

Hybrid PSOGWO-MPPT Based Renewable BESS–STATCOM for Reactive Power Enhancement and Power Quality Improvement

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ABSTRACT

This research demonstrates a reactive power boosting technique for a Battery Energy Storage System (BESS) linked to a STATCOM using a single-stage power conversion system. The proposed technique improves reactive power injection even at low battery State of Charge (SoC) by briefly disconnecting the battery and charging the DC-link capacitor to its rated voltage. The principal input, which originates from renewable energy sources like solar PV and wind turbines, is efficiently harvested by a DC–DC boost converter employing a hybrid Maximum Power Point Tracking (MPPT) algorithm based on Particle Swarm Optimization–Grey Wolf Optimization (PSOGWO). Furthermore, the system employs a hybrid supercapacitor-battery configuration to control abrupt power swings, prolonging battery life and improving system reliability.

Sliding Mode (SM) and Synchronous Reference Frame (SRF) controllers are part of the control strategy to regulate the bidirectional energy flow between the

storage units, grid, and loads. MATLAB/Simulink simulation is used to evaluate reactive and active power flow, harmonic mitigation, voltage sag/swell response, total harmonic distortion (THD), and energy balancing under different load and renewable generating scenarios. The results show that the recommended approach maximizes energy utilization, maintains grid stability, significantly increases reactive power capability, and ensures efficient coordination between PV, storage, and STATCOM functions.

KEYWORDS: *Examples of index terms are Battery State of Charge (SoC), STATCOM, Battery Energy Storage System (BESS), Synchronous Reference Frame (SRF), and Sliding Mode (SM) controllers.*

1. INTRODUCTION:

Renewable energy sources, such as solar photovoltaic (PV) and wind systems, have become more incorporated into modern power grids due to their intermittent and variable nature. This has caused problems

with reactive power management, voltage regulation, and overall power quality. These oscillations can lead to harmonics, voltage instability, and reduced grid reliability, especially in subpar grid settings [1]. Battery Energy Storage Systems (BESS) in combination with Flexible AC Transmission System (FACTS) devices like STATCOMs offer an effective solution by providing dynamic reactive power assistance and active power balancing. However, because of insufficient DC-link voltage, low battery State of Charge (SoC) restricts the reactive power capability of standard BESS-STATCOM systems.

As part of a reactive power boosting technique that employs a single-stage power conversion system to solve this issue, the battery can be momentarily disconnected and the DC-link capacitor can be charged from renewable sources to maintain rated voltage. Because of this, STATCOM may operate continuously without depending on the battery SoC. In order to manage abrupt power fluctuations, reduce battery stress, extend battery life, and improve system reliability, a hybrid super capacitor–battery configuration is also employed.

2. OBJECTIVE :

The primary objective of this project is to develop an improved reactive power boosting approach for a Battery Energy

Storage technology (BESS) coupled to a STATCOM using a single-stage power conversion technology. The proposed approach aims to increase reactive power injection capability even under low battery State of Charge (SoC) situations in order to provide continuous voltage support and improved grid stability during dynamic operation scenarios. Another crucial objective is to successfully gather and manage energy from renewable energy sources, such as solar PV and wind systems [2].

This means using an intelligent hybrid PSO–GWO-based MPPT algorithm to optimize power extraction, using a hybrid supercapacitor–battery configuration to manage fast power transients and extend battery life to improve system reliability, and using harmonic mitigation to improve power quality.

3. PROBLEM STATEMENT :

Significant issues with voltage instability, reactive power insufficiency, and power quality degradation have been brought about by the growing integration of renewable energy sources into power systems [3]. Because typical BESS-STATCOM systems rely primarily on battery availability and their ability to sustain reactive power is greatly impeded when the battery SoC is low, their effectiveness is reduced during major grid interruptions such as voltage sags and

swells. Furthermore, traditional control and energy management techniques often cannot handle the rapid power changes caused by intermittent renewable generation and variable load needs. This leads to increased harmonic distortion, excessive energy use, accelerated battery degradation, and reduced system reliability.

4. ALGORITHM :

1. Synchronous Reference Frame (SRF) control
2. Sliding Mode (SM) Control
3. The hybrid particle swarm optimization and gray wolf optimization (PSO–GWO)-based MPPT algorithm

5. EXISTING SYSTEM:

Conventional reactive power support systems combine BESS-STATCOMs or STATCOMs with independent or multi-stage power conversion systems. The battery in these systems provides both active and reactive power support, whereas the STATCOM primarily regulates voltage and adjusts for changes in reactive power in the grid. The energy storage unit is directly connected to the grid via inverters and converters, and traditional control methods like PI or PID controllers regulate power flow. Maximum Power Point Tracking (MPPT) for renewable energy sources is typically done using traditional methods like Perturb & Observe (P&O) or Incremental Conductance (INC). The

battery's State of Charge (SoC) greatly affects these technologies' performance, even though they function well under normal working conditions [4].

At low SoC, the system's ability to inject reactive power is limited, which reduces its capacity to supply voltage during critical grid events. A battery's lifespan may be shortened and system instability may result from rapid load transients. Additionally, traditional MPPT algorithms may struggle to efficiently collect energy in scenarios with highly changing solar irradiance or wind speed.

5.1. DISADVANTAGES:

1. Reactive power injection is restricted with low battery SoC.
2. A shorter battery life due to frequent handling of rapid power fluctuations. Why standard MPPT algorithms are less effective and respond more slowly in changeable settings.
3. In the case of grid outages, limited support is provided for voltage stability.
4. Under dynamic loads, total harmonic distortion (THD) increases and power quality deteriorates.

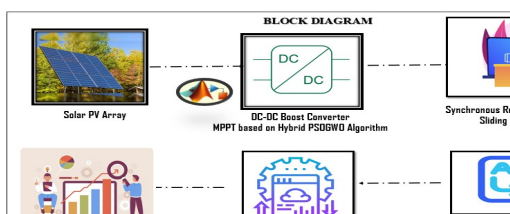
6. PROPOSED SYSTEM:

The proposed system offers a reactive power boosting method for a single-stage BESS-STATCOM system with a hybrid supercapacitor–battery architecture. By briefly removing the battery and charging the DC-link capacitor to its rated voltage,

the system can enhance reactive power injection even when the battery SoC is low. To enhance the harvesting of renewable energy, a hybrid PSO–GWO Maximum Power Point Tracking (MPPT) algorithm is employed, which provides greater efficiency and quicker convergence than conventional methods [5]. Bidirectional DC–DC converters controlled by Synchronous Reference Frame (SRF) and Sliding Mode (SM) controllers regulate the precise energy flow between the battery, supercapacitor, and grid.

The system's design reduces the load on the battery and extends its operating life by guaranteeing that the supercapacitor can handle quick transients. Advanced control algorithms enable harmonic mitigation, grid support, and dynamic load management. MATLAB/Simulink simulations are used to evaluate system performance, with a focus on energy balance, THD, active/reactive power flow, and voltage sag/swell [6]. The integrated solution enables efficient coordination between grid-connected loads, storage devices, and renewable energy sources while maintaining high power quality and system dependability.

Fig.1. ARCHITECTURE DIAGRAM



6.1.WORK DESCRIPTION:

The proposed system design illustrates an integrated renewable energy-based power system that includes solar PV, wind turbines, hybrid energy storage, power converters, STATCOM, grid, and loads. The power generated by the renewable sources is processed by a DC–DC boost converter with MPPT before being sent to a shared DC-link. A hybrid energy storage system that is connected to the DC-link and comprises of a battery and supercapacitor controlled by a Battery Management System (BMS) offers energy balance and rapid transient support.

The DC-link provides electricity to a three-phase DC-AC inverter that communicates with the grid and loads, in addition to acting as a STATCOM to offset reactive power. Advanced control strategies like SRF and Sliding Mode Control regulate voltage, current, and power flow to guaranty efficient energy conversion and dependable grid performance [7]. The flow diagram explains how the system operates from grid interface to renewable electricity generation. Before being delivered to the DC-link for storage management and conditioning, power from wind and solar PV sources is optimized using MPPT.

Based on load demand, grid conditions, and battery State of Charge (SoC), the control system determines whether

electricity should be supplied to loads, stored in the battery, or used for reactive power support through STATCOM operation.

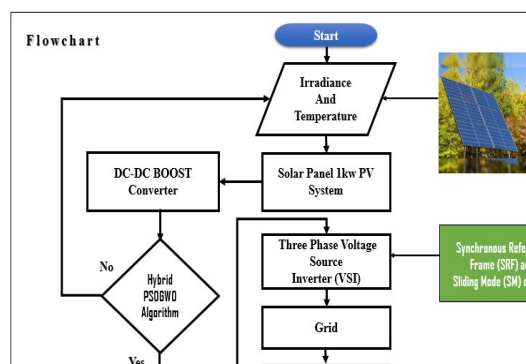


Fig.2. FLOW CHART DIAGRAM

This coordinated control ensures reliable grid integration, improved voltage stability, and smooth energy management under dynamic conditions.

6.2.ADVANTAGES:

1. Enhanced reactive power infusion despite low battery SoC.
2. The hybrid supercapacitor-battery setup results in a longer battery life.
3. The hybrid PSO-GWO MPPT makes it possible to capture renewable energy more quickly and efficiently.
4. Enhanced harmonic reduction, voltage stability, and load matching in dynamic settings [8].
5. Improved SRF and SM control to maximize energy consumption and system efficiency.

7.LITERATURE SURVEY:

7.1. Mehta and Jain (2024) developed a Maximum Power Point Tracking (MPPT) technique based on Particle Swarm Optimization (PSO) for solar PV systems operating in partial shade. In terms of tracking accuracy and convergence speed, the proposed method performed better than conventional MPPT techniques. However, it needed careful parameter adjustment and increased computing complexity.

7.2. El-Sayed and Noor (2024) used the Gray Wolf Optimization (GWO) technique to optimize control parameters in renewable energy systems. Their results showed improved system stability and reduced steady-state inaccuracy. The algorithm's pace of convergence varied based on population size and could be slower in certain circumstances, even though it was simple to apply and effective in global optimization.

7.3. Verma and Rao (2025) introduced a hybrid PSO-GWO algorithm for MPPT in hybrid PV-wind renewable systems. By combining the global search capability of GWO with the fast convergence capabilities of PSO, the hybrid method reduced oscillations and improved tracking efficiency. However, the method increased the algorithm's complexity and processing requirement.

7.4. Chen and Wu (2025) proposed a DC-

link voltage boosting method for STATCOM operating under low energy conditions. Their technique improved the capacity to inject reactive power without continuously relying on battery backup. The technique required precise control coordination and had short-term energy storage limits, despite improving grid support performance.

8.IMPLEMENTATION

METHODOLOGY:

1. Renewable Energy Sources (Solar PV and Wind Turbine): This module's primary power sources are solar PV and wind turbine systems. Solar PV converts sunlight into electrical energy, while wind turbines convert wind energy into power. Because the outputs from both sources are irregular due to environmental changes, they are modeled in MATLAB/Simulink to investigate dynamic behavior. For grid integration and efficient energy utilization, the combined power is sent to the DC–DC converter step [9].

2. Boost Converter (MPPT DC-DC Converter): The DC–DC boost converter regulates and raises the variable DC voltage from renewable sources to maintain a constant DC-link voltage. An MPPT algorithm based on a hybrid PSO–GWO is used to extract maximum power under various situations. This ensures high efficiency, reduced losses, and reliable

operation for downstream components such as the inverter and STATCOM [10].

3. Hybrid Supercapacitor–Battery Management System (BMS): This kind of storage system uses a battery to supply long-term energy and a supercapacitor to control brief high-power spikes. The BMS monitors variables including SoC, voltage, and current to regulate power sharing and ensure safe operation. This configuration reduces battery stress, extends battery life, and improves overall system reliability [11].

4. Three-Phase DC–AC Inverter: This apparatus converts DC power from the DC-link into AC electricity for the grid and load supply. It is managed using sinusoidal PWM, which ensures minimal harmonic distortion and accurate active/reactive power management. It also enables bidirectional power transfer, which enables STATCOM and energy exchange [12].

5. Load Integration and STATCOM Operation: This module integrates loads with reactive power compensation at the PCC based on STATCOM. To maintain a steady voltage during interruptions, the STATCOM dynamically injects or absorbs reactive power. It reduces voltage swings, enhances power quality, and ensures continuous grid support even with low battery SoC [13].

6. Control Strategies (SRF and Sliding Mode Control): The system employs SRF control to separate the active and reactive power components. It makes advantage of Sliding Mode Control for steady dynamic performance. This hybrid control approach ensures fast response, rejection of disturbances, and stable operation in nonlinear and variable renewable conditions [14].

7. Performance Estimation and Analysis: System performance is evaluated using MATLAB/Simulink simulations under different operating conditions. Power flow, THD, voltage stability, and DC-link voltage are among the factors that are analyzed. Better reactive power capacity, improved voltage management, and efficient utilization of renewable energy are all supported by the findings [15].

9. RESULTS AND DISCUSSION:

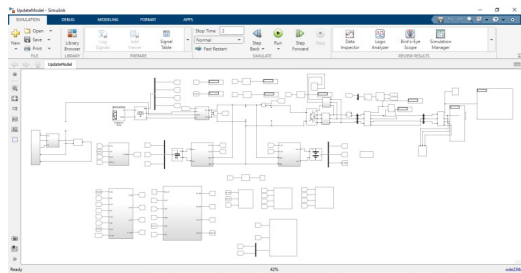


Fig.3. Simulink

This image displays the whole Simulink system design for a hybrid renewable energy microgrid. The model incorporates a photovoltaic (PV) array (left) and a DC-DC boost converter that shares a DC bus with a battery energy storage system

(BESS) and a supercapacitor (SC) system. These storage units employ bi-directional DC-DC converters to regulate charge and discharge cycles. After receiving the combined DC power, a DC-AC Voltage Source Inverter (VSI) (center-right) connects to the utility grid using circuit breakers and an LCL filter. Several control subsystems found in the lower portion of the model handle inverter control logic, battery management, and Maximum Power Point Tracking (MPPT) [16].

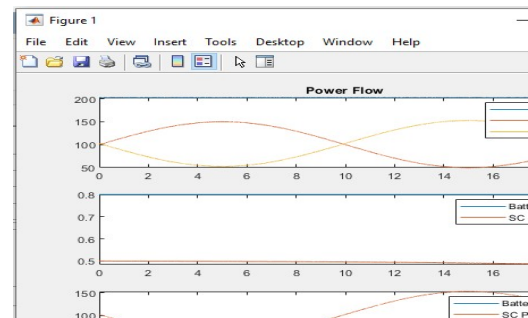


Fig.4. Power Flow

This image shows the power dynamics between the load and the different energy sources across a 20-second simulation. The top subplot shows that the PV power generation is relatively consistent, whereas the load and supply power follow a sinusoidal envelope, displaying a variable demand profile. The middle subplot [17] shows the State of Charge (SOC) of the battery and supercapacitor, which shows a slow decrease or stability in response to energy use. The bottom subplot displays the storage devices' exact power contributions. The Supercapacitor (SC)

managing the high-frequency fluctuations (transients) and the battery managing the steady-state baseline power demonstrate an effective hybrid storage management technique.

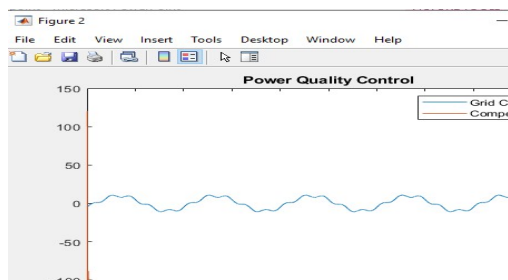


Fig.5. Power Quality Control

The primary focus of this picture is the system's capacity to maintain power quality by adjusting for current harmonics or disturbances in a very brief period of time (0.1 seconds). The blue line ("Grid Current") shows the AC waveform bouncing about zero, while the red line ("Compensated") appears to show the injection current required to smooth out the waveform or the subsequent DC offset correction [18]. The graph illustrates how the grid current is stabilized as soon as it is initialized ($t=0$) by the inverter's fast-acting control loop (Active Power Filter feature).

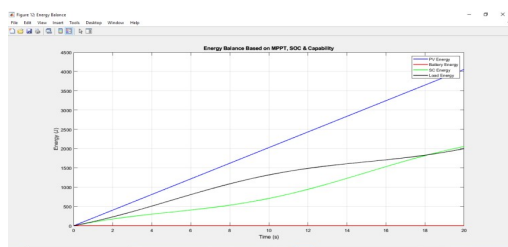
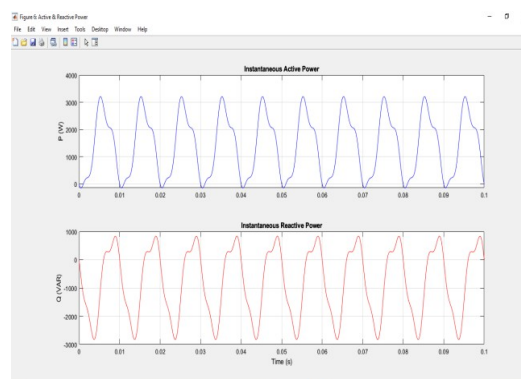


Fig.6: MPPT, SOC, and Capability-Based Energy Balance

This cumulative graph displays the total energy generated and consumed over time, expressed in Joules. The blue line, which climbs linearly and displays consistent power generation, represents PV energy. The black line, which shows a steady increase in consumption, represents the load energy. The green line shows the Supercapacitor (SC) energy contribution, while the red line (Battery Energy) remains flat at zero [19]. This implies that either the PV and SC were the primary active components managing the load during this specific simulation frame, or the battery scale is much different. This number attests to the simulation's adherence to the Law of Conservation of Energy.



Active and Reactive Power Instantaneously (Fig. 7)

This image provides a detailed representation of the electrical output characteristics during a 0.1-second interval. The top graph shows the Instantaneous Active Power (P) in Watts. With peaks reaching roughly 3200W, it

oscillates at twice the grid frequency, which is typical for single-phase or unbalanced systems. The bottom graph shows the Instantaneous Reactive Power (Q) in VAR, which varies negatively. These waveforms allow engineers to analyze the power factor and the immediate load on the inverter switches.

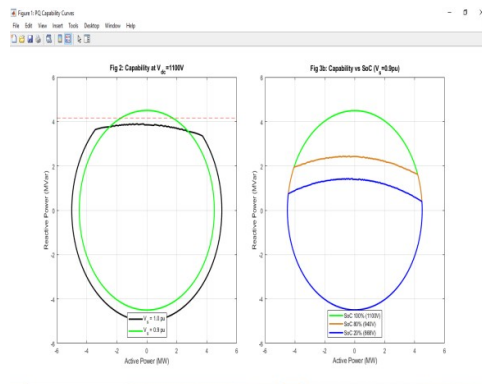
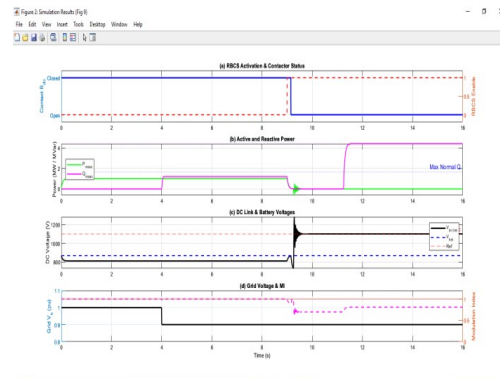


Figure 8: PQ Capability Curves
This technical graphic shows the functional limits of the grid-connected inverter. The safe working area (circular P-Q plane) shown in the left plot ("Capability at $V_{dc}=1100V$ ") is defined by the DC link voltage constraints; the system must operate inside these circles to avoid instability or hardware damage. The right plot ("Capability vs SoC") illustrates how the available Active (P) and Reactive (Q) power capacity decreases when the Battery State of Charge (SoC) decreases (from Green/100% to Blue/20%) and as the grid voltage (Vs) reduces to 0.9pu. This determines how much grid assistance the system can provide in low-charge scenarios.



Results of the simulation (Fig. 9): RBCS activation

This composite figure illustrates the system's response to a specific control sequence over a 16-second period. At about $t=9s$, it shows the Reactive Power Capability Support (RBCS) activation. At $t=11s$ following this activation, the Active and Reactive Power (subplot b) drastically alter, with Reactive Power jumping to meet a new demand. The DC Link voltage (subplot c) briefly spikes at $t=9s$ and then stabilizes, demonstrating the durability of the DC bus controller. Subplot (d) shows how the grid voltage and Modulation Index change as a result of these control adjustments.

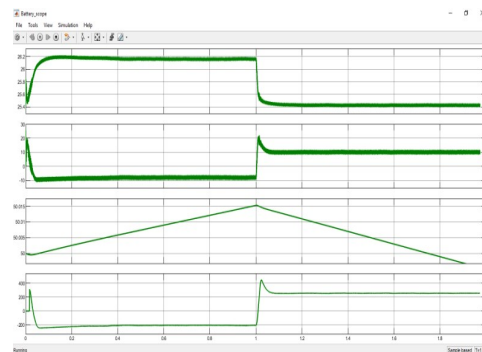


Fig.10. Battery_scope

This scope records the internal dynamics of the battery model throughout a two-second simulation with a load step change at $t=1.0$ s. The first subplot shows the battery voltage, which progressively drops as the load rises. The second subplot shows the battery current, which shifts from low discharge or negative (charging) to a higher discharge rate at $t=1$ s. The third subplot tracks the SOC, while the fourth subplot shows the battery power [20]. This subplot simulates the current by first being negative (absorbing/idling) and then, after a second, turning positive (delivering roughly 250–400W).

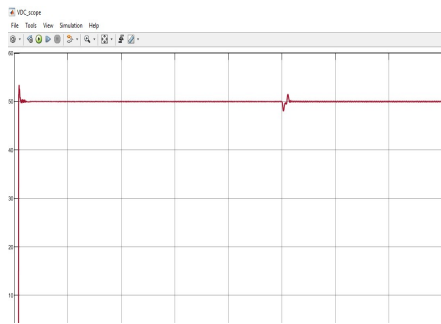


Fig.11. VDC_scope

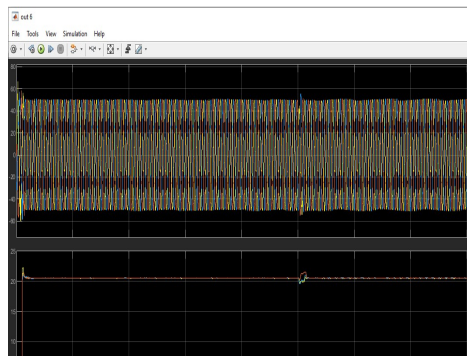


Figure 12. The simulation results show that the system functions steadily and well in dynamic conditions. The DC-link voltage is kept at about 50V (or 500V

depending on scale) for the duration of the 2-second operation, with a transient dip and slight overshoot observed at $t = 1.0$ s due to an unforeseen load or source disruption. The controller's quick adjustment for this fluctuation, which instantly resets the voltage to its reference value, demonstrates strong DC bus regulation. The three-phase grid output's waveforms likewise exhibit balanced sinusoidal behavior, with only a minor amplitude disturbance at the same instant ($t = 1.0$ s).

The RMS or frequency signal, which oscillates momentarily between 21 and 22 units before stabilizing, confirms reliable grid synchronization, constant inverter operation, and effective disturbance rejection.

10. CONCLUSION :

This study successfully demonstrates a reactive power boosting method for a BESS coupled to a STATCOM for renewable energy-based power networks using a single-stage power conversion system. By using the DC-link capacitor charged to its rated voltage and briefly disconnecting the battery at low State of Charge, the proposed approach ensures continuous reactive power support. Combining solar PV and wind energy with a hybrid PSO–GWO-based MPPT algorithm enables efficient energy gathering. Furthermore, the hybrid

supercapacitor–battery architecture extends battery life and effectively manages sudden power fluctuations. The system maintains balanced active and reactive power flow, reduced total harmonic distortion, and voltage stability for a variety of load and renewable generating scenarios, according to MATLAB/Simulink simulation results.

The coordinated control approach using Synchronous Reference Frame and Sliding Mode controllers provides fast dynamic response and dependable performance during grid disturbances like voltage sag and swell. All things considered, the recommended strategy effectively and reliably improves grid stability, power quality, and the utilization of renewable energy.

11. FUTURE ENCHANCEMENT:

Future studies can focus on putting the proposed system into practice on hardware and using digital controllers like FPGA or DSP platforms to validate it in real time. Experimental testing under real-world grid settings would further validate the effectiveness of the reactive power boosting technology and control algorithms. Additionally, introducing state-of-the-art defenses and real-time monitoring tools can enhance operating safety and dependability. Additional advancements could include the integration of machine learning-based

control techniques and artificial intelligence for fault prediction and adaptive energy management. By expanding the system to support multi-microgrid or smart grid environments and including other energy storage technologies like flywheel or hydrogen systems, future renewable energy networks' scalability, adaptability, and resilience could be further enhanced.

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