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Analysis of Renewable Energy Generation Using a Hybrid Energy Storage System

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Abstract- With the growing demand for efficient and reliable Energy Storage Systems (ESS), conventional battery-based systems face limitations such as low power density, slow charging, and reduced lifespan due to aging. Supercapacitors, on the other hand, offer high power density and rapid charge-discharge capability but suffer from low energy density. This paper presents the design and simulation of a Supercapacitor Based Hybrid Energy Storage System (HESS) that combines the advantages of both battery and supercapacitor. The proposed system ensures efficient power sharing, fast dynamic response, reduced battery stress, and stable DC bus voltage under varying load conditions. The system is built and simulated in MATLAB/Simulink, and the results demonstrate improved efficiency and enhanced performance.

Index Terms- Hybrid Energy Storage System, Supercapacitor, Battery, DC-DC Converter, Power Sharing, DC Bus.

I. INTRODUCTION

The rapid growth in global energy demand, along with increasing environmental concerns, has accelerated the integration of renewable energy sources such as solar photovoltaic (PV) and wind energy into modern power systems. Renewable energy systems are clean and sustainable; however, their intermittent and fluctuating nature creates challenges in maintaining stable and reliable power supply. Variations in irradiance, temperature, and load demand lead to voltage instability and power imbalance in electrical networks. Therefore, efficient Energy Storage Systems (ESS) have become an essential component in modern power systems.

Among various storage technologies, batteries are widely used due to their high energy density and ability to supply power over long durations. Lithium-ion and lead-acid batteries are commonly employed in renewable energy systems, electric vehicles, and microgrid applications. However, batteries suffer from several limitations:

- Low power density: This limits their ability to deliver large bursts of power within short time intervals. In renewable energy systems where sudden fluctuations in generation or load occur, batteries alone may not effectively handle rapid power transients, potentially leading to voltage deviations and reduced system stability.
- Slow response to sudden load changes: During abrupt load changes or short-duration disturbances in microgrids and distributed generation systems, batteries may not respond instantaneously, which can compromise power quality and frequency regulation performance.
- Limited charge-discharge cycle life: Frequent cycling, especially under partial state-of-charge conditions common in renewable applications, accelerates battery degradation. Over time, repeated deep charge-discharge cycles reduce storage capacity and efficiency, increasing maintenance requirements and replacement costs.
- Thermal stress and aging effects: Elevated operating temperatures, high discharge rates, and improper thermal management can lead to thermal stress, capacity fading, internal resistance growth, and safety concerns.

Supercapacitors provide an alternative energy storage solution characterized by:

- Very high power density: Unlike batteries, supercapacitors possess exceptionally high power density. This makes them highly effective in handling sudden load changes, voltage sags, and power fluctuations commonly observed in solar PV and wind energy systems.

- Fast charging and discharging capability: Supercapacitors store energy in the form of electrostatic charge rather than chemical reaction, allowing rapid charging and enabling immediate compensation of transient disturbances, thereby improving voltage regulation and enhancing grid stability.
- High cycle life: Due to the absence of significant chemical degradation mechanisms, supercapacitors can withstand millions of charge-discharge cycles with minimal performance degradation.

However, supercapacitors have relatively low energy density, meaning they cannot supply power for long durations. To overcome the individual limitations of batteries and supercapacitors, a Hybrid Energy Storage System (HESS) is proposed. The hybrid system combines the high energy density of batteries with the high power density of supercapacitors, ensuring optimal utilization of both storage devices.

II. SYSTEM CONFIGURATION

A. Battery Energy Storage System

The battery acts as the primary energy storage source and is responsible for supplying long-term and average power demand. It has high energy density and is suitable for steady-state operation. During normal operating conditions, the battery supplies constant power to the load. When excess energy is available, the converter operates in buck mode to charge the battery. During load demand, it operates in boost mode to supply energy to the DC bus.

B. Supercapacitor Energy Storage System

The supercapacitor is integrated to handle high peak power demand and transient load variations. Due to its high power density and fast response, it compensates for sudden changes in current demand. The supercapacitor is also connected to the DC bus via a bidirectional DC-DC converter. The supercapacitor operates mainly during dynamic conditions and protects the battery from frequent high current fluctuations.

C. Bidirectional DC-DC Converters

Two separate buck/boost converters are used: (1) Battery Side Converter and (2) Supercapacitor Side Converter. These converters enable bidirectional power flow and allow independent current control, voltage regulation, and controlled charging/discharging. The converters consist of MOSFET/IGBT switches, an inductor, an output capacitor, and a PWM control circuit. A unidirectional DC-DC converter is also used between the MPPT and DC Bus.

D. DC Bus

The DC bus acts as the central power distribution point where both energy storage systems and load are connected. The DC bus voltage is maintained constant. The DC link capacitor connected across the bus minimizes voltage ripple, stabilizes system operation, and supports transient response. Maintaining constant DC bus voltage is the primary control objective of the system.

E. Control Unit and PWM Generation

A PI (Proportional-Integral) controller is implemented to regulate the DC bus voltage and manage power sharing between battery and supercapacitor. The controller performs:

1. DC bus voltage sensing
2. Error calculation (Reference − Actual Voltage)
3. Generation of reference current
4. Distribution of current between battery and supercapacitor
5. PWM pulse generation for converters

F. Sensors and Feedback System

Sensors provide real-time feedback to the controller, ensuring stable operation and accurate power sharing. The system includes voltage sensors (DC bus, battery, supercapacitor) and current sensors (battery current, supercapacitor current, load current).

III. MATHEMATICAL MODEL OF A HYBRID ENERGY STORAGE SYSTEM

To analyse the performance and stability of the proposed Supercapacitor Based Hybrid Energy Storage System (HESS), mathematical modelling of each subsystem is required. The dynamic behaviour of the battery, supercapacitor, and DC-DC converters determines the overall system performance.

A. Battery Modelling

The battery is modelled using an equivalent circuit consisting of Open Circuit Voltage (Voc), Internal Resistance (Rb), and an RC network for transient behaviour. The terminal voltage of the battery is given by:

$$Vb = Voc - Ib \times Rb \quad ...(1)$$

where Vb = Battery terminal voltage, Voc = Open circuit voltage, Ib = Battery current, Rb = Internal resistance. The State of Charge (SOC) of the battery is:

$$SOC = SOC0 - (1/Cb) \int Ib\, dt \quad ...(2)$$

where Cb = Battery capacity (Ah). The battery mainly supplies low-frequency and steady-state power.

B. Supercapacitor Modelling

The supercapacitor is modelled as a capacitor in series with an equivalent series resistance (ESR). The voltage across the supercapacitor is:

$$Vsc = (1/Csc) \int Isc\, dt - Isc \times Rsc \quad ...(3)$$

where Csc = Supercapacitor capacitance, Rsc = ESR, Isc = Supercapacitor current. Due to its high capacitance and low internal resistance, the supercapacitor responds quickly to high-frequency load variations.

C. DC-DC Converter Modelling

The bidirectional DC-DC converter operates in buck mode (charging) and boost mode (discharging). For boost operation:

$$Vo = Vin / (1 - D) \quad ...(4)$$

For buck operation:

$$Vo = D \times Vin \quad ...(5)$$

where D = Duty cycle of PWM, Vin = Input voltage, Vo = Output voltage. The inductor current equation is:

$$L\, (di/dt) = Vin - Vo \quad ...(6)$$

These equations are used to design the controller and ensure stable operation.

IV. CONTROL STRATEGY AND POWER MANAGEMENT

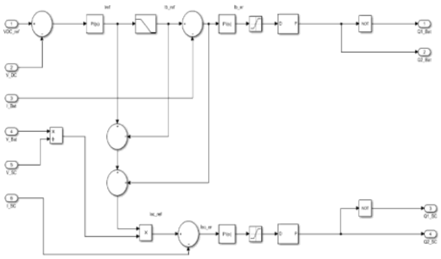

Fig. 1. Proposed Control Strategy

Efficient control is essential for proper power sharing between the battery and supercapacitor.

A. Voltage Control Loop

The DC bus voltage is continuously monitored and compared with the reference voltage. The error signal is:

$$e(t) = Vref - Vdc \quad ...(7)$$

This error is processed through a PI controller:

$$Iref = Kp \times e(t) + Ki \int e(t)dt \quad ...(8)$$

The output of the voltage controller generates the total reference current required by the system.

B. Current Sharing Strategy

The total reference current is divided into low-frequency component (Battery) and high-frequency component (Supercapacitor). A Low Pass Filter (LPF) separates the signals:

$$Ibattery = LPF(Iref) \quad ...(9)$$

$$Isc = Iref - Ibattery \quad ...(10)$$

- Battery Handles Steady (Low-Frequency) Power: The low-frequency component corresponds to gradual changes in load demand. Batteries are well-suited for supplying steady-state power due to their high energy density, reducing thermal stress and extending battery life.
- Supercapacitor Handles Transient (High-Frequency) Power: The high-frequency component represents rapid load variations. Supercapacitors have very high power density and fast dynamic response, preventing the battery from experiencing sharp current fluctuations and improving overall system stability.

C. PWM Pulse Generation

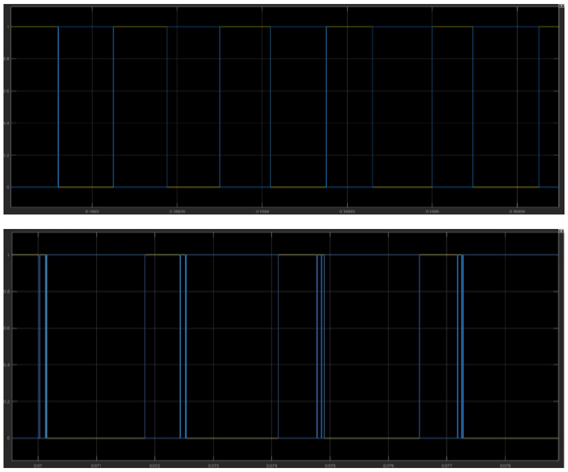

Fig. 2. PWM Switching Pulse

The current error signal is processed through a PI current controller to generate a control voltage. This control voltage is compared with a high-frequency triangular carrier waveform to produce PWM gating signals for the MOSFET/IGBT switches. High switching frequency ensures: (1) Reduced Ripple - lower amplitude of current and voltage ripple; (2) Improved Efficiency - smaller passive components and reduced conduction losses; and (3) Better Dynamic Response - faster correction of current errors during sudden load variations.

V. PERFORMANCE ANALYSIS

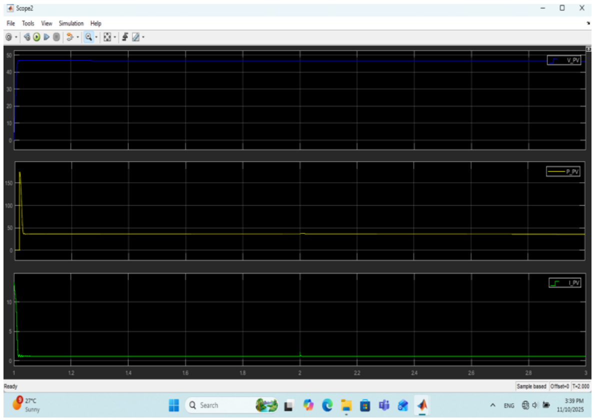

Fig. 3. Output of MPPT

The performance of the system is evaluated under dynamic load conditions.

A. Transient Response

When load suddenly increases, the supercapacitor supplies immediate current due to its high power density and low internal resistance, preventing a sharp drop in DC bus voltage. The battery gradually increases output through the low-pass filtered current reference. When load decreases, excess energy is quickly absorbed by the supercapacitor, minimizing voltage overshoot and stabilizing the system.

B. Battery Stress Reduction

Because peak current is handled by the supercapacitor, battery current ripple is reduced, thermal stress decreases, and cycle life improves. By avoiding frequent high-current spikes and deep rapid cycling, battery aging mechanisms slow down, extending usable cycle life and improving long-term reliability.

C. Efficiency Improvement

The hybrid configuration provides reduced energy losses as supercapacitors handle high transient currents with minimal internal resistance losses. Smoother battery current reduces stress on DC-DC converters, enabling more stable duty cycle control. The coordinated operation results in faster settling time, improved voltage regulation, reduced component stress, and increased operational lifespan.

VI. CONCLUSION

This paper presented the design and simulation of a Supercapacitor Based Hybrid Energy Storage System (HESS) that effectively combines the complementary characteristics of batteries and supercapacitors. The battery handles steady-state and low-frequency power demands while the supercapacitor manages transient and high-frequency power requirements. The PI controller-based voltage regulation ensures stable DC bus voltage under dynamic load conditions. Simulation results in MATLAB/Simulink demonstrate improved efficiency, reduced battery stress, minimized voltage ripple, and enhanced overall system performance. The proposed HESS proves to be a viable and efficient solution for modern renewable energy applications.

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