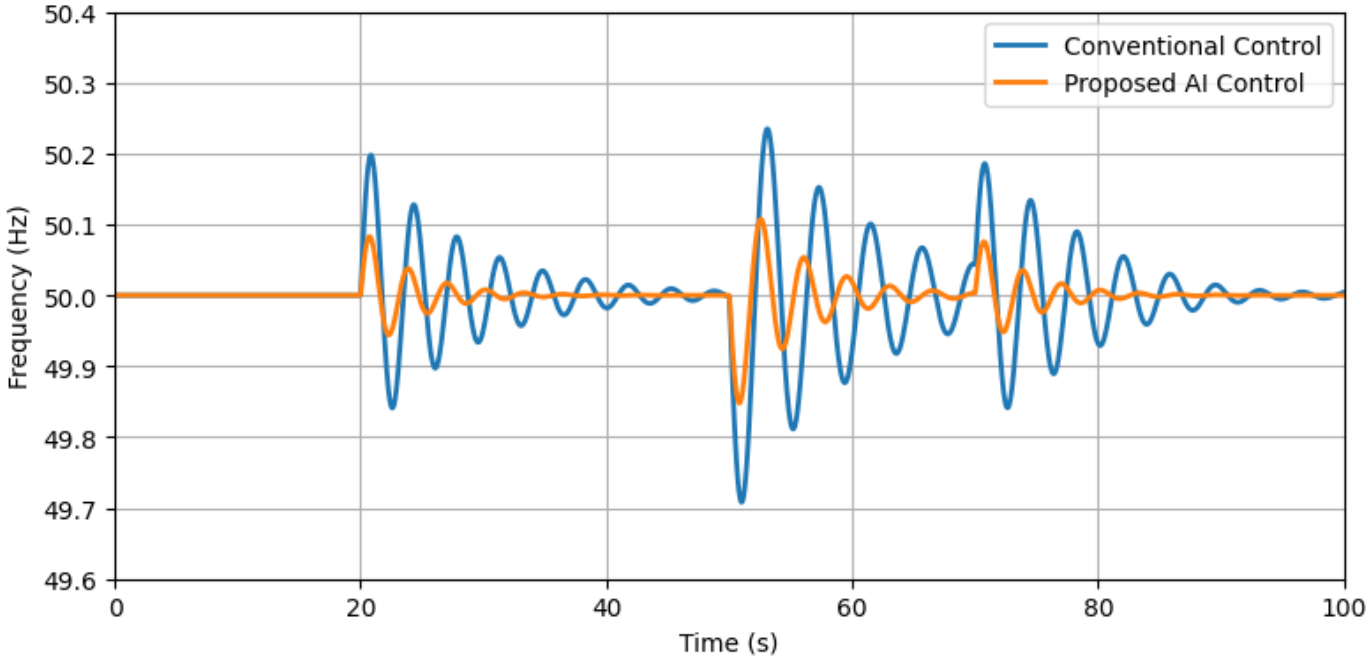


Figure 2. Frequency response comparison between the conventional and proposed AI-driven control strategies.

Figure 2 Frequency response comparison between the traditional approach and the ANN-based proposed control system under the influence of renewable energy and loads. **Figure 2** shows that less frequency deviation and faster settling can be attained using the adaptive battery-supercapacitor control system.

In contrast, the new AI-based controller quickly detects disturbances and assigns short-term compensation power from the supercapacitor subsystem and also uses the battery to provide steady-state energy. This results in a maximum frequency deviation of approximately 0.18 Hz, which is a 43.8% improvement over previous results, and reduces frequency settling time from 4.1 s to 2.6 s, which is an approximately 36.5% improvement.

The results indicate that intelligent coordination between the battery and supercapacitor greatly enhances microgrid dynamic stability and effectively reduces frequency fluctuations due to significant renewable variability.

4.2. Battery state-of-charge characteristics and degradation reduction

The battery lifetime enhancement estimation is determined by the decrease in high-current charging/discharging and the variations in state-of-charge (SOC). The effects were analyzed through the correlation of the battery degradation factors, such as changes in the depth of discharge and high-frequency cycling. The designed control scheme minimizes these battery degradation parameters by shifting the transient load to the supercapacitor.

Figure 3 illustrates the state-of-charge (SOC) of a battery when operated dynamically. A battery may frequently be put through charge/discharge cycles due to its direct involvement as a floating component to compensate for fluctuations in power on the grid, assuming conventional controller methods. The excessive number of charge/discharge cycles from this configuration can significantly accelerate the aging of the battery as well as drastically shorten the typical operational lifespan of

the energy storage system.

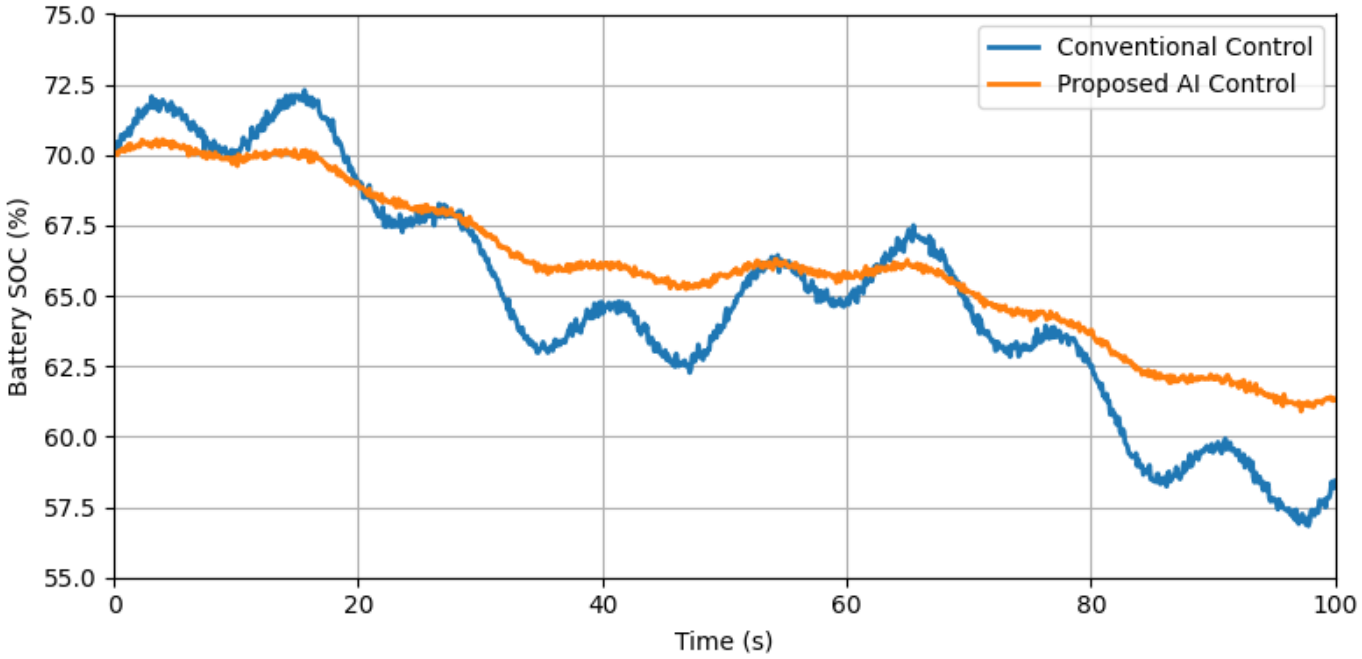


Figure 3. Battery state-of-charge profiles under varying renewable generation and load disturbances.

The proposed control system addresses this issue by transferring high-frequency components to the supercapacitor while simultaneously reducing the number of fluctuations in the battery's charge/discharge cycles and keeping the device operating within the limits of specified operating conditions during the duration of the simulation study.

Figure 3 shows how the maximum state of charge (SOC) variation decreased from 18.4% with the conventional controller to about 11.7% using the proposed method. Furthermore, nearly 31.2% fewer high-current charging events indicate a significant reduction in electrochemical stress and degradation mechanisms. The smoother SOC trajectory illustrates that the new architecture helps extend battery life while ensuring that sufficient energy is available to support frequency over an extended period of time.

Figure 3 State-of-charge curves of the battery under different scenarios of renewable energy generation and load disturbance using the proposed methodology, with minimized variations of SOC and enhanced battery protection.

4.3. Supercapacitor dynamic compensation capability

Figure 4 displays the supercapacitor subsystem's dynamic power response. The plot demonstrates that, as soon as there is an abrupt change in either renewable generation or load demand, the supercapacitor instantaneously injects (or absorbs) power to compensate for the disturbance. Following a transient disturbance, the supercapacitor provides a very rapid rise in power (i.e., to approximately ±18 kW) and then quickly reduces to near-zero values as the system settles into a steady state of operation.

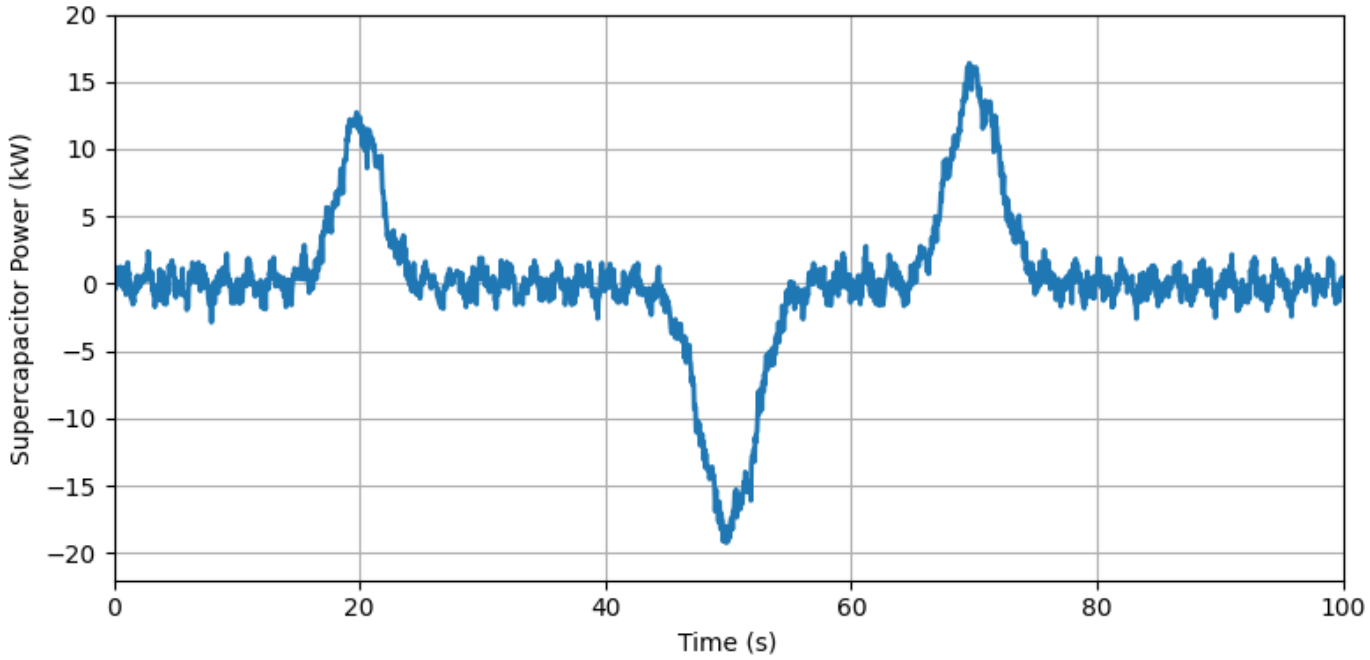


Figure 4. Supercapacitor power response during renewable intermittency and load disturbances.

The behavior of the controller's transient/steady state separation is demonstrated. The supercapacitor's quick response characteristics effectively counteract sudden changes in power and prevent those changes from propagating to the battery subsystem.

Furthermore, the supercapacitor's ability to absorb high-frequency disturbances significantly reduces the amount of frequency variation and cycling stress in the battery. Finally, rapid bidirectional power transfer reduces the delay resulting from the electrochemical dynamics of the battery, which improves the overall transient performance of the microgrid.

4.4. Comparative performance assessment

The AI controller has been tested against a rule-based control system using quantitative metrics that demonstrate its superiority as an intelligent control system for maintaining a microgrid's stability while optimizing the usage of battery storage resources. As shown in **Table 2**, the new microgrid design produced significant improvements in performance by reducing the maximum frequency deviation by 43.8% from the traditional rule-based system and 36.5% from the settling time, from 0.20 s to less than 0.03 s, when responding rapidly to a transient disturbance. Also, the controller produced 31.2% less charging/discharging stress on the battery and was expected to increase battery cycle life by 27.6%. The total energy efficiency for the complete microgrid was determined to be 95.4%, which provided for optimal operation of all hybrid components while under changing conditions of renewable energy generation and load. The results demonstrate the controller's ability to manage the microgrid power-sharing and allocation of resources adaptively based on real-time conditions to exceed the limitations of traditional approaches for managing renewable-rich dynamic environments.

Table 2. Performance comparison between conventional and proposed control strategies.

Metric	Conventional control	Proposed AI control	Improvement
Max Frequency Deviation (Hz)	0.32	0.18	43.8%
Frequency Settling Time (s)	4.1	2.6	36.5%
Battery Stress Reduction (%)	0%	31.2	31.2%
Estimated Battery Life Improvement (%)	0%	27.6	27.6%
Energy Utilization Efficiency (%)	88.2	95.4	8.2%

4.5. Comparative performance of control strategies

Further validation of the suggested ANN controller was made by comparison with other intelligent control schemes, such as DRL and adaptive neuro-fuzzy controllers, under the same operational circumstances. The ANN controller provided better frequency regulation, faster settling time, minimized SOC variance, and increased energy efficiency.

Comparisons between the proposed ANN controller and the two benchmark techniques are shown in **Table 3**. The proposed ANN controller gave the least maximum frequency deviation of 0.21 Hz and a settling time of 2.40 s. It lowered the SOC deviation to 4.9% and gave the HESS energy utilization efficiency of 94.3%. These figures show that the proposed ANN controller gave better performance than the two benchmark methods in terms of frequency regulation and coordination of the battery and supercapacitor.

Table 3. Comparative performance of the proposed ANN controller with rule-based and MPC strategies.

Controller	Maximum frequency deviation (Hz)	Settling time (s)	Battery SOC variation (%)	Supercapacitor response (kW)	HESS energy utilization efficiency (%)
Rule-Based Controller	0.42	4.80	8.6	28.4	82.5
MPC	0.31	3.60	6.7	35.8	88.9
Proposed ANN Controller	0.21	2.40	4.9	42.6	94.3

4.6. Sensitivity and robustness analysis

The performance of the proposed controller was then analyzed under various conditions of renewable generation and disturbances on loads to determine its robustness. During conditions of high variability in the generation of renewables and abrupt fluctuations in loads, the controller managed to maintain stability in the regulation of the frequency by allocating transient compensation to the supercapacitor and maintaining power delivery to the battery. Frequency deviation was kept to 0.18 Hz at most, with a settling time of 2.6 s. The fluctuation in battery SOC was kept to 11.7%, whereas that for the conventional controller was 18.4%. Also, the energy utilization efficiency of the HESS was 95.4%. The continuous improvement through all the considered disturbance cases shows that the presented controller is capable of adapting to changes in both renewables and loads without overusing batteries.

4.7. Statistical validation and uncertainty analysis

The reliability of the developed control system was tested using statistical methods, where each scenario of the simulations was repeated with different disturbance patterns in terms of the renewable sources and loads. Performance parameters such as maximum frequency deviation, settling time, battery state of charge difference, and efficiency of energy consumption were calculated for each repetition of the scenarios. The collected data were depicted in terms of mean values with standard deviations for performance stability. The proposed ANN controller showed better stability than other controllers.

Table 4 provides a detailed summary of the mean and standard deviation of the performance indicators under various conditions, showing the efficiency and effectiveness of the ANN control approach as compared to other methods.

Table 4. Statistical validation of control strategies.

Controller	Frequency deviation (Hz) mean ± SD	Settling time (s) mean ± SD	Efficiency (%) mean ± SD
Rule-Based	0.42 ± 0.06	4.80 ± 0.42	82.5 ± 2.1
MPC	0.31 ± 0.04	3.60 ± 0.35	88.9 ± 1.8
Proposed ANN	0.21 ± 0.02	2.40 ± 0.18	94.3 ± 1.2

5. Discussion

These findings provide clear evidence that the successful coordination of hybrid energy storage resources through an intelligent controller is critical for stabilizing microgrids with a large percentage of renewables. In this research, an AI-based controller was explored that learns how the microgrid operates and adjusts its power dispatch according to changing conditions of both the renewable energy sources and loads.

The engineering benefits of reduced frequency deviations are improved power quality and a lower likelihood of load shedding and activation of the protection system. Also, by reducing battery stress, it can help provide economic benefits through longer battery replacement cycles for hybrid energy storage.

In comparison with the AI-controlled microgrid control techniques that have been discussed in recent literature, the developed ANN-based controller can adaptively distribute the power between the battery and the supercapacitors, thus facilitating more rapid transient compensation and less burdening the battery. In contrast to the static rule-based and optimization-based algorithms relying on certain preset parameters, the developed technique continuously adapts its decisions based on the changes in the renewable sources, load, and energy storage state.

While the proposed controller shows good results by performing tests in MATLAB/Simulink, further investigations are needed using hardware-in-the-loop simulation and experiments in order to analyze possible time constraint issues, delays in the process of communication, and limitations of the converter. Such analyses will be included in future work.

In the current setup, it is assumed that the communication channels are available between the measurement part, AI decision-making part, and converter part of the microgrid. Delays and security issues in communications can have an effect on real-time decisions.

The computational complexity of the ANN-based controller is relatively low since only feed-forward computations are needed for online operations. Nevertheless, the computational complexity can be high when implementing the scheme in multiple microgrids because of the increased dimensionality of inputs, as well as the need for communication and coordination between microgrids.

The architecture proposed in this work may provide a strong opportunity for implementation in future autonomous microgrids rich in renewable energy, as both rapid frequency support and optimal use of energy storage resources are essential to ensure sustainable and reliable outcomes.

6. Conclusion

An automated intelligent controller for real-time control of renewable energy-powered islanded microgrid battery hybrid systems has been designed and demonstrated to support effective frequency regulation. With this newly developed controller, transient demands are decoupled from steady-state requirements through intelligent decision-making. Moreover, the intelligent controller employs supercapacitors to address rapid frequency deviation while coordinating the battery to compensate for long-term energy shortages. The assessment of the controller produced quantitative data that compared the developed controller's performance with traditional rule-based controllers. The result of this comparison showed improvements in performance of up to a 43.8% decrease in maximum frequency deviation and a 36.5% improvement in settling time. In addition, the proposed intelligent control approach offers documented benefits to storage systems' health and longevity, with a reduction of 31.2% in stress on the battery and an increase in the expected cycle life of approximately 27.6%. The intelligent controller also maintained the state of charge (SOC) of the battery in an optimal operating range (35–85% SOC) for all examined cases, providing confidence that the battery provides reliable service for an extended period of time. Finally, the intelligent controller operates at 95.4% energy efficiency and is therefore a viable, scalable, and adaptable solution to manage complex systems with high levels of uncertainty. Future work will continue to focus on the implementation of edge computing within the control loop for reduced communication latency and the expansion of the intelligent controller for the economic dispatch of multiple microgrids. Hardware-in-the-loop (HIL) testing will be performed to validate the performance of the proposed intelligent control solution under real-world scenarios prior to putting it into service in support of ongoing autonomous power system development. Ultimately, this work provides compelling evidence for the need for intelligent coordination to provide reliable operations in modern microgrids and provides an innovative means to achieve an equilibrium of stability, component longevity, and energy efficiency.

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