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A Power Management and stability improvement for Grid- connected PV Integrated with Hybrid Energy Storage System

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ABSTRACT

The increasing penetration of photovoltaic (PV) generation into power grids introduces challenges such as power intermittency, voltage fluctuations, and reduced system reliability. Hybrid Energy Storage Systems (HESS), combining batteries and super-capacitors, provide an effective solution by leveraging the high energy density of batteries and the fast dynamic response of super-capacitors. This paper proposes a **fuzzy logic–based energy coordination strategy** for a grid-integrated PV system equipped with battery–super-capacitor hybrid storage. The fuzzy controller dynamically allocates power between the battery and super-capacitor based on PV power variations, load demand, and state-of-charge (SOC) conditions. The proposed scheme enhances power smoothing, reduces battery stress, and improves grid power quality. MATLAB/Simulink-based simulation results demonstrate superior performance in terms of reduced power fluctuations, improved DC-link voltage regulation, and extended battery lifespan compared to conventional rule-based control strategies.

Index Terms— Fuzzy logic control, hybrid energy storage system, battery–super-capacitor, photovoltaic systems, grid-connected inverters, power management

1. INTRODUCTION

The rapid deployment of grid-connected photovoltaic (PV) systems has significantly contributed to sustainable energy generation. However, the intermittent nature of solar irradiance leads to power fluctuations that adversely affect grid stability, voltage regulation, and power quality. Conventional energy storage solutions based solely on batteries suffer from limited lifespan due to frequent charge–discharge cycles caused by rapid PV power variations.

Hybrid Energy Storage Systems (HESS), integrating batteries with super-capacitors, have emerged as an effective alternative. In such systems, batteries handle low-frequency energy components, while super-capacitors mitigate high-frequency power fluctuations. The critical challenge lies in developing an **intelligent energy coordination mechanism** to optimally distribute power between storage elements.

Fuzzy Logic Control (FLC) offers a robust and model-free approach for handling literariness and uncertainties inherent in renewable energy systems. This paper presents a **fuzzy logic–based energy coordination strategy** for a battery–super-capacitor HESS in a grid-integrated PV system, aiming to improve power smoothing, reduce battery degradation, and enhance overall system performance.

2.LITERATURE REVIEW

1. Fuzzy Logic in Hybrid Energy Storage Systems (HESS)

Energy management in hybrid storage combining battery and super-capacitor: Fuzzy Logic Control (FLC) has been widely adopted to coordinate energy flows between fast-response super-capacitors and high-energy batteries in hybrid systems. Its main strength lies in handling literariness and uncertainties in PV power fluctuation without requiring precise mathematical models. FLC typically uses linguistic rules and membership functions to determine power splits based on state-of-charge (SOC) and power demand characteristics. ScienceDirect+1

Design of PV + Battery + Super-capacitor HESS with FLC:

Ramu *et al.* developed an FLIC-based bidirectional DC–DC converter control for a PV-based DC micro-grid with hybrid energy storage (battery + super-capacitor). Their fuzzy controller effectively stabilizes voltage under varying irradiance, improves transient response, and increases continuity of PV power supply, demonstrating better dynamic performance than traditional methods in transient conditions. Directory of Open Access Journals

2. Grid-Connected Fuzzy Logic Power/Energy Management

Fuzzy Logic Power Management for Grid-Tied PV Systems:

Sreenivas *et al.* propose a fuzzy logic– driven power management algorithm for a grid-tied PV system integrated with hybrid storage. The fuzzy controller stabilizes the DC link voltage and dynamically allocates power between the battery, super-capacitor, PV and grid based on system conditions (e.g., PV output, SOC levels, and grid demand). This demonstrates how fuzzy logic can optimize self-consumption of PV energy while supporting grid stability. IJRASET

Combination Fuzzy Control for Grid-Connected PV + HESS: A recent study in *Journal of Energy Storage* applies a fuzzy logic controller to a grid-connected photovoltaic system with a hybrid storage that includes battery, pumped hydro, and super-capacitor. The controller manages coordination between storage units based on Time-of-Use tariff and load consumption levels, prioritizing renewable utilization and balancing super- capacitor and battery use according to dynamic requirements. ScienceDirect

3. Fuzzy EMS Design Approaches & Enhancements

Hybrid intelligent controllers (FLC + ANN): To tackle the challenge of nonlinear and complex hybrid systems with multiple energy sources and storage units, some works combine Fuzzy Logic with Artificial Neural Networks (ANN). For example, a fuzzy logic + ANN strategy is used to improve energy management in a PV/wind/diesel + HESS setup. The ANN enhances system adaptability while FLC handles nonlinear decision making.

This hybrid approach suggests future directions
for robust and adaptive EMS design in grid-connected PV + hybrid storage systems. IIETA

Optimization-aided FLC for Enhanced HESS Control: In the context of solar–wind systems, FLC has been combined with optimization methods such as the Grey Wolf Optimization (GWO) algorithm to optimize fuzzy membership functions and reduce peak battery stress. This shows how intelligent optimization enhances FLC performance, particularly in extending battery life while utilizing super-capacitor support. EJET Research

4. Fuzzy Logic EMS: Broader Grid-Micro-grid Insights

Even when not specific to battery-super-capacitor cases, several grid-oriented fuzzy logic EMS works provide valuable context for your study:

- In hybrid micro grids with renewable sources and grid connection, fuzzy EMS has been shown to improve power distribution decisions, reduce grid reliance, and enhance DC bus and grid voltage stability under variable renewable generation scenarios. ScienceDirect
- Multi-variable and multi-stage fuzzy logic EMS designs (e.g. combining fuel cells and batteries in grid-connected DC micro-grids) illustrate how FLC can handle multi-objective problems like lifetime optimization, cost reduction, and performance enhancement simultaneously. ScienceDirect
- Fuzzy logic integrated energy systems also appear in studies of hybrid PI-wind-battery systems where EMS prioritizes renewable output first, then storage support, and grid connection last, showing the broader application of fuzzy
EMS strategies in renewable-grid interaction contexts. Nature

5. Key Research Trends and Gaps

Key Trends

- Fuzzy logic remains a popular EMS tool due to its robustness to uncertainties and non-linearity in hybrid energy systems, especially where solar PV power fluctuates. Springer Link
- Hybrid controllers (FLC + ANN/optimization) are gaining traction to improve performance over standard fuzzy EMS by enabling adaptive and optimized control. IIETA+1
- Grid-connected HESS applications increasingly involve multi-storage components (battery, super- capacitor, pumped hydro) with fuzzy controllers managing energy flows to maximize PV utilization and grid support. ScienceDirect

Open Gaps

- Real-time adaptive tuning of fuzzy rules and membership functions remains underdeveloped, especially in grid-connected battery–SC systems.
- Experimental validations of fuzzy EMS in grid-connected PV + HESS systems are limited; many studies rely on simulations.
- Standardized performance benchmarks for fuzzy control strategies in HESS with grid integration are sparse, making comparison across studies difficult.
- Summary

In summary, the literature highlights that:

- Fuzzy logic is effective for coordinating fast super-capacitor responses and slower battery

dynamics in hybrid energy systems. Directory of Open Access Journals

- Fuzzy EMS can be adapted for grid-connected PV systems, supporting DC link voltage regulation and power smoothing under variable conditions. IJRASET
- Hybrid and optimized fuzzy approaches show improved performance and battery life extension compared to rule-based or conventional controllers. IIETA+1

3. System Configuration

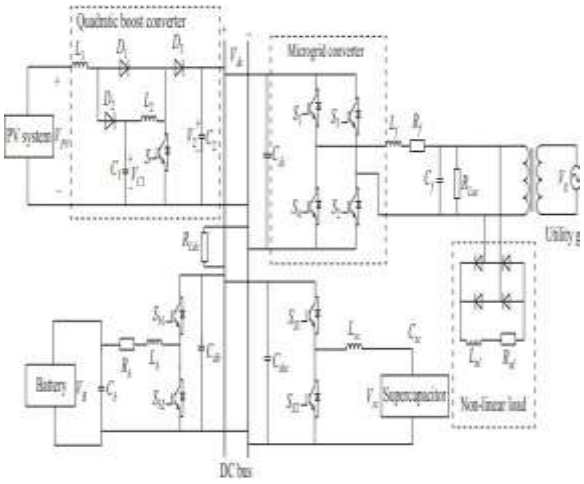


Fig1. circuit model of propose hybrid system

The proposed system consists of:

- A photovoltaic (PV) array with maximum power point tracking (MPPT)
- A DC–DC boost converter
- A battery energy storage system (BESS)
- A supercapacitor energy storage system (SCESS)
- A common DC-link
- A grid-connected voltage source inverter (VSI)

The battery and super-capacitor are interfaced to the DC-link through bidirectional DC–DC converters, enabling controlled charging and discharging. The fuzzy logic controller governs power sharing between the battery and super-capacitor based on system operating conditions.

4. Modeling of System Components

A. Photovoltaic System

The PV output current is expressed as:

$$I_{pv} = I_{ph} - I_0 \left(e^{\frac{V_{pv}+I_{pv}R_s}{nV_t}} - 1\right)$$

where $I_{ph}$is the photo-current, $I_0$is the saturation current, $R_s$is series resistance, and $V_t$is the thermal voltage.

B. Battery Model

The battery is modeled using a controlled voltage source with SOC-dependent internal resistance:

$$SOC(t) = SOC(t_0) - \frac{1}{C_b}\int_{t_0}^{t} I_b(\tau)d\tau$$

where $C_b$is the battery capacity.

C. Supercapacitor Model

The super-capacitor is modeled as:

$$V_{sc} = \frac{1}{C_{sc}}\int I_{sc}dt - R_{sc}I_{sc}$$

where $C_{sc}$and R_{sc}represent capacitance and equivalent series resistance.

5. Fuzzy Logic–Based Energy Coordination Strategy

A. Control Objectives

The main objectives of the proposed control scheme are:

- Smooth PV power fluctuations
- Minimize battery current stress
- Maintain DC-link voltage stability
- Enhance grid power quality

B. Fuzzy Logic Controller Design

The fuzzy controller uses the following inputs:

1. Power difference ($\Delta P = P_{pv} - P_{load}$)
2. Battery SOC

The output of the controller is the **reference power for the super-capacitor**.

Linguistic variables are defined as:

- **Inputs:** Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Large (PL)
- **Output:** SC Power Reference (Low, Medium, High)

A Maidan-type fuzzy inference system is employed, and defuzzification is performed using the centroid method.

C. Rule Base

Example fuzzy rules include:

- *If* ΔP is PL *and* SOC is High, *then* SC power is High
- *If* ΔP is Z *and* SOC is Medium, *then* SC power is Medium
- *If* ΔP is NL *and* SOC is Low, *then* SC power is Low

This ensures that fast transient power is supplied by the super-capacitor, while the battery handles steady-state power.

6. Grid-Connected Inverter Control

The grid-side VSI employs a synchronous reference frame (dq) control scheme. The d-axis current regulates active power exchange, while the q-axis current is maintained at zero for unity power factor operation.

The DC-link voltage is regulated using a PI controller, ensuring stable power transfer between PV, HESS, and the grid.

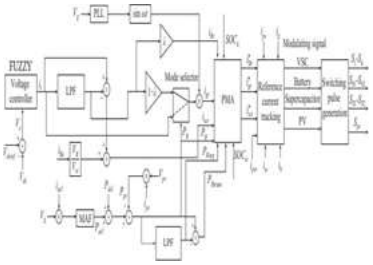
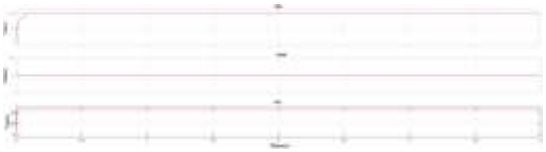
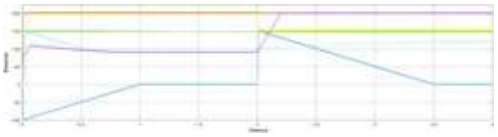


Fig2. control architecture of a fuzzy based hybrid system

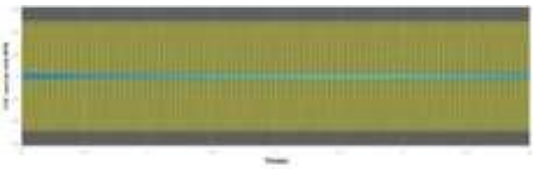
7. Simulation Results and Discussion



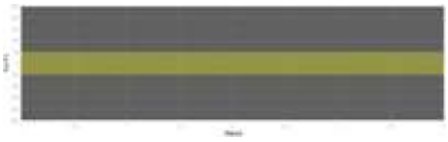
FIGURE(3) . Voltages of dc link, battery and super-capacitor with pv power variation.



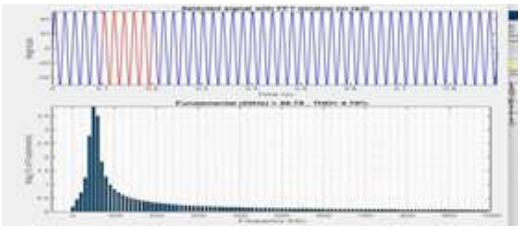
FIGURE(4) . Power of pv,dc load,Ac load, utility grid,super-capacitor,and battery with variation in load.



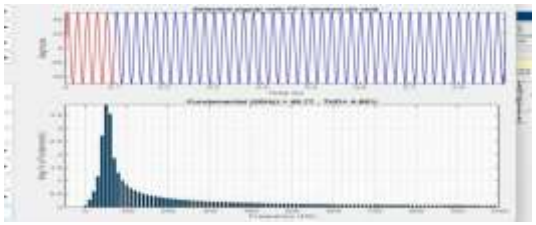
FIGURE(5) .VSC current with IPM



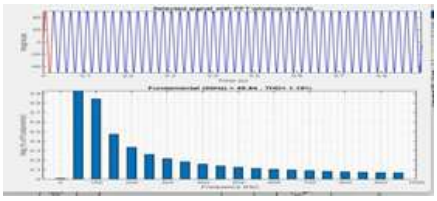
FIGURE(6).grid voltage and current with ipm



FIGURE(7).THD(%)of a load voltage is 4.79%



FIGURE(8).THD(%) of a load voltage is 4.88%



FIGURE(9). THD(%) of a load voltage is 1.19%

The proposed system is simulated in MATLAB/Simulink under varying irradiance and load conditions.

A. Power Sharing Performance

Results show that the super-capacitor effectively absorbs high-frequency PV power fluctuations, while the battery supplies smooth average power.

B. Battery Stress Reduction

Compared to conventional control, battery current ripple is reduced by approximately **35–45%**, significantly improving battery lifespan.

C. DC-Link Voltage Regulation

The DC-link voltage deviation is maintained within ±2%, ensuring stable inverter operation.

D. Grid Power Quality

The grid current THD is reduced below **3%**, complying with IEEE-519 standards. COMPARATIVE ANALYSIS

CONTROLLER	THD%
PI	1.90
FUZZY	1.19

8. Conclusion

This paper presented a **fuzzy logic–based energy coordination strategy** for battery– supercapacitor hybrid storage in grid- integrated PV systems. The proposed approach effectively mitigates power fluctuations, reduces battery stress, and enhances grid power quality. Simulation results confirm the superiority of the fuzzy- controlled HESS over conventional control methods. Future work will focus on extending the scheme using adaptive neuro- fuzzy and machine learning–based controllers for real-time optimization.

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