Photovoltaic with Battery and Supercapacitor Energy Storage System for Better Performance Devices and Modelling

Somesh Harinkhede and Prajakta Vaidya

Abstract This paper's objective is to show how battery and supercapacitor devices are superior. When compared with traditional battery energy storage systems (BEES), the proposed different energy storage system by battery and supercapacitor has advantages that it can store surplus energy and use it again when necessary. This paper discusses several energy storage systems that can be utilized with renewable energy sources like solar energy and as remote or backup energy storage systems when there is no functioning electrical grid. In order to maximize this system's efficiency, supercapacitors will be employed in parallel with the battery and load pulsed. In addition to the foregoing, this paper presents the modelling of battery and supercapacitor-based different energy storage systems using MATLAB/Simulink software.

Keywords Photovoltaic (PV) · Energy storage system (ESS) · Battery energy storage system (BESS) · Supercapacitor (SC) · Supercapacitor energy storage system (SCESS)

1 Introduction

An energy storage system, which is the process of converting excess electricity into other kinds of energy, can then be used to produce electrical energy (ESS). We concentrate on battery and supercapacitor energy storage systems among others, but energy storage systems (ESS) can be applied to both traditional and renewable energy sources, storing energy in the form of mechanical, electrostatic, electrochemical, thermal energy, etc., that can be used whenever necessary. When demand exceeds supply, there is an imbalance between the two, which leads to various issues with the power grid, including decreased power quality, decreased efficiency, decreased

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dependability and stability of the system, and introduces many losses that are avoided by ESS systems. Energy storage devices are commonly utilized in both permanent and transient activities, making them one of the most prominent and effective instruments for the proper operation of smart grids and micro grids. Electric energy storage systems (EESS) are frequently utilized for frequency and voltage control (stability enhancement), as well as dynamic compensation of energy with high renewable energy penetration, in the latter instance. Batteries are a common technique for peak shaving in the former [1–3].

The following are four more major advantages of EESS:

(a) There is no need to convert electrical energy into chemical or mechanical energy.
(b) Bidirectional functionality.
(c) A deep discharge capacity and high-power density.
(d) Less useable life deterioration per charge/discharge cycle. EESS frequently includes flywheel energy storage (FWES), superconducting magnetic energy storage (SMES), and supercapacitor energy storage (SCES) technologies.

In order to preserve system stability and prevent the negative effects of power transients on battery life, the battery/supercapacitor hybrid energy storage system (HESS) concept was developed. In this hybrid system, batteries and supercapacitors are used combined. Batteries, with their enormous storage capacity, offer a steady source of energy, while SC, with their high power efficiency and rapid adaptability, supply unexpected peak powers during transients. As a result, the battery experiences less strain, lives a longer time, avoids expensive battery replacement, and the system reliability is improved.

In this study, a solar power system that operates independently with an operational battery and SC HESS is investigated. A method is developed to control power sharing between the PV and ESS sections in order to assure energy balance and preserve voltage stability at the DC-bus. The battery makes up for consistent power drifts while the SC is forced to handle quick transients by the applied ESS control. In addition, the PV control has been changed to optimize charging a battery according to its maximum state of charge (SOC), preventing degradation and lengthening battery life. To test the effectiveness of the system under various load and irradiance profiles, simulation tests are conducted using MATLAB/Simulink. The latter is reassured by a new test of system performance using a commercial load and real-time weather information [2–4].

2 Energy Storage Systems Devices

2.1 Energy Storage System (ESS)

Wind and photovoltaic (PV) energy are two examples of renewable energy sources that are widely employed as independent power systems to support a variety of electrical demands in remote and rural areas. Because of the sporadic nature of these sources, storage battery banks should be included in stand-alone power systems. When extra energy is stored in storage battery banks and sent to the load bank when solar or wind energy is unavailable or insufficient, this increases system reliability. As storage battery banks, mostly lithium-ion and lead-acid batteries are employed. After hundreds of charging-discharging cycles, battery energy storage systems (BESS) require routine battery replacement because cycle efficiency is low. Because of its high-energy density, efficiency, long battery life, low cost, and environmental friendliness, lead acid has advantages in the energy storage system (ESS) market. Because lead-acid batteries have a cheap cost per energy, they are appropriate for large-scale energy storage. Both pulsing power loads and continuous power loads can be handled by lead-acid batteries [3].

2.2 Lead-Acid Battery

The energy storage system (ESS) industry benefits from lead-acid batteries' high-energy density, efficiency, long battery life, low cost, and environmental friendliness. Lead acid batteries are useful for large-scale energy storage because of their relatively low cost per energy. Both steady and pulsing power loads can be handled by lead-acid batteries.

2.3 Lithium-Ion Cell

Lithium-ion batteries have a greater energy density than lead-acid batteries, a longer lifespan, higher efficiency, less weight, and are more environmentally friendly, but they are also more expensive. Mobile and automotive applications, among others, frequently use lithium-ion batteries.

2.4 Different Energy Storage Methods

A method for storing energy is something that differs from two or more other energy storage systems. In this study, we employed both a supercapacitor battery energy storage system and an energy storage system. The photovoltaic system benefits from the various systems for storing energy in batteries (BESS) and supercapacitors (SCESS), such as the ability to meet peak power demands temporarily, stabilize system voltage, enhance system capabilities, etc. This means battery supercapacitor-based energy storage systems (BSESS) increase the efficiency of the system. Peak load demand and load demand are consistent because diverse storage methods based on battery supercapacitors are too expensive for large-scale deployment. A hybrid storage system can provide more specific power than a battery storage system when a supercapacitor is added. This happens when the system efficiency increases. As the supercapacitor has a higher power density and can thus deliver more power for a shorter time or peak power for a shorter time, we may conclude that the hybrid storage system's charging capacity has increased. Supercapacitors (SC) play a key function in raising the buffer level in various energy storage systems. The battery provides the lower constant power requirement, while the supercapacitor provides reduced size of the battery pack for large storage while providing the load's peak power needs. We may claim that the battery improves the system's storage capacity and the peak power requirements of the load, resulting in a reduction in the size of the battery pack for big storage. We may say the battery enhances the storage system capacity and reduces the system's discharge capacity because it can store more energy and release it over a longer period of time, giving it a much higher density [3–5].

2.5 Benefits of a Battery Supercapacitor Energy Storage System

Long cycle life, energy buffering, increased reliability, and high cycle efficiency are all being pushed as high-energy density and power density, and low rate of self-discharge. Enhance uniformity and efficiency, boost the effectiveness of the electricity system, and use low-cost, lightweight technology for widespread deployment [5–8].

3 Methodology

Consider the electrical connections and control mechanisms between the battery and the supercapacitor (Fig. 1).

Electrical connections and control mechanisms in a photovoltaic (PV) system with a battery and supercapacitor hybrid storage system mechanisms are crucial for proper integration and optimal performance. Here are the key aspects of the electrical connections and control mechanisms between the PV system, battery, and supercapacitor.

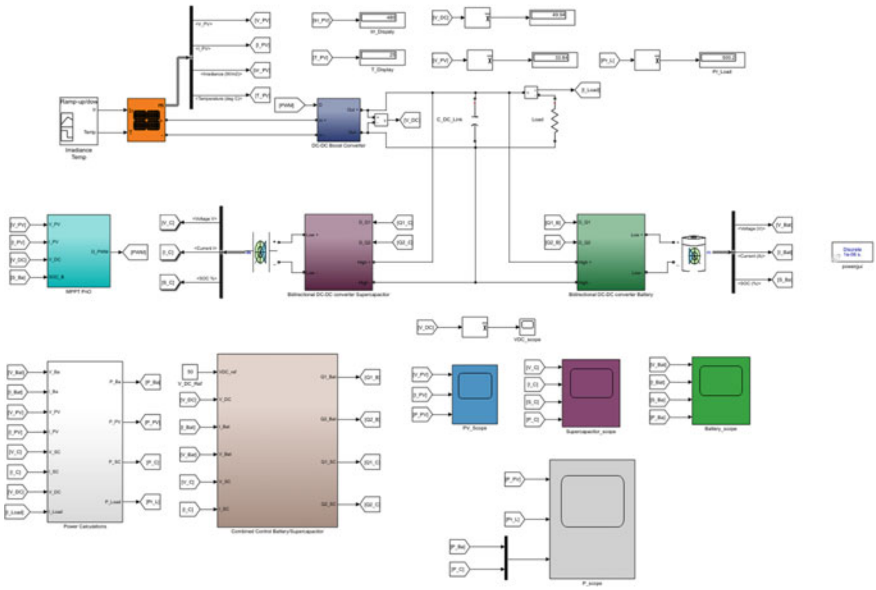

Fig. 1 Block diagram

3.1 Electrical Connections

PV Array to Battery: The photovoltaic array is connected through a charge controller and the battery. The charge controller regulates the charging process, ensuring that the battery receives the appropriate current as well as voltage from the PV array.

Battery to Supercapacitor: The battery and supercapacitor are interconnected through a DC–DC converter. This converter enables the transfer of energy between the two storage devices, allowing efficient energy management and balancing between them.

Supercapacitor and Battery to Load: Both the battery and supercapacitor are connected to the load, which represents the electrical devices or systems that consume energy. The load receives power from either the battery, supercapacitor or a combination of both, depending on the system's control mechanism and energy requirements.

3.2 Control Mechanisms

Energy Management System: The photovoltaic (PV) system, battery, with supercapacitor are all under the supervision of the energy management system (EMS). The EMS monitors the state of charge (SOC) and state of health (SOH) of the battery and supercapacitor, as well as the PV array's output. Based on this information and predefined algorithms, the EMS determines the optimal distribution and utilization of energy between the battery, supercapacitor, and load.

Charger Controller: The controller that controls the charge is necessary for controlling how the battery is charged. In order to avoid overcharging or undercharging, which can reduce battery performance and longevity, it makes sure that the battery receives the proper voltage and current from the PV array.

DC–DC Converter: The converter DC–DC between the battery and supercapacitor manages energy flow and ensures efficient transfer between the two storage devices. It controls the charging and discharging processes, allowing energy to be transferred based on the system's needs and performance requirements.

These electrical connections and control mechanisms enable the seamless integration of the PV system, battery, and supercapacitor. The coordination between these components ensures efficient energy harvesting from the PV array, optimal storage, and discharge of energy using the battery and supercapacitor, and effective management of energy distribution to the load. The control mechanisms play a vital role in maintaining system stability, maximizing energy utilization, and extending the lifespan of the storage devices.

3.3 Elements Are Interconnected as Follows

The DC-DC converter, which controls the voltage and current from the PV array, is linked to the PV array and provides the appropriate input to charge the battery and supercapacitor. Supercapacitor and battery are linked in parallel through the DC–DC converter, allowing energy transfer between the two storage devices based on the system's control mechanism. The load is coupled with the supercapacitor and battery, drawing power from either or both, depending on the energy management system's control strategy. The equivalent circuit model captures the key electrical connections and components in the PV system with a battery and supercapacitor. It provides a simplified representation that helps in analyzing and understanding the energy flow and interactions between the different components in the system [4–15].

3.4 Power Flow and Control

In this study, a power flow control approach is presented to maintain the necessary balance between the production and consumption of energy, maintaining steady DC load voltage. This entails managing the bidirectional converters in the ESS elements to coordinate the distribution of power between the battery and the supercapacitor. It also comes into contact with PV boost converter control in order to accomplish PV MPPT. When the battery is full, the MPPT should switch to DC voltage control mode to prevent battery overcharging.

Power Flow

PV Power Generation: The PV array converts solar energy into electrical power. The generated power depends on factors such as solar irradiation, temperature, and shading. The energy storage system and the load are both powered by the PV array.

Charging and Discharging of Batteries: Battery is charged during periods of excess PV power generation or low load demand. Transferring electrical energy from the PV array to the battery is the process of charging. When demand for load is high or low PV power generation, the battery discharges stored energy to supply power to the load.

Supercapacitor Charging and Discharging: The supercapacitor is primarily used for short-term power requirements and fast response times. It rapidly charges and discharges electrical energy to compensate for sudden load fluctuations and provides power during transient events.

Power Distribution to the Load: The load receives power from both the battery and supercapacitor, depending on the system control strategy. The control mechanism determines the optimal power distribution to the load based on factors such as load demand, available energy from the PV array, battery state of charge (SOC), and supercapacitor voltage [8–12].

Control Strategies

Energy Management System (EMS): The power flow between the PV system, battery, and supercapacitor is monitored and managed by an EMS. It optimizes energy utilization and ensures the efficient operation of the system.

Charge Control: The charge controller regulates the charging process of the battery, ensuring optimal charging voltage and current levels. It prevents overcharging or undercharging, which can affect battery performance and lifespan.

Power Electronics Control: The DC–DC converter between the battery and supercapacitor manages the energy flow and facilitates efficient transfer between the two storage devices. The converter's control mechanism adjusts the voltage conversion ratio and controls the direction of power flow based on system conditions and requirements.

Load Management: The control system manages the distribution of power to the load, optimizing the utilization of available energy from the PV array, battery, and supercapacitor. It considers factors such as load demand, priority settings, and battery and supercapacitor states to determine the plan for distributing the power.

State of Charge (SOC) Voltage Control: The control system monitors the SOC of the battery and voltage of the supercapacitor to ensure they remain within safe and optimal operating ranges. It may implement algorithms to balance the charging and discharging rates to extend the lifetime of the storage devices.

By effectively controlling the power flow and managing energy storage, the system can ensure stable power supply, minimize reliance on the grid, optimize energy utilization, and enhance overall system performance and reliability. It is important for one to understand that the system design might affect the specific power flow and

Table 1 Array module data

Parallel strings	4
Series connect module per string	2
Module Waaree energies	WV-120
Maximum power	120.7 W
Cell per module	72Ncell
Open circuit voltage (*Voc*)	21 V
Short circuit (*Isc*)	8 A
Voltage at maximum power point (*Vmp*)	17 V

control tactics, requirements, and the desired application. Advanced control algorithms and monitoring techniques are often employed to achieve optimal performance and efficiency in PV systems with supercapacitor and battery energy storage.

In summary, the hybrid storage system using batteries and supercapacitors employs chemical reactions in batteries and electrostatic charge separation in supercapacitors to store and release electrical energy. By combining the strengths of these mechanisms, the hybrid system achieves a balance between high-energy capacity and rapid power delivery, enhancing overall performance and ensuring a reliable and efficient energy storage solution [5, 6, 8–23].

4 Calculations and Tables

At various irradiance measurements from the PV array, the characteristics between current and voltage explain the voltage/current and power/voltage characteristics. The irradiance values on the model validate the array's operation and are calibrated in KW/m^2. The highest power is at 1000 irradiance when the current reading is 8A and the voltage is 21 V. According to the results, the voltage at the 0 V reading is 21 V, the open circuit voltage of the PV module and the current at the 0 V reading is 8 A, which represents the short circuit current. The next is a representation of the shift in voltage and power. The highest output power is listed as 12 W with a voltage of 21 V at 1000 irradiance, although this fluctuates (Tables 1 and 2).

5 Result

In Fig. 2 supercapacitor waveform shows the initial voltage (32 V), current (0–10 A), SOC (98.9–99%), and power (0–500).

Simulations may show the outcomes and the system's effectiveness in fulfilling the load's energy requirements and coordinating. The real output voltage's reaction is simulated in the simulation, current, SOC, power of supercapacitor.

Table 2 System component data

Data/quantities	Supercapacitor	Battery
Rated capacitance/capacity	29 F	14 Ah
Operating temperature	25 °C	25 °C
Rated voltages	32 V	24 V
Fully charged voltage	32 V	27.9357 V
Nominal discharge current	10 A	6.087 A
Charge current	10 A	5 Ah
Initial state of charge	98.9%	50%

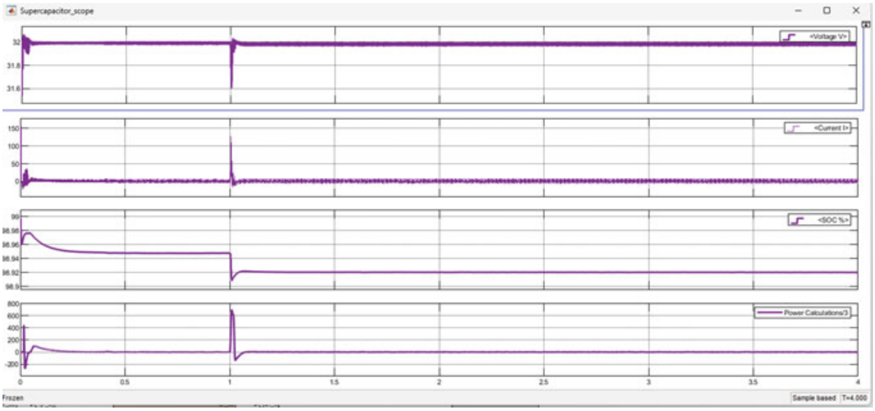

Fig. 2 Behaviour of voltage and current of supercapacitor

For supercapacitor

X axis = time in second (t = 01–04 s).
Y axis = voltage (32 V).
Y axis = current (10 A).

With a starting voltage of 32 V and a current of 10 A, figure depicts the simulation findings and system performance in fulfilling the energy demands of the load and coordination.

The above graph depicts the responsiveness of the real output voltage and current. As illustrated in the simulation, the system reacts by continuing from its origin point and attaining steady state response at time $t = 1$ s and constant voltage as voltage and current are gradually altered from 32 V at time $t = 0$, 31.6 V at time $t = 1$ s, 32 V at time $t = 2$ s, and 32 V at time $t = 3$ s.

Figure 3 shows the battery response with voltage (25–26.5), current (0–10 A), and SOC (50%).

For battery

X axis = time in second (t = 01–04 s).

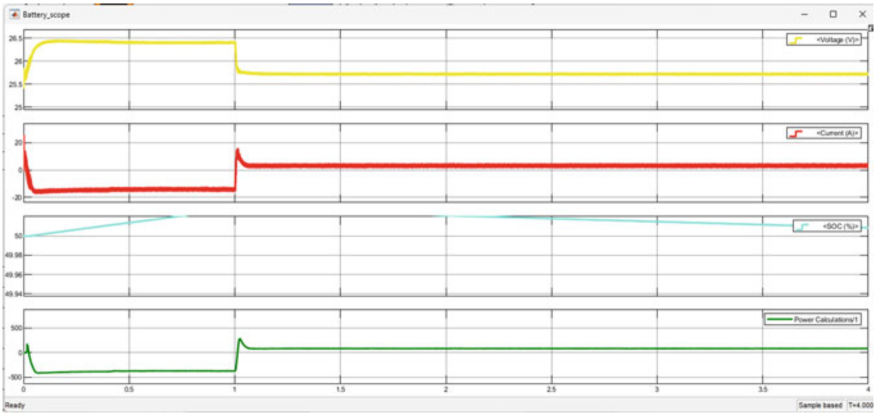

Fig. 3 Response of voltage and current battery

Y axis = voltage (24 V).
Y axis = current (0–10 A).

With a starting voltage of 25.5 V and a current of (0–10A), the figure depicts the simulation findings and system performance in fulfilling the energy demands of the load and coordination. The graph depicts the responsiveness of the real output voltage and current. As illustrated in the simulation, voltage and current are progressively changed.

6 Conclusion

The outcomes show that the overall control technique effectively regulated the power flows between system components in the model. As a result, it established the required balance, met the variable load demand, and preserved DC voltage stability. Supercapacitor significance in enhancing performance and offering the necessary buffer during transients was also clear and readily apparent.

It can be determined from the analysis and discussion findings from the design and modelling of PV integration using the simulation tools MATLAB/Simulink, this combined ESS modelling approach not only enhances system performance but also promotes the utilization of renewable energy sources and reduces reliance on conventional grid infrastructure. By efficiently storing and utilizing excess solar energy, the dependence on non-renewable energy sources is minimized, contributing to a more sustainable and environmentally friendly energy landscape. The project is accelerating the transition to a cleaner and more resilient energy future and the potential of renewable energy.

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