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PERFORMANCE OPTIMIZATION AND ENERGY MANAGEMENT OF A GRID-CONNECTED PHOTOVOLTAIC SYSTEM INTEGRATED WITH BATTERY–SUPERCAPACITOR HYBRID ENERGY STORAGE

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Abstract: This paper presents the design, modeling, and dynamic performance evaluation of an intelligent energy management framework for a grid-connected photovoltaic (PV) DC microgrid integrated with a Hybrid Energy Storage System (HESS). Modern electrical networks increasingly adopt solar PV technology due to its clean characteristics and sustainability; however, its output remains highly susceptible to environmental fluctuations such as changing solar irradiance. To overcome these challenges, a battery–supercapacitor hybrid storage configuration is interfaced via bidirectional DC–DC converters (BDDC) to decouple average energy demand from high-frequency power transients. A high-gain quadratic boost converter interfaces the PV array with the common DC bus, and a voltage source converter (VSC) with an LC filter provides bidirectional synchronization with the AC utility grid. A Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm replaces conventional proportional-integral (PI) current controllers to optimize energy harvesting. Implemented in MATLAB/Simulink, the system maintains a regulated DC-link voltage of 100 V across dynamic transitions. Under an irradiance reduction from 1000 W/m² to 700 W/m² at t = 2 s, the proposed MPPT scheme sustains PV power at 430 W compared to 250 W under conventional PI control. Furthermore, utility grid current total harmonic distortion (THD) is restricted to 1.05%.

***Index Terms* -** Photovoltaic Microgrid, Hybrid Energy Storage System, Quadratic Boost Converter, Perturb and Observe MPPT, DC-Link Voltage Regulation.

I. INTRODUCTION

1.1 Background

Modern power systems are increasingly emphasizing the adoption of clean and sustainable energy technologies in response to growing concerns regarding energy conservation and environmental protection. Today, the combustion of fossil fuels such as coal, oil, and natural gas accounts for approximately 80% of atmospheric CO_2, with roughly half of this total originating from the generation of electricity. Non-renewable resources are finite, undergo severe price volatility, and emit hazardous pollutants including SO_2, CO, NO_x, hydrocarbons, and greenhouse gases that accelerate global warming and climate change.

Among available renewable energy options, solar photovoltaic (PV) systems have achieved widespread deployment due to cost-effectiveness, zero fuel consumption, silent operation, modular scalability, and minimal maintenance requirements. Despite these benefits, solar PV power generation is inherently intermittent and heavily dependent on environmental parameters such as solar irradiance, ambient temperature, humidity, and partial shading. To address power generation mismatches and maintain power quality, Energy Storage Systems (ESS) are integrated into microgrids. Chemical batteries provide high energy density for sustained energy delivery but suffer from limited power density, restricting their capability to handle rapid charging and discharging transients. Conversely, supercapacitors possess high power density and fast dynamic response but store limited energy. Therefore, a Battery–Supercapacitor Hybrid Energy Storage System (HESS) exploits these complementary characteristics to smooth fluctuations, reduce battery current stress, and prolong battery service life.

1.2 Research Problem

The integration of solar PV generation and hybrid energy storage into grid-connected DC microgrids poses severe operational and control difficulties. Unpredictable variations in solar irradiance create rapid power imbalances between generation and connected loads, leading to DC-link voltage fluctuations, poor power quality, and dynamic instability. In standard microgrid topologies, PV arrays are regulated using conventional proportional-integral (PI) current controllers that fail to operate continuously at the Maximum Power Point (MPP) during sudden environmental transitions. Consequently, solar energy utilization remains sub-optimal, placing excessive energy balancing burdens on the storage bank and the AC utility grid.

Furthermore, traditional energy storage configurations rely exclusively on chemical batteries to absorb both steady-state imbalances and high-frequency power spikes. This continuous dynamic stress accelerates electrochemical degradation, reduces system efficiency, and shortens battery operational lifespan. Additionally, stepping up low-voltage PV generation to distribution DC bus levels requires large voltage conversion ratios, which standard single-stage boost converters cannot deliver efficiently without operating at extreme duty ratios and high conduction losses.

1.3 Research Objectives

The primary objectives of this study are formulated as follows:

- To design and model an intelligent, coordinated energy management architecture for a grid-connected PV system integrated with a battery–supercapacitor HESS in MATLAB/Simulink.
- To implement a high-gain single-switch quadratic boost converter to interface the low-voltage PV array with the common 100 V DC distribution bus.
- To integrate a Perturb and Observe (P&O) MPPT control technique, replacing conventional PI current control, to maximize power extraction under variable irradiance.
- To establish a Power Management Algorithm (PMA) that coordinates power sharing between the battery, supercapacitor, utility grid, and loads based on the battery State of Charge **(SOC_b)** and dynamic frequency decomposition.
- To perform comparative evaluations between conventional PI control and the proposed MPPT-based scheme regarding DC-bus stability, PV power yield, battery stress reduction, and grid current total harmonic distortion (THD).

II. LITERATURE REVIEW

2.1 Overview of Renewable and Energy Storage Systems

Distributed generation, converter topologies, and energy storage coordination have been extensively explored in recent literature. Sadek et al. [8] introduced fuzzy logic-based MPPT controllers to enhance tracking speed and stability over conventional tracking under variable ambient conditions. Patel [1] evaluated bidirectional buck–boost converters using PWM switching to provide stable voltage conversion and low ripple for storage and vehicle applications. Abouobaida and Cherkaoui demonstrated coordinated converter control for grid-integrated DFIG wind systems, achieving unity power factor and effective active/reactive power management. Rana et al. [7] compared P&O and Incremental Conductance algorithms, establishing the necessity of dynamic duty-ratio adjustment for peak power harvesting.

Regarding energy storage architectures, Ogunniyi and Pienaar [3] highlighted the critical role of battery storage in balancing renewable intermittency, while Mousavi et al. presented comprehensive reviews of flywheel storage interfaces. Dalla Vecchia et al. [6] verified that hybrid active switched-capacitor commutation cells achieve conversion efficiencies near 95%, demonstrating the viability of high-gain DC–DC converter structures. Furthermore, Dida [2] proposed adaptive MPPT control combining fuzzy logic with P&O for wind conversion systems, highlighting the importance of independent active and reactive power regulation across grid-side and machine-side converters. Additional studies by Shahgholian [4] and Asif & Sardar Ali [5] underlined microgrid stability and power quality enhancement via coordinated battery interfaces.

2.2 Gap in the Existing Literature

Despite advancements, several notable gaps remain in existing research:

- Most reported microgrid energy management schemes rely solely on battery storage, causing excessive battery current stress and premature aging during sudden generation and load shifts.
- The coordinated power-sharing dynamics of battery–supercapacitor hybrid configurations remain under-investigated regarding high-frequency transient decoupling.
- Many conventional topologies fail to combine high-gain DC step-up conversion, MPPT optimization, and HESS power-flow coordination within a unified control loop.
- Prior systems frequently rely on complex, computationally heavy control strategies that increase hardware complexity, whereas simple current PI controllers fail to extract peak solar energy during dynamic irradiance drops.

III. RESEARCH METHODOLOGY & SYSTEM MODELING

3.1 System Architecture and Topology

The investigated microgrid topology incorporates a PV array, a battery bank, an electric double-layer supercapacitor, and an AC utility grid serving both DC and AC loads. A high-gain single-switch quadratic boost converter interfaces the PV array with the common DC bus. The battery and supercapacitor are connected to the DC bus via independent Bidirectional DC–DC Converters (BDDCs). A bidirectional Voltage Source Converter (VSC) with an output LC filter **(L_f = 10 mH, C_f = 1 μF)** provides interfacing with the 230 V, 50 Hz AC utility grid.

3.2 Power Management Algorithm (PMA)

The PMA evaluates the net power mismatch **$P_{net} = P_{pv} - P_{load}$.** A low-pass filter (LPF) splits the uncompensated power into high-frequency transient components and low-frequency average components. The supercapacitor absorbs or supplies the rapid transient currents **(I_{sc}*),** shielding the battery from high dynamic stress. The battery and utility grid share the low-frequency average current demand according to a weighting parameter λ, determined by the battery state of charge **(SOC_b)**:

- **$0.7 < SOC_b < U$: $\lambda = 1.0$, $1 - \lambda = 0.0$** (Battery provides full average support).
- **$0.5 < SOC_b < 0.7$: $\lambda = 0.6$, $1 - \lambda = 0.4$** (Shared battery and grid support).
- **$0.1 < SOC_b < 0.5$: $\lambda = 0.3$, $1 - \lambda = 0.7$** (Grid provides primary deficit).
- **$SOC_b < L$: $\lambda = 0.0$, $1 - \lambda = 1.0$** (Grid supplies total load demand).

3.3 Converter Control and MPPT Integration

Discrete PID controllers regulate converter duty ratios to track generated reference currents **(I_{sc}*, I_b*, I_g*)**. The P&O MPPT controller periodically samples instantaneous PV voltage **(V_{pv})** and current **(I_{pv}),** calculating power **$P(k) = V(k) \times I(k)$**. Perturbations in duty ratio **($\Delta D = \pm 0.05$)** are executed based on the gradient signs of ΔP and ΔV to track the maximum operating point where **$dP_{dc}/dV_{dc} = 0$**.

IV.PRESENT WORK

4.1 Mathematical Modeling of Energy Storage Elements

The battery terminal voltage **V_b** and State of Charge **(SOC)** are modeled as nonlinear functions of discharge current **i_b** and operational time:

$$V_b = V_o + R_b \cdot i_b - K \cdot [\, Q / (Q - \textstyle\int i_b\, dt) \,] + A \cdot \exp(B \textstyle\int i_b\, dt) \qquad (1)$$

$$SOC = 100 \cdot [\, 1 + (\textstyle\int i_b\, dt / Q) \,] \qquad (2)$$

where **V_o** is open-circuit voltage, **R_b** is internal resistance (0.5 Ω), **K** is polarization voltage, **Q** is nominal capacity (14 Ah), and **A**, **B** are exponential parameters.

Bidirectional buck–boost converters interface the storage elements with the DC bus. In forward step-down mode, switch **T_1** is modulated while **T_2**, **T_3**, **T_4** remain open; in step-up mode, **T_2** is pulsed while **T_1** remains closed. Reverse power flow is achieved symmetrically by modulating switches **T_3** and **T_4**.

4.2 Quadratic Boost Converter Dynamics

The single-switch quadratic boost converter provides a quadratic voltage conversion ratio **$1 / (1 - D)^2$,** allowing significant step-up conversion from low-voltage PV modules to the 100 V DC bus without extreme duty cycles. The circuit operates in two continuous conduction modes:

Mode 1 (Switch S Closed): Active switch S is turned ON, forward-biasing diode $\mathbf{D_2}$ while reverse-biasing diodes $\mathbf{D_1}$ and $\mathbf{D_3}$. Inductors $\mathbf{L_1}$ and $\mathbf{L_2}$ store energy simultaneously from input source $\mathbf{V_{in}}$ and intermediate capacitor $\mathbf{C_1}$.

Mode 2 (Switch S Open): Active switch S is turned OFF, causing $\mathbf{D_2}$ to become reverse-biased while $\mathbf{D_1}$ and $\mathbf{D_3}$ become forward-biased. Inductors $\mathbf{L_1}$ and $\mathbf{L_2}$ release stored magnetic energy, charging capacitors $\mathbf{C_1}$ and $\mathbf{C_2}$ and supplying power to the DC bus load.

4.3 Simulation Parameters

The microgrid was modeled in MATLAB/Simulink (R2016) using the technical parameters listed in Table 1.

Table 1: microgrid system simulation parameters

Subsystem / Component	Design Specification
PV Open-Circuit Voltage (**Voc**)	41.8 V
PV Short-Circuit Current (**Isc**)	5.05 A
PV Maximum Continuous Current (**Imc**)	19 A
Battery Capacity (**Q**) / Voltage (**VB**)	14 Ah / 12 V
Battery BDDC Parameters	$\mathbf{R_b = 0.5\ \Omega, L_b = 5\ mH, C_b = 220\ \mu F, C_{db} = 220\ \mu F}$
Supercapacitor BDDC Parameters	$\mathbf{L_{sc} = 5\ mH, C_{dsc} = 220\ \mu F}$
VSC Grid Filter Parameters	$\mathbf{L_f = 10\ mH, C_f = 1\ \mu F, C_{di} = 2200\ \mu F}$
DC Bus Voltage (V_{dc}) / Grid Rating	100 230 V, 50 Hz

4.4MPPT and Energy Management Control Implementation

The Tracking Algorithm Samples **V(K)** And **I(K)** To Compute Power **P(K)**. If **ΔP > 0** And **ΔV > 0**, The Duty Ratio Is Decremented **(D(K) = D(K−1) − ΔD)**; If **ΔP > 0** And **ΔV < 0**, It Is Incremented **(D(K) = D(K−1) + ΔD)** With Step Size ΔD = 0.05. The Discrete PID Controller Stabilizes The Operating Point Around The Maximum Power Curve ($\mathbf{Dp_{dc}/Dv_{dc} = 0}$). Concurrently, The Grid-Side VSC Regulates Bidirectional AC/DC Power Flow Using Phase-Locked Loop (PLL) Synchronization, Maintaining Grid Current At
Unity Power Factor.

V. RESULTS AND DISCUSSION

The proposed microgrid model was evaluated under dynamic environmental variations in MATLAB/Simulink. At **t = 2.0** s, a step reduction in solar irradiance from 1000 W/m² to 700 W/m² was applied to assess tracking dynamic performance and bus stability.

Table 2: comparative performance summary (conventional pi vs. proposed mppt)

Performance Metric	Conventional PI Control	Proposed P&O MPPT
Extracted PV Power (t < 2 s, 1000 W/m²)	500 W	500 W
Extracted PV Power (t > 2 s, 700 W/m²)	250 W	430 W (+72% yield)
Grid Current THD	Uncompensated	1.05% (IEEE 519 Compliant)
DC-Link Voltage Regulation	Sluggish recovery	Fast recovery (100 V nominal)
Grid Operating Frequency	Frequency fluctuations	50.0 Hz stabilized

Under conventional PI current control, PV power dropped steeply from 500 W to 250 W when irradiance decreased. In contrast, the P&O MPPT controller adjusted the converter duty cycle, maintaining power extraction at 430 W—representing a 72% relative gain in harvested solar energy under reduced irradiance. Throughout the transition at t = 2 s, the supercapacitor absorbed the high-frequency power surge, while the battery and utility grid supplied the average deficit according to λ rules. This frequency decoupling effectively eliminated battery current stress, suppressed DC voltage dips, and restored the DC bus to 100 V nominal rapidly. Fast Fourier Transform (FFT) analysis confirmed that the grid current THD remained at 1.05%, well within the IEEE 519 standard threshold of 5%.

VI. FUTURE SCOPE

- Integration of additional renewable energy sources such as Doubly-Fed Induction Generator (DFIG) wind turbines and fuel-cell units into the existing DC microgrid bus.
- Upgrading the conventional fixed-step P&O MPPT algorithm to advanced techniques, such as Beta MPPT or adaptive neuro-fuzzy algorithms, to eliminate steady-state oscillations.
- Replacement of conventional linear PI converter controllers with nonlinear adaptive sliding mode or hybrid controllers for improved transient voltage settling.
- Hardware-in-the-loop (HIL) experimental prototyping to evaluate real-time switching losses and hardware efficiency.

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