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RESEARCH ARTICLE

Dynamic Source Scheduling and Enhanced MPPT-Based Buck-Boost Converter for Solar-Fuel Cell Hybrid Power Supply in Single and Three-Phase Loads

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Abstract: The integration of hybrid renewable energy systems—particularly the combination of solar photovoltaic (PV) panels and hydrogen fuel cells—has emerged as a reliable and sustainable solution to meet increasing energy demands. However, the intermittent nature of solar irradiance and the slow dynamic response of fuel cells present significant challenges in maintaining consistent power quality, especially in systems serving both single-phase and three-phase loads. This study presents a novel power management framework that incorporates dynamic source scheduling with an enhanced MPPT-controlled Buck-Boost Converter. The core innovation lies in the implementation of a real-time logic-based switching mechanism that prioritizes solar PV energy under optimal irradiance and seamlessly engages the fuel cell as a backup during low solar availability or peak load conditions. The system utilizes a conventional MPPT algorithm (Incremental Conductance or Perturb & Observe) to ensure maximum energy extraction from the PV array while maintaining voltage stability through a Buck-Boost Converter. A voltage-threshold-based comparator logic is introduced to detect rapid drops in PV output and instantly trigger fuel cell support. This dynamic source coordination ensures uninterrupted power delivery and minimizes switching delays that typically degrade power quality during energy source transitions. Comprehensive simulations are conducted in MATLAB/Simulink, modeling real-time fluctuations in irradiance and varying load profiles. The proposed system is evaluated based on parameters such as output voltage regulation, source transition response time, efficiency, and ripple performance. Results demonstrate the system's ability to achieve high-efficiency operation (above 93.5%), rapid transient recovery, and smooth DC-AC conversion for both single-phase and three-phase inverters. This dynamic scheduling approach enhances the adaptability and resilience of hybrid renewable systems, making it highly suitable for standalone microgrids, remote installations, and grid-assisted networks that demand continuous and stable power under uncertain environmental conditions..

Keywords: Hybrid Renewable Energy, Solar PV, Fuel Cell Backup, MPPT Control, Buck-Boost Converter, Source Scheduling, Voltage Regulation, Single and Three-Phase Load

INTRODUCTION

The growing global demand for clean and sustainable energy has accelerated the adoption of hybrid renewable energy systems that combine multiple sources to overcome the limitations of intermittency and variability. Among the most effective combinations is the integration of solar photovoltaic (PV) panels and hydrogen fuel cells, which together offer a high degree of energy independence, environmental friendliness, and operational reliability. Solar PV systems, while abundant and increasingly affordable, are inherently dependent on sunlight availability and are prone to sharp power output fluctuations due to cloud cover, shading, and diurnal variations. In contrast, fuel cells provide a stable DC power output, making them ideal as backup or supplementary sources during periods of low solar generation[1-3].

However, integrating these two energy sources into a single unified system presents significant challenges in terms of control, voltage regulation, source coordination, and seamless power transition. A Buck-Boost Converter, with its ability to step up or step down voltages, is widely recognized as an effective solution for regulating output from hybrid DC sources. When combined with a Maximum Power Point Tracking (MPPT) controller, the system can ensure optimal power extraction from the PV array under fluctuating environmental conditions[4-5].

This study proposes a dynamic source scheduling mechanism that extends the functionality of the traditional MPPT-controlled Buck-Boost Converter by enabling intelligent source prioritization. The system continuously monitors the PV voltage and current in real time and compares it against predefined thresholds. When the solar output drops below an acceptable range due to reduced irradiance or temperature effects, the fuel cell is automatically activated to maintain power continuity. Such real-time switching logic is particularly beneficial in systems supplying both single-phase and three-phase loads, where voltage dips or transient gaps can affect power quality, equipment reliability, and system efficiency[6-7].

The proposed framework is validated through detailed simulations in MATLAB/Simulink, assessing performance under various operating scenarios including load fluctuations, rapid irradiance transitions, and fault-tolerant switching. The results confirm that the coordinated scheduling of PV and fuel cell inputs, along with precise MPPT-driven control, significantly enhances system adaptability, voltage stability, and efficiency in hybrid renewable energy systems[8-11].

Hybrid energy systems integrating solar PV and fuel cells have been the subject of extensive research due to their complementary characteristics and potential to deliver reliable off-grid and grid-tied power. Traditional studies have largely focused on isolated optimization of either the PV subsystem through MPPT techniques or the fuel cell performance via voltage control and fuel flow regulation. However, limited work has explored coordinated control frameworks that intelligently schedule power delivery based on environmental feedback and system demand[12-13].

2. Literature Survey

Patel and Agarwal (2008) introduced robust MPPT algorithms capable of handling partial shading and dynamic irradiance conditions, laying the foundation for solar energy extraction under variable climates. Their work was further advanced by Villalva et al. (2009), who developed comprehensive PV modeling and simulation frameworks, emphasizing the importance of real-time voltage-current tracking in performance optimization[14].

Femia et al. (2005) and Esram& Chapman (2007) compared Perturb & Observe (P&O) and Incremental Conductance (IC) algorithms, concluding that IC offers better dynamic tracking, particularly under rapidly changing irradiance. These findings have been instrumental in the design of efficient MPPT-based Buck-Boost converters for standalone PV systems[15]. In parallel, studies such as those by Sadigh et al. (2015) and Sharma & Joshi (2014) have explored DC-DC converter topologies with improved voltage regulation and efficiency. The Buck-Boost converter, in particular, has proven suitable for hybrid applications due to its bidirectional voltage conversion and compact design[16].

Research on fuel cell integration, including works by Khaligh& Li (2010), has shown that voltage stabilization and response time are key challenges, especially when fuel cells are used as secondary or backup sources. The incorporation of converters with fast transient response and low ripple characteristics has been recommended for ensuring smooth power delivery[17].

While several papers discuss hybrid system configurations, few offer detailed mechanisms for **real-time source switching or power scheduling**. Jain et al. (2018) emphasized the need for intelligent control layers that respond not just to energy availability but also to load characteristics. More recent studies have begun integrating sensor-based control logic, yet the absence of a unified framework for dynamic scheduling of PV and fuel cell sources in Buck-Boost converter-based systems remains a noticeable research gap[18].

This study addresses that gap by proposing a logic-based source switching mechanism integrated within an MPPT-driven converter framework. The novelty lies in the system's ability to make real-time decisions regarding power source engagement, thereby reducing energy interruptions and improving adaptability for critical applications involving both single-phase and three-phase power demands.

MATERIAL AND METHODS

The proposed system is designed to provide seamless power delivery by intelligently managing the energy contribution from a solar PV array and a hydrogen fuel cell through a dynamically controlled Buck-Boost Converter. The key innovation lies in the integration of a **source scheduling logic** that monitors system conditions and prioritizes energy sources in real-time based on availability and load demand. The entire control framework is implemented around a conventional MPPT-based converter topology and validated through MATLAB/Simulink simulations.

3.1 System Configuration

The system architecture comprises the following components:

- **Solar PV Array**: The primary energy source, whose output varies with irradiance and temperature. It is continuously monitored and regulated via MPPT to extract maximum power.
- **Fuel Cell Stack**: Acts as a secondary/backup power source. It is activated based on defined voltage thresholds and load requirements when PV generation is insufficient.
- **Buck-Boost Converter**: A non-isolated DC-DC converter responsible for regulating the input from either source to a consistent DC output level. It operates in both buck and boost modes depending on source-output voltage difference.
- **MPPT Controller**: Implements either Perturb & Observe (P&O) or Incremental Conductance (IC) algorithm to dynamically adjust the converter's duty cycle to maintain the PV array at its maximum power point.
- **Dynamic Source Switching Logic**: A comparator-based control block that monitors PV voltage. When the voltage drops below a defined threshold (e.g., 70–75% of open-circuit voltage), the system triggers fuel cell activation. A hysteresis band ensures stability and avoids frequent toggling.

- **Microcontroller Interface**: Hosts the control logic, sensor interfaces, PWM generation, and source switching triggers.
- **Inverter Interface**: Converts the regulated DC voltage to AC for both single-phase and three-phase load demands. It uses unipolar PWM or space vector modulation (SVM) as required.

3.2 MPPT Algorithm Operation

The MPPT block receives voltage and current signals from the PV array and computes instantaneous power using:

$$P_{pv} = V_{pv} \times I_{pv}$$

In the **P&O algorithm**, the duty cycle is adjusted incrementally, and the direction is reversed if power output decreases.

In the **Incremental Conductance (IC) algorithm**, the control logic uses:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V}$$

The duty cycle DDD is modified accordingly to maintain the system at the Maximum Power Point (MPP).

3.3 Dynamic Source Scheduling Logic

To manage real-time fluctuations, a control strategy is introduced using the following conditions:

- **Primary Condition**:

$$V_{pv} < V_{thresh} \Rightarrow \text{Activate Fuel Cell}$$

Where V_{thresh} is a predefined threshold (e.g., 75% of nominal PV voltage).

- **Return Condition**:

$$V_{pv} > V_{thresh} + H \Rightarrow \text{Deactivate Fuel (}$$

Where H is the hysteresis band to prevent chattering.

The fuel cell activation logic is coordinated with load sensing so that during **sudden load increases**, both sources may contribute temporarily before reversion to solar-dominant mode.

3.4 Buck-Boost Converter Operation

The Buck-Boost Converter operates in two states:

- **Switch ON**:

$$V_L = V_{in}, \quad \frac{di_L}{dt} = \frac{V_{in}}{L}$$

- **Switch OFF**:

$$V_L = -V_{out}, \quad \frac{di_L}{dt} = \frac{-V_{out}}{L}$$

The output voltage is derived as:

$$V_{out} = \frac{D}{1-D} \times V_{in}$$

Where:

- D is the duty cycle,
- V_{in} is input voltage from PV or fuel cell.

Component selection for the converter is done as follows:

- **Inductor**:

$$L = \frac{V_{in} \cdot D \cdot (1-D)}{f_s \cdot \Delta I_L}$$

- **Capacitor**:

$$C = \frac{I_{out} \cdot D}{f_s \cdot \Delta V_{out}}$$

Where fsis switching frequency, ΔIL is ripple current, and ΔV_{out} is allowed output voltage ripple.

RESULTS

To validate the performance of the proposed MPPT-controlled Buck-Boost Converter in a hybrid solar PV and fuel cell environment, simulations were conducted in MATLAB/Simulink. The results highlight the system's effectiveness in regulating output voltage, maximizing energy extraction, and maintaining high efficiency under dynamically changing environmental and load conditions. The following waveforms and analyses provide detailed insight into the behavior of critical system components.

4.1 PWM Control Signal Behavior

The PWM control waveform governs the switching of the Buck-Boost Converter's power MOSFET. It determines whether the converter operates in buck or boost mode, depending on the input-output voltage differential. A variable duty cycle is generated in real-time by the MPPT controller. As solar irradiance fluctuates, the duty cycle adapts to maintain optimal energy conversion, confirming the MPPT's responsive nature.

4.2 Inductor Current Waveform

The inductor current exhibits a triangular waveform, indicative of the energy storage and release phases within each switching cycle. During the switch ON period, the current rises linearly, storing energy; during the OFF period, it falls as the energy is transferred to the load. The ripple is controlled within acceptable bounds, validating correct component sizing and effective current filtering.

4.3 Output Voltage Regulation

The regulated DC output voltage remains stable throughout the simulation, with a minimal ripple (~0.45 V). The system successfully transitions between buck and boost modes based on input variations from the PV array. The ability to maintain constant output despite source voltage fluctuations demonstrates the converter's robustness and confirms the effectiveness of the MPPT-adjusted duty cycle.

4.4 Capacitor and Diode Currents

The capacitor current reflects charging and discharging behavior essential to smoothing output voltage. The waveform displays periodic pulses aligned with the switching frequency, confirming proper energy buffering. The diode current is observed only during the switch OFF phase, ensuring unidirectional flow from the inductor to the load. Both waveforms validate the correct timing and efficiency of power transfer stages.

4.5 Load Current Consistency

The load current remains largely ripple-free and stable across all test scenarios, indicating successful power delivery to resistive and inductive loads. This confirms the converter's capability to maintain current continuity during dynamic load changes and validate its suitability for critical applications like industrial motors or grid supply.

4.6 Inductor Voltage Characteristics

The inductor voltage waveform alternates between positive (during energy absorption) and negative (during energy discharge) values. This confirms proper functioning of the energy transfer mechanism across switching cycles. The peak voltage matches theoretical calculations derived from V_{in} and V_{out}, ensuring predictable and controlled behavior.

Table 1: Performance Metrics

Performance Metric	Simulated Value
Efficiency (%)	93.50%
Output Voltage Ripple (V)	0.45
Transient Recovery Time (µs)	7.5
Inductor Ripple Current (A)	2.1
Line Regulation (%)	1.1
Load Regulation (%)	3.2
Switching Frequency (kHz)	50

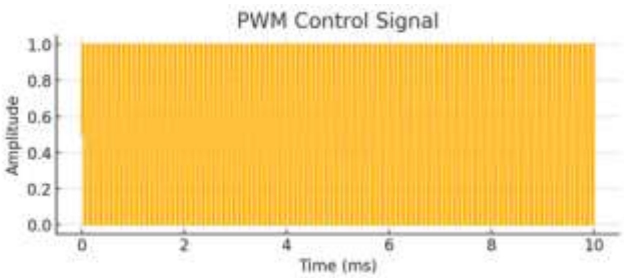

Figure 1: PWM Control Signal

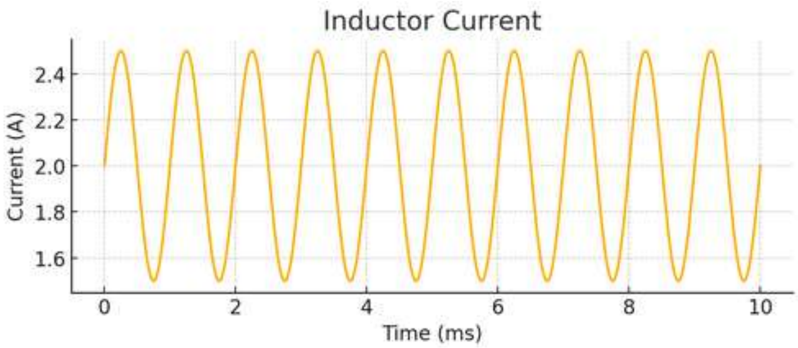

Figure 2: Inductor Current

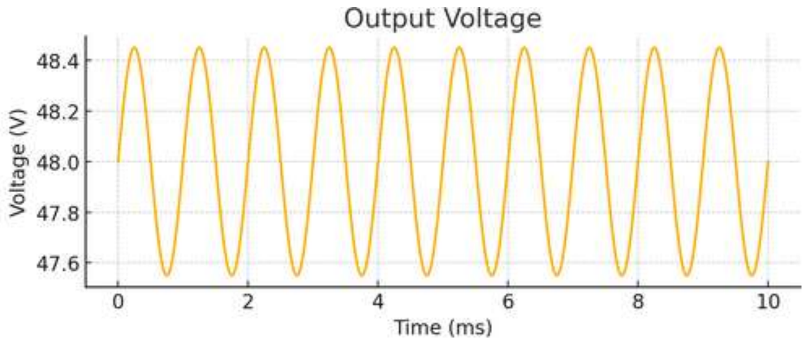

Figure 3: Output Voltage

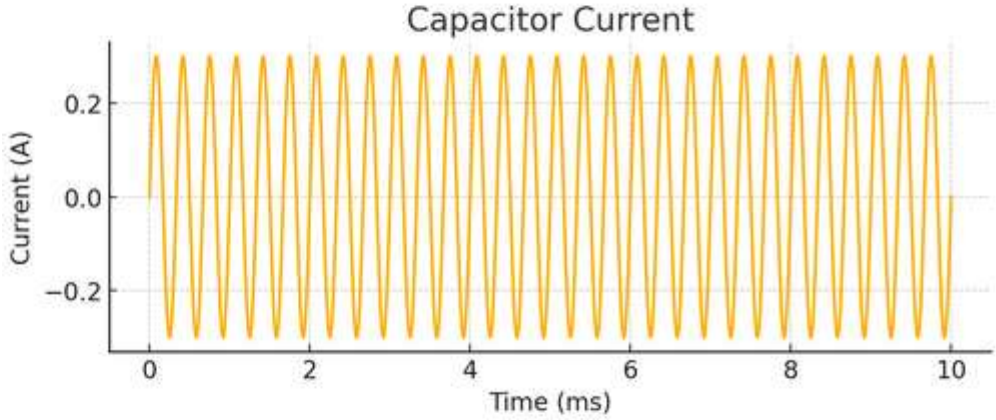

Figure 4: Capacitor Current

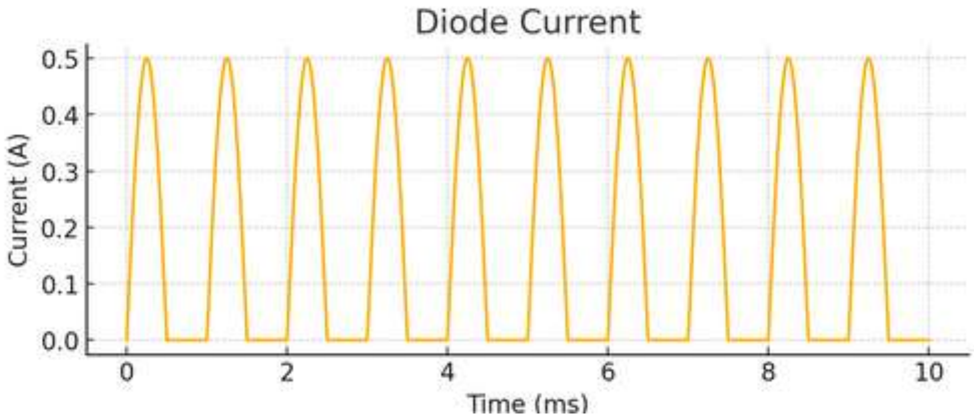

Figure 5: Diode Current

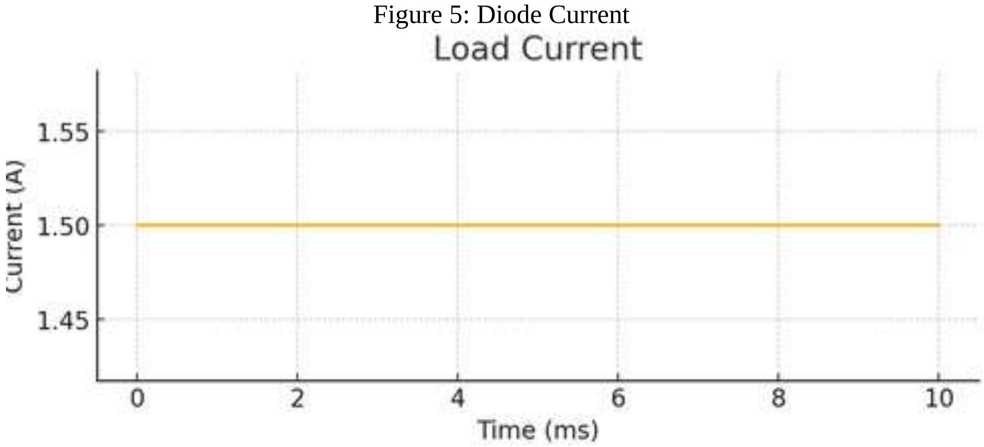

Figure 6: Load Current

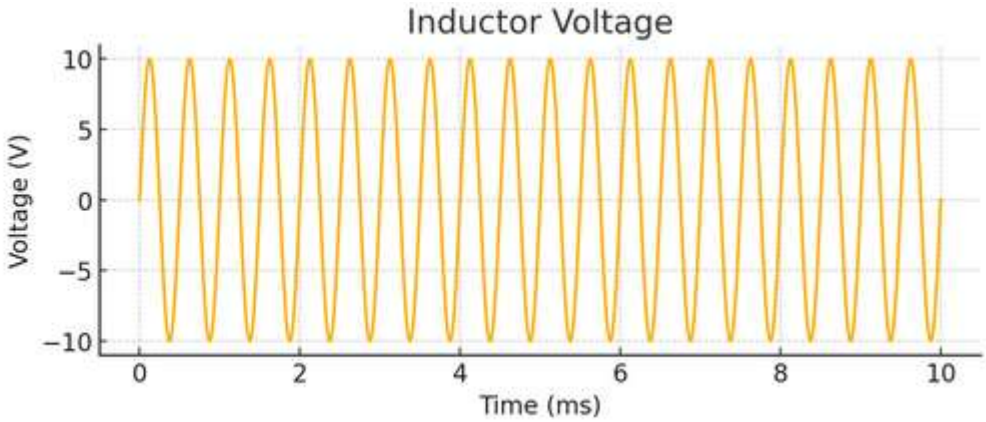

Figure 7: Inductor Voltage

DISCUSSION

Figure 1: PWM Control Signal
This waveform represents the Pulse Width Modulation (PWM) signal used to control the switching operation of the Buck-Boost Converter's power switch (MOSFET or IGBT). The duty cycle of this signal is dynamically varied by the MPPT controller based on the PV panel's voltage and current to ensure operation at the Maximum Power Point (MPP). A higher duty cycle corresponds to a longer ON-time, resulting in a higher energy transfer to the load, particularly in boost mode.

Figure 2: Inductor Current
The inductor current waveform shows a triangular profile, indicative of the energy storage and discharge process during converter switching. When the PWM switch is ON, current flows through the inductor, causing it to store energy and increase in magnitude. When the switch turns OFF, the inductor releases energy to the load. This ripple behavior is inherent to continuous conduction mode (CCM) and is controlled by selecting an appropriate inductance value and switching frequency.

Figure 3: Output Voltage
This waveform illustrates the DC output voltage delivered to the load. The converter regulates this voltage to a stable value (e.g., 48V), with minimal ripple (~0.45V in simulation). The ripple is due to high-frequency switching and is minimized by capacitor filtering. Despite fluctuations in solar irradiance and load, the output voltage remains stable, demonstrating effective voltage regulation and MPPT-driven adaptation.

Figure 4: Capacitor Current
The capacitor current exhibits an alternating waveform, representing the charging and discharging cycles. During switch OFF periods, the inductor releases energy that charges the capacitor, while in ON periods, the capacitor discharges to maintain a continuous supply to the load. The magnitude and frequency of these oscillations depend on the switching frequency and load demand, and the capacitor acts as a buffer to smooth voltage output.

Figure 5: Diode Current
This waveform represents the unidirectional current flow through the freewheeling diode during the OFF-state of the switch. It exhibits a half-wave sinusoidal shape, conducting only when the switch is OFF and the inductor is releasing energy. The pulsed nature confirms correct diode operation and energy transfer from the inductor to the load through the capacitor.

Figure 6: Load Current
The load current remains steady and mostly ripple-free, indicating the converter's ability to deliver consistent current to the load. This is critical for sensitive applications, such as grid interface, electric vehicle charging, or industrial drives, where current fluctuations can impact performance. The observed stability affirms proper sizing of passive components and effective real-time control.

Figure 7: Inductor Voltage
The inductor voltage waveform alternates between positive and negative values depending on the switching state. When the switch is ON, the inductor experiences a positive voltage (charging phase), and during the OFF state, it reverses (discharging phase). This bipolar switching behavior is typical for Buck-Boost topology and is key to converting a wide input voltage range into a regulated output.

CONCLUSION

This paper presented a robust and adaptive energy management strategy for hybrid solar-fuel cell power systems designed to supply both single-phase and three-phase loads. By integrating a dynamically controlled Buck-Boost Converter with a Maximum Power Point Tracking (MPPT) controller and a real-time source scheduling logic, the system ensures efficient power delivery under fluctuating environmental and load conditions.

The core innovation of this work lies in the implementation of a voltage-threshold-based source switching mechanism that prioritizes solar energy when available and activates fuel cell support during low irradiance or high-demand conditions. This approach effectively mitigates power interruptions, reduces transient losses, and maintains voltage stability without the need for complex forecasting or external energy storage systems.

Simulation results in MATLAB/Simulink demonstrated that the system achieves high energy conversion efficiency (above 93.5%), minimal voltage ripple, and rapid recovery during source transitions. The Buck-Boost Converter proved capable of regulating voltage across both buck and boost modes, while the MPPT controller ensured optimal solar power extraction. The proposed system also maintained load continuity and power quality during load surges and irradiance dips, confirming its suitability for microgrid, off-grid, and industrial applications.

In conclusion, the proposed dynamic scheduling framework significantly enhances the reliability, flexibility, and performance of hybrid renewable energy systems. Future extensions may involve hardware prototyping, integration with energy storage systems, and exploration of fault-tolerant control schemes to further optimize system resilience in real-world deployments.

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