Grid connected solar panel with battery energy storage system

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ABSTRACT

A grid-connected battery energy storage system (BESS) is a crucial component in modern electrical grids that enables efficient management of electricity supply and demand. BESS consists of a set of batteries connected to the power grid, allowing for the storage and release of electricity when needed. This paper addresses the challenges associated with intermittent renewable energy sources and enhancing grid stability and reliability. The primary objective of this work is to store surplus electricity during low demand and supply it to the grid during peak demand periods or when renewable energy generation is low. By storing surplus energy, BESS helps balance supply and demand fluctuations, reducing the need for expensive fossil fuel-based power plants and minimizing greenhouse gas emissions. Additionally, BESS provides frequency regulation, voltage support, and grid stabilization. Furthermore, BESS reduces the intermittency of renewable energy sources like solar and wind, allowing for its integration into the grid. It allows the captured energy to be stored and utilized when the renewable sources are not actively generating electricity. Grid-connected BESS are a vital component in the transition towards a more sustainable and resilient energy future. They facilitate the effective utilization of renewable energy, enhance grid flexibility, and contribute to the reduction of carbon emissions, ultimately promoting a cleaner and more reliable electricity supply. The simulation of grid connected solar system with BESS is carried out using MATLAB/Simulink environment.

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1. INTRODUCTION

A grid-connected solar panel with a battery energy storage system (BESS) is a setup that combines solar power generation with the ability to store excess energy for later use. This system allows to generate electricity from solar panels, use it to power home or business, and store any surplus energy in batteries. It is a type of energy storage system that can store electricity when it is abundant or inexpensive and release it when demand is high or electricity prices are higher.

BESS consists of a set of batteries, power conversion systems, and control equipment. The batteries store electrical energy in chemical form and can be charged and discharged multiple times. The power conversion systems manage the flow of electricity to and from the batteries, converting it to the appropriate voltage and frequency for the connected grid or electrical system. Battery energy storage systems have various applications. They are commonly used to support renewable energy sources by storing excess energy generated during periods of high production and supplying it during periods of low production or high demand. This helps balance the intermittent nature of renewable energy and ensures a more reliable and stable power supply.

BESS also provides grid stabilization services, such as frequency regulation and voltage support. They can respond rapidly to fluctuations in power demand and supply, helping maintain grid stability and improving overall power quality. In addition, battery energy storage systems can be deployed at a smaller scale, such as in homes or commercial buildings, to store energy during low demand and reduce peak demand, thereby optimizing electricity consumption and lowering energy costs.

BESS are often grid-connected due to several advantages and benefits they offer to the electrical grid and energy system as a whole. Here are some reasons why BESS is typically connected to the grid:

- Energy management and grid balancing: Grid-connected BESS allows for efficient management of energy supply and demand. They can store excess electricity during periods of low demand or high renewable energy generation and release it back to the grid when demand is high or renewable generation is low. This helps balance the grid and ensures a reliable and stable power supply.
- Integration of renewable energy: BESS plays a crucial role in integrating renewable energy sources, such as solar and wind, into the grid. These sources are often intermittent and subject to fluctuations. By storing excess energy during peak production periods, BESS can supply electricity during times of low or no renewable generation, thus ensuring a consistent power supply.
- Grid stability: BESS respond rapidly to changes in demand and supply, helping maintain grid stability, improve power quality, and support reliable operation of the electrical grid.
- Demand response and load shifting: Grid-connected BESS allows for demand response and load shifting strategies. They can be charged during off-peak hours when electricity prices are low and supply the stored energy during peak demand periods when electricity prices are higher. This helps reduce peak demand and lowers electricity costs for consumers.
- Grid resilience and backup power: In the event of a power outage or grid failure, grid-connected BESS can provide backup power to critical loads or entire communities. They can be used as an emergency power source to ensure uninterrupted electricity supply during such situations.

These advantages make them an essential component of modern electrical grids, facilitating a more reliable, efficient, and sustainable energy system.

2. LITERATURE SURVEY

Research shows that energy storage systems (ESSs) play a crucial role in the control and stability of microgrids (MGs), offering solutions to the challenges posed by these systems. Various ESS operation configurations and control methods have been discussed in research, highlighting the potential benefits and drawbacks of each approach. A framework for optimizing grid-connected PV/battery systems using TLBO technique is proposed in [1]. The study finds that using backup PV/battery systems can significantly reduce electricity bills and that such systems are more economically efficient than non-renewable alternatives. A methodology for evaluating the performance of a grid-connected system with storage and a time-of-use tariff is provided in [2]. It finds that current battery costs make the system economically unfeasible under existing Spanish TOU tariffs, but backup PV/battery systems can still electricity bills significantly. The profitability of an energy storage system with a lithium-ion battery and power electronic converter connected to a distribution grid is analyzed in [3]. The study finds that the cost of battery storage makes the system unprofitable for consumers at current prices, but proposes the use of a novel optimization algorithm for further analysis. Improving power quality [4] and power factor [5] in a grid-connected system is crucial to ensure efficient and reliable operation of the electrical network while minimizing energy losses and maintaining stable voltage levels. Feehally *et al.* [6] examines the financial viability of grid-connected battery energy storage systems with fast acting control. The study finds that at current battery storage costs, the systems are not profitable for consumers, but introduces a new optimization algorithm and highlights how backup PV/battery systems can still lower electricity bills even in countries with cheap electricity. Malakondareddy *et al*. [7] also explores the potential profitability of using storage systems, but highlights that current costs make it not yet economically viable for consumers. Mousavi *et al.* [8] explores using irrigation infrastructure to store surplus photovoltaic energy in a farmhouse, proposing a controller to efficiently manage the pump and turbine, reducing overall electricity costs and providing a sustainable solution for storing excess energy. Zia *et al*. [9] presents a degradation cost model for the battery to optimize its scheduling and minimize operational cost, along with an islanding-responsive demand response incentive, to enable optimal operation of a grid-connected DC grid consisting of a PV system and Li-ion battery, and emphasizes the importance of considering nodal voltages, system losses, and network constraints for optimal DC microgrid operations, which is validated through numerical simulations. The previous studies [10], [11] explore how integrating battery energy storage with photovoltaic systems in residential houses can increase self-consumption and self-sufficiency rates, but also result in longer payback periods. The research includes technical and economic analysis and reveals that higher self-sufficiency rates lead to more schedulable photovoltaic production, sold electricity, and lower battery usage, resulting in larger profits despite higher initial investment. A genetic algorithm is proposed in [12] to optimize grid-connected photovoltaic-battery systems for residential houses, which greatly reduces electricity imports and costs while minimizing environmental impact through joint battery and photovoltaic optimization. Sharma *et al*. [13] proposes a method to determine the optimal size of a BESS for a net zero energy home with rooftop solar, which by transferring less energy to the grid can assist in lowering the electricity cost. The study shows that installing a BESS is economically beneficial for homeowners in South Australia. Frequency management in interconnected hybrid renewable energy systems is essential to ensure the stability and reliable operation of the electrical grid. Khezri *et al*. [14] explores the factors involved in the planning of PV-battery systems for residential sectors. It emphasizes the importance of considering economic and technical factors, design constraints, and pricing programs for successful implementation of these systems. Hybrid systems combine different renewable energy sources, such as solar, wind, hydro, and energy storage, to provide a more consistent and reliable power supply [15], [16]. Hybrid energy storage systems (HESS) combine various energy storage technologies to achieve optimal performance for microgrid operation, addressing the limitations of any single technology [17]. This paper reviews the use of HESSs, including capacity sizing, power converter topologies, and energy management. The authors highlight the industry's current state and future trends for research and development. A powerful droop control method of the BESS is suggested in order to lessen the frequency fluctuation of the multi-machine grid system brought on by variable active power injected from the PV panel [18].

The placement of DG units should be carefully analyzed to minimize power losses, improve voltage profiles, and ensure stable operation [19]. Tripathy and Kar [20] emphasizes the benefits of integrating renewable energy sources and electric vehicles into a conventional distribution system, demonstrating improvements in efficiency and voltage profile with the use of solar PV sources, and GA algorithm. Hariri *et al*. [21] focuses on the challenges and development of a grid-connected solar PV generation system that maximizes renewable energy use. Arani *et al*. [22] explores the challenges of integrating microgrids in power systems and proposes energy storage systems (ESSs) as a solution for the control and stability of MGs. It discusses ESS types, control methods, and their advantages/disadvantages, emphasizing its role in stability and economy. The paper also highlights future trends in ESS control, providing valuable insights into MG integration. A new system of a grid-connected PV-battery is proposed in [23] to address the intermittency issue of renewable energy sources using an optimal management algorithm for energy flows. A control method based on the application of artificial neural network technology was created in [24] to address the issues linked to the random operation that is associated with the use of solar systems. On MATLAB Simulink, the entire system was designed and simulated. Chekira *et al*. [25] suggested that a hybrid microgrid composed of PV and battery storage devices can manage energy effectively. Though several research has been carried out, still different challenges such as optimization of energy harvesting, battery management, and grid integration have to be considered carefully. These problems have been solved in this paper.

3. SYSTEM MODELLING

A grid-connected solar panel system with battery storage combines the benefits of solar energy generation with the ability to store excess electricity for later use. By combining solar panels, a battery storage system, and a connection to the electrical grid, this setup enables the utilization of clean energy, reduces reliance on the grid, and provides backup power during grid outages or times of high demand. The specific components and configurations may vary depending on the system's size, battery capacity, and local regulations.

The block diagram is depicted in Figure 1. The working of such a system is explained as:

- Solar panel array: The system starts with a solar panel array installed on the rooftop or open ground. These solar panels consist of photovoltaic (PV) cells that convert sunlight into direct current (DC) electricity when exposed to sunlight.
- Inverter: An inverter receives the DC electricity generated by the solar panels. The main job of the inverter is to change the direct current (DC) electricity into alternating current (AC), which is the common form of electricity in homes and businesses.
- Load consumption: The AC electricity generated by the inverter is used to power electrical loads within the building or facility. These loads can include lights, appliances, electronics, and any other electrical devices.
- Battery storage: Excess electricity generated by the solar panels that is not immediately consumed by the loads is diverted to a battery storage system. The battery system stores the excess electricity for later use, typically during periods when the solar panels are not producing electricity (e.g., at night or during cloudy weather).

- Battery inverter: The battery storage system usually includes a battery inverter. This device converts the DC electricity stored in the batteries back into AC electricity when needed.
- Grid connection: In a grid-connected system, there is a connection to the electrical grid. This allows the system to draw electricity from the grid when solar production is insufficient to meet the load demand or when the batteries are depleted.
- Net metering: A key feature of grid-connected solar systems is net metering. When the solar panels produce more electricity than is currently being used, the excess electricity is fed back into the grid. In return, the utility company credits the system owner for the excess electricity, usually in the form of a reduction in their electricity bill.

System control and monitoring: The solar panel system with battery storage is typically equipped with a control and monitoring system. This system ensures the optimal operation of the system by managing the flow of electricity between the solar panels, batteries, loads, and the grid. It may also provide data on energy production, consumption, and battery status.

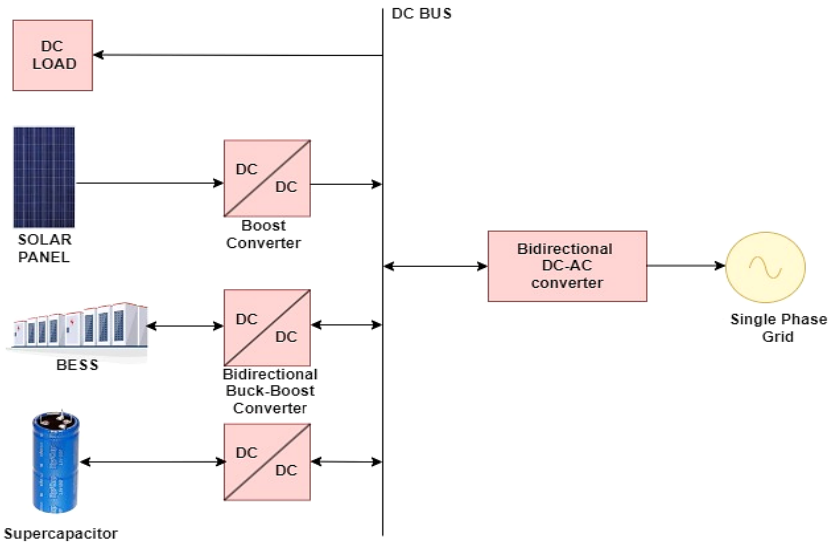

Figure 1. Block diagram of storage system of solar panel incorporated grid system

4. MATHEMATICAL MODELING

The mathematical expressions can be used to describe the behavior and performance of a grid-connected solar panel with battery storage system.

- Solar panel output power (P_{PV}).

The power generated by the solar panel array can be calculated using (1).

$$P_{PV} = A_{PV} * G * \eta_{PV} \tag{1}$$

Where P_{PV} is the output power of the solar panel array (in watts); A_{PV} is the total area of the solar panel array (in square meters); G is the solar irradiance (in watts per square meter); and η_{PV} is the efficiency of the solar panels (a unitless value between 0 and 1).

- Inverter efficiency (η_{inv})

The efficiency of the inverter, which converts DC power from the solar panels to AC power, can be represented as given in (2).

$$P_{inv} = \eta_{inv} * P_{PV} \tag{2}$$

Where P_{inv} is the AC power output of the inverter (in watts).

- Battery efficiency (η_{bat})

The efficiency of the battery system, which stores and releases electrical energy, can be considered using the (3).

$$P_{bat-in} = \eta_{bat} * P_{PV-excess} \tag{3}$$

Where P_{bat-in} is the power input to the battery system (in watts) and $P_{PV-excess}$ is the excess power generated by the solar panels (in watts).

- Battery state of charge (SOC)

The state of charge of the battery (i.e., the amount of energy stored) can be calculated using (4).

$$SOC(t) = SOC(t-1) + (P_{bat-in}(t) - P_{bat-out}(t)) * \Delta t/Capacity\_bat \quad (4)$$

Where SOC(t) is the state of charge at time t; $P_{bat-in}(t)$ is the power input to the battery at time t (in watts); $P_{bat-out}(t)$ is the power output from the battery at time t (in watts); Δt is the time interval (in hours); and Capacity_bat is the capacity of the battery (in watt-hours or kilowatt-hours).

5. RESULTS AND DISCUSSION

Figure 2 reveals the voltage output of the solar panel under various operating conditions. It provides data on how the panel voltage changes with changes in solar irradiance, temperature, and system configuration. This information helps assess the panel's performance, voltage stability, and compatibility with the rest of the system components. The solar voltage output is obtained as 34.05 V. Figure 3 depicts the current output of the solar panel. It illustrates how the current varies with different levels of solar irradiance, temperature, shading, and other factors that affect panel performance. This data aids in understanding the current flow within the system, helps optimize the sizing of wiring and protective devices, and ensures efficient energy conversion.

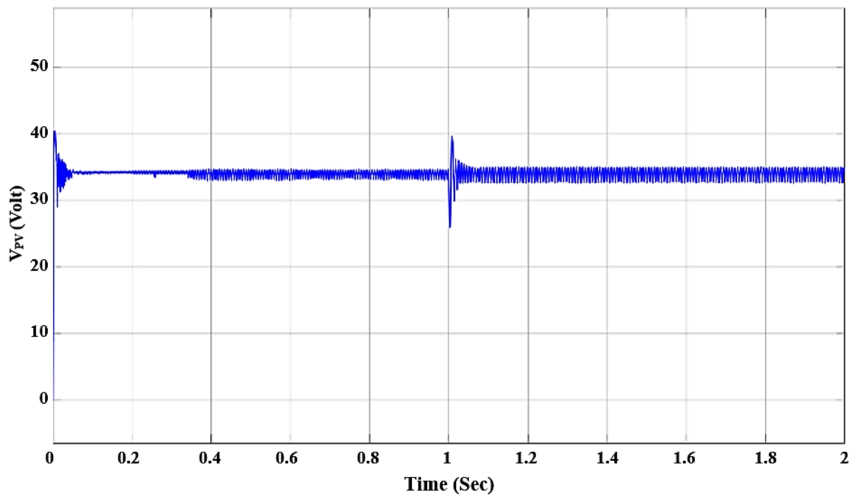

Figure 2. Voltage output of solar panel

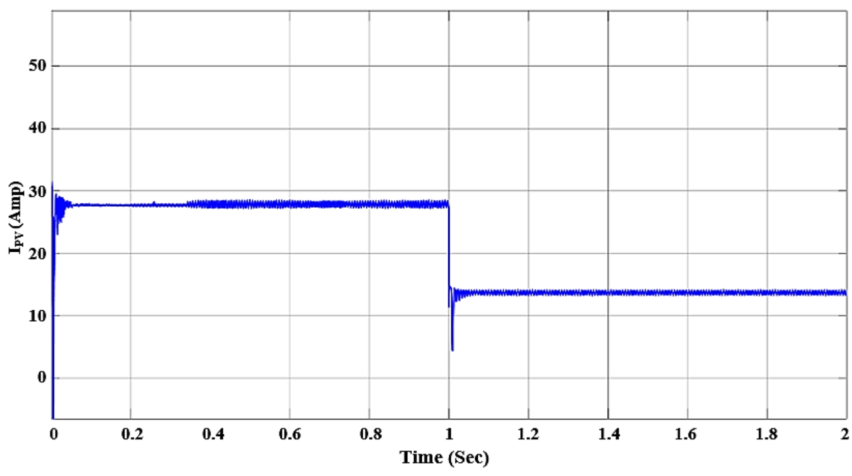

Figure 3. Current output of solar panel

Figure 4 reveals the power output of the solar panel array under different weather conditions, including variations in solar irradiance and temperature. It provides data on the system's ability to harness solar energy and generate DC electricity. The simulation calculates the power output of the solar panel by multiplying the voltage and current values. It provides insights into the instantaneous and cumulative power generation of the panel. Analyzing the power output helps evaluate the panel's efficiency, performance degradation over time, and the impact of environmental conditions on power production.

The simulation results of DC voltage shown in Figure 5 and load power shown in Figure 6 helps in assessing the system's performance, energy balance, and ability to meet load requirements. It also aids in evaluating the effectiveness of the battery storage system in managing the power flow and ensuring uninterrupted power supply. The DC voltage is maintained as 50.1 V.

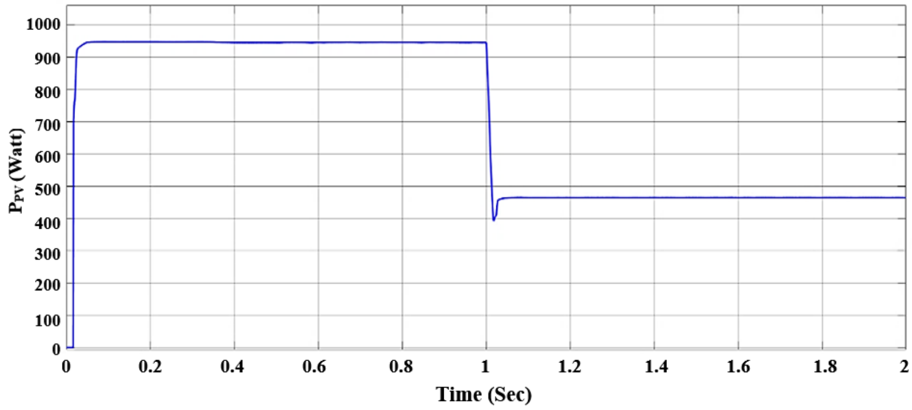

Figure 4. Power output of solar panel

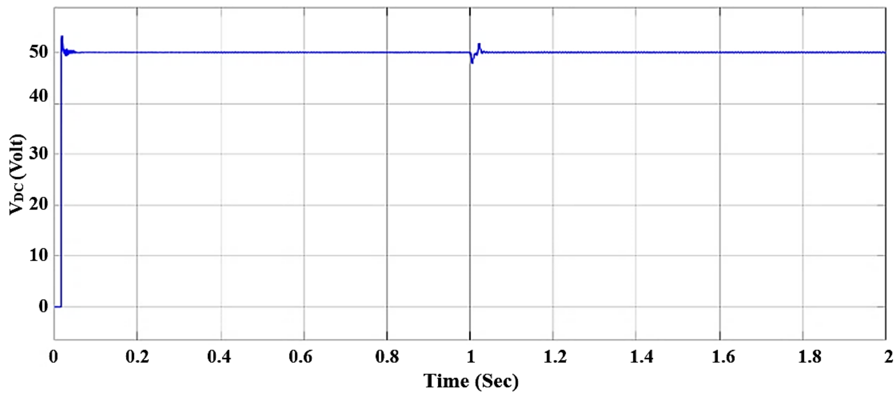

Figure 5. DC voltage response

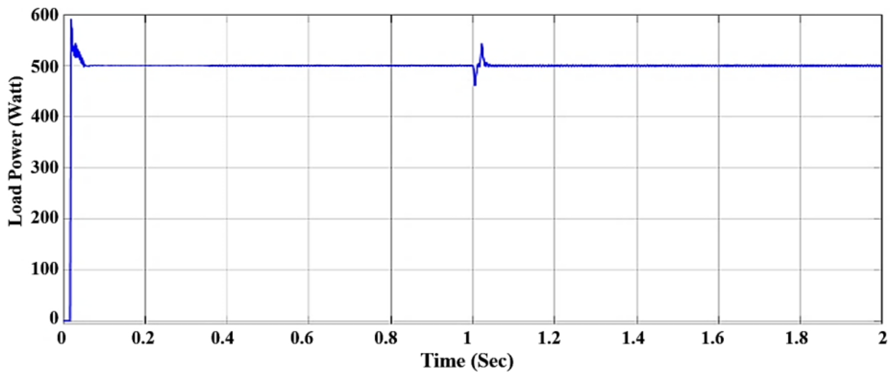

Figure 6. Power demand response

Figures 7-10 depict the response of battery in terms of voltage, current, SOC, and power respectively. The simulation shows the charging and discharging behavior of the battery. It illustrates how the battery charges during periods of excess solar energy generation and discharges when there is a higher demand for electricity than the solar panels can meet. This analysis helps understand the storage capacity, energy utilization, and cycling patterns of the battery. When irradiance changes, change in solar power occurs and then battery will supply power to dc load. From Figure 8, it is clear that battery gets charged when PV power is sufficient to fulfill the load demand i.e., 500 watts. When power demand is more than power supplied by PV panel, then battery fulfills the demand and it starts getting discharged.

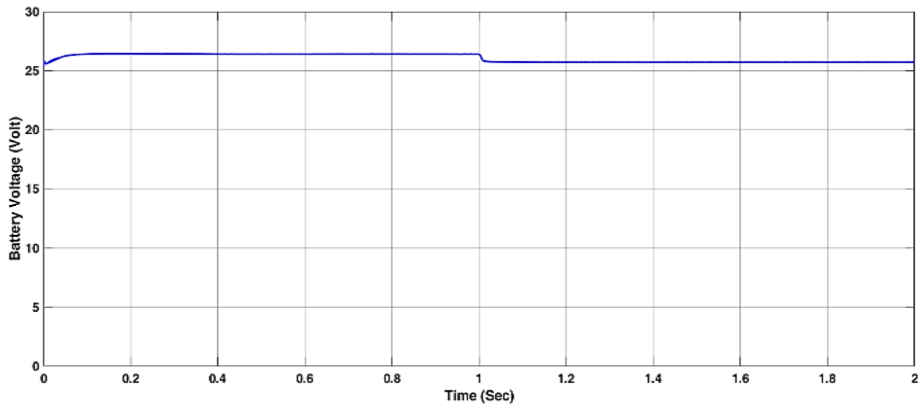

Figure 7. Battery voltage response

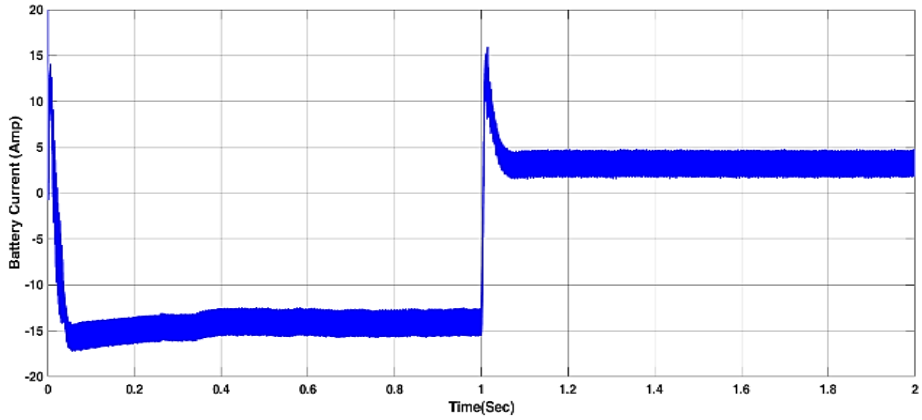

Figure 8. Battery current response

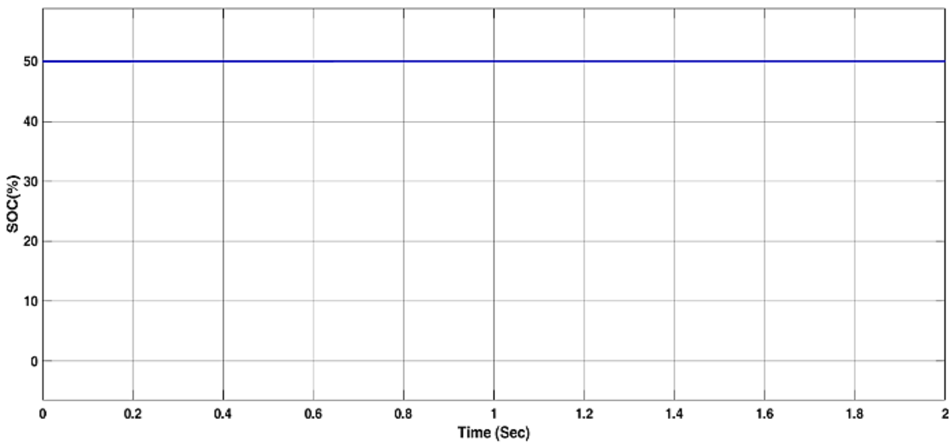

Figure 9. SOC response of battery

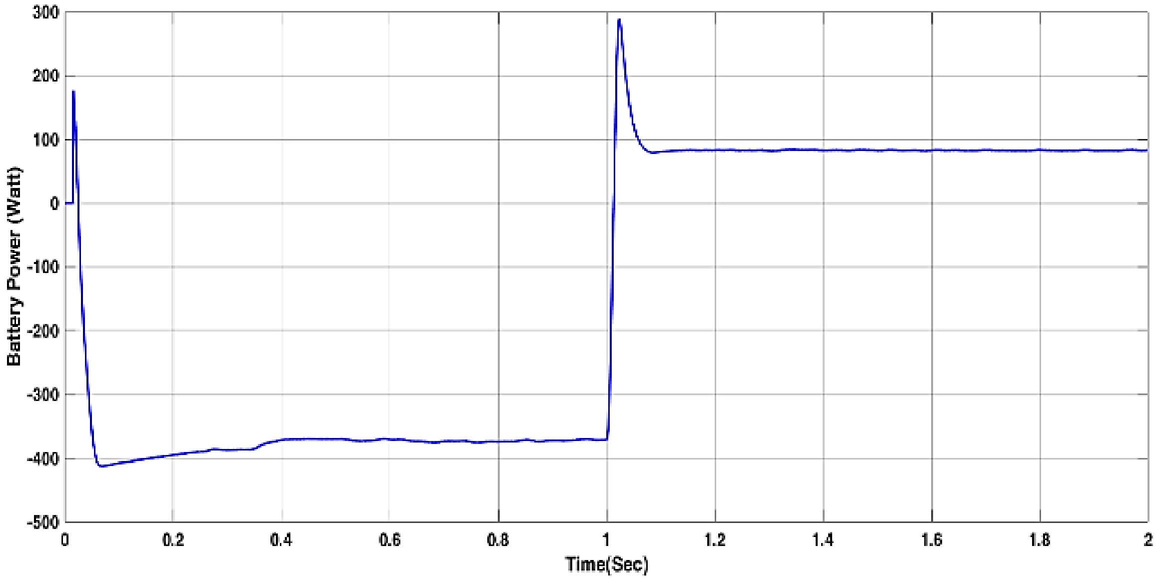

Figure 10. Power response of battery

Supercapacitors are energy storage devices that can quickly store and release electrical energy. They are sometimes referred to as ultracapacitors or electrochemical capacitors. They have numerous advantages such as energy smoothing, peak power management, energy harvesting, backup power, and pulsed power applications. Figures 11 and 12 depicts the voltage and current response of the supercapacitor. Supercapacitor voltage is around 32 V. It shows how the supercapacitor quickly absorbs and releases energy, providing short-term power bursts when there is a sudden increase in load demand or during transient events. This analysis helps assess the responsiveness and power delivery capability of the supercapacitor.

Figure 13 shows SOC of supercapacitor. Supercapacitors can charge and discharge quickly, allowing them to store and release electrical energy rapidly. Unlike batteries, which have slower charging and discharging rates. Figure 14 signifies the power of a supercapacitor lies in its ability to deliver and absorb electrical energy quickly. Supercapacitors have a high-power density, meaning they can deliver high power output in a short amount of time. This characteristic makes them suitable for applications that require rapid energy transfer.

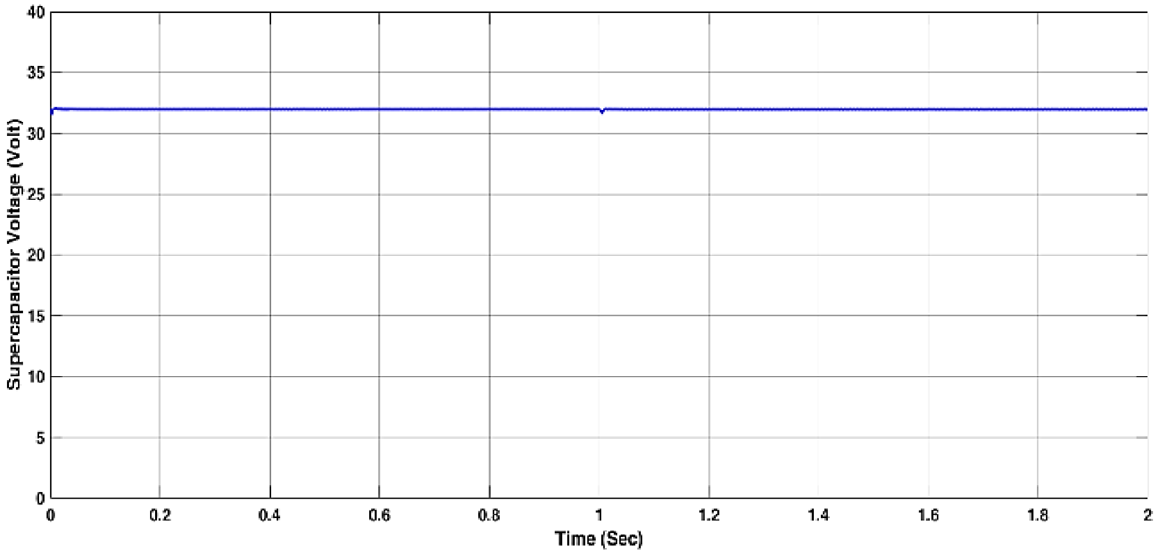

Figure 11. Voltage response of a supercapacitor

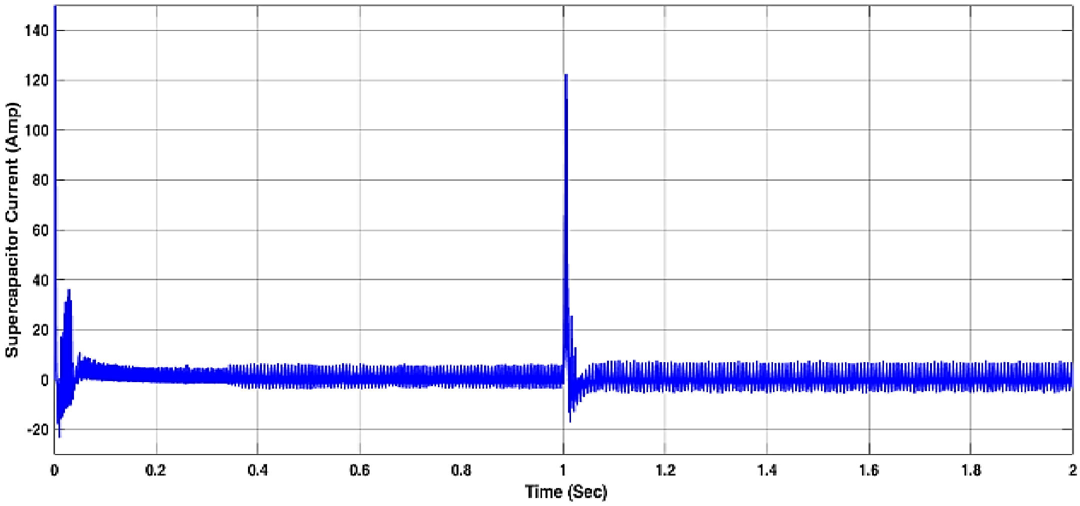

Figure 12. Current response of a supercapacitor

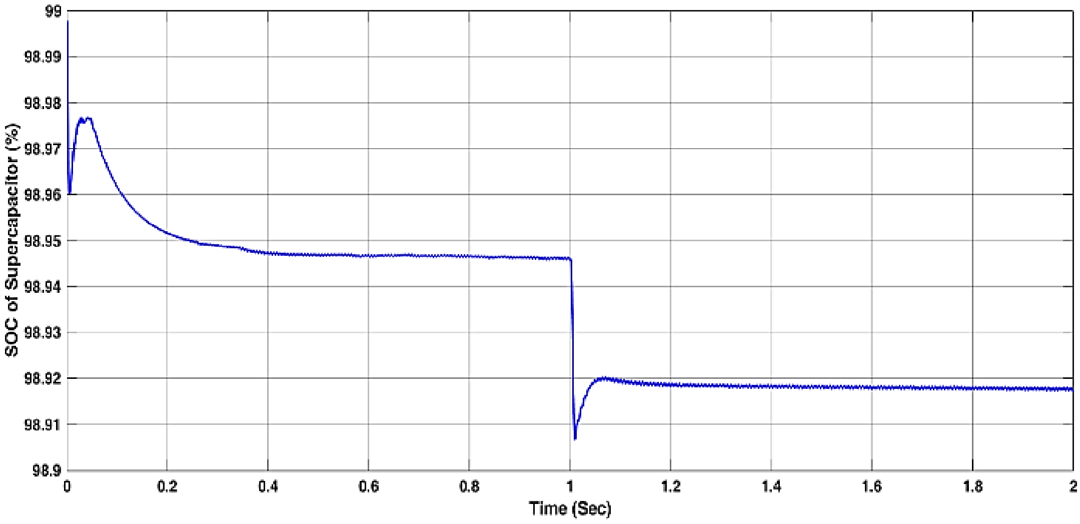

Figure 13. SOC of supercapacitor

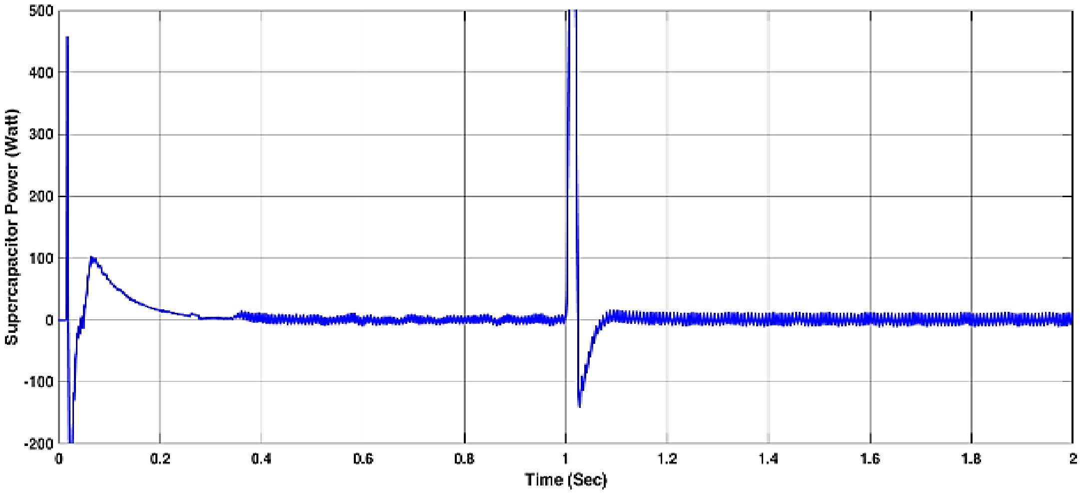

Figure 14. Power response of supercapacitor

6. CONCLUSION

This work focused on simulating and analysing the performance of a grid-connected solar panel with battery storage system. Through extensive simulations, the behaviour of the system under various conditions and explored its potential benefits has been investigated. The findings demonstrate that the integration of a battery storage system with the grid-connected solar array offers significant advantages. The battery storage enables the capture and utilization of excess solar energy, thereby maximizing self-consumption and reducing reliance on the electrical grid. This contributes to increased energy independence and cost savings for the system owner. Furthermore, the simulations highlight the system's ability to provide backup power during grid outages or periods of high demand. The battery storage system acts as a reliable source of stored energy, ensuring uninterrupted power supply and enhancing grid resilience. The results indicate that, over the system's lifespan, the financial benefits can outweigh the upfront costs, resulting in long-term profitability. It may be concluded that a grid-connected solar panel with battery storage system has the potential to deliver environmental, economic, and reliability benefits. The insights gained from this simulation study provide valuable information for system design, optimization, and decision-making, paving the way for wider adoption of this sustainable energy solution. Future work may focus on real-world implementation, validation, and further optimization of the system based on the simulation results.

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