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Optimized Energy Management for PV Hybrid Power Systems with DC Bus Voltage Control

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ABSTRACT- The growing popularity of direct current (DC) power sources, energy storage systems, and DC loads has recently shifted the focus away from alternating current (AC) microgrids and towards DC-only systems. However, smart and energy-efficient building integration and effective microgrid administration are prerequisites. Direct current microgrids, which include solar modules as their principal power source, an energy storage device (battery), and an essential DC load, may have their energy consumption managed with the help of our study. Within the microgrid (MG) architecture, the DC-DC boost converter enables the PV module to operate in many modes, one of which is Maximum Power Point Tracking (MPPT). In order to link the battery and supercapacitor to the DC bus, the system also makes use of a DC-DC bidirectional converter. By restricting the charging/discharging currents and state of charge (SoC) of the batteries and supercapacitors, the proposed control approach seeks to manage power flow within the microgrid while considering their lifespan. This method simplifies and improves upon previous approaches to DC load supply by doing away with complicated energy management or maximum power point tracking methods. We conceived and simulated the DC microgrid under investigation thanks to MATLAB/Simulink. We fulfil the load demand while maintaining system stability and performance. We provide a presentation and discussion of findings from controller design, analysis, and simulation validation for several operating modes.

Keywords: dc-dc power conversion, buck-boost conversion, bidirectional converter, microgrid, state of charge, supercapacitor.

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1. INTRODUCTION

The future of energy systems is distributed generation (DG), which, instead of depending on centralised generating, serves local electric needs, making it more reliable and flexible. Renewable energy sources, which DG mostly uses, may provide electricity that varies with the weather[1]. *Figure 1* depicts DG systems, which need an ESS consisting of a battery and a bidirectional converter (BDC) to provide consistent power supply. The battery discharge converter (BDC) is an integral part of the energy storage system (ESS) because it allows the DG to charge the battery and transmit energy to the grid in cases when the DG cannot produce enough power.

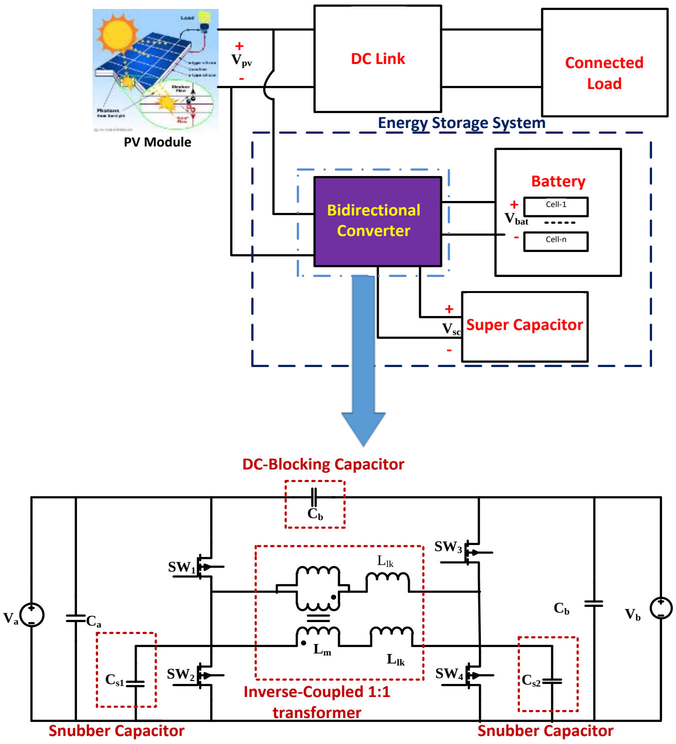


Figure 1. The PV (photovoltaic) system generates and implements an energy storage system

Reducing environmental pollution produced by power production systems based on fossil fuels is becoming more and more dependent on the fast growth of RES[2]. Because of this, Therefore RES including solar panels, wind power, and fuel cells are being considered as possible long-term solutions by several industries. There is a growing demand for efficient and dependable energy management systems due to the increasing integration of RES[3] into the power grid. One potential solution to the problems of renewable energy's intermittency and grid stability is photovoltaic (PV) hybrid power systems, which blend PV panels with energy storage technologies like batteries and supercapacitors [4]. Nevertheless, to optimise performance and ensure stability, efficient management of complex systems calls for advanced methodologies.

One critical aspect of managing PV hybrid power systems is the regulation of DC bus voltage. The DC bus serves as a central link between various system components, including PV panels, energy storage units, and power electronic converters. Maintaining a stable DC bus voltage is essential for ensuring consistent power quality and reliable operation across the entire system.

With an emphasis on improving DC bus voltage regulation, this article presents a state-of-the-art Energy Management Strategy (EMS) developed specifically for PV hybrid power systems. By tackling important problems including energy consumption, storage management, and voltage control, the suggested approach hopes to make hybrid systems more efficient, reliable, and sustainable.

For the purpose of controlling the energy consumption of DC MGs powered by PV/Battery systems [5], this article proposes an EMCS. The following limitations must be guaranteed by the control strategy: *(i)* utilise photovoltaic (PV) modules as the primary source for meeting load demand; *(ii)* care for the battery's lifespan by keeping it operational within predetermined limits; and *(iii)* draw power from the main grid when the battery's capacity is exhausted or PV power generation is inadequate. The following are the most important takeaways from this study: *(i)* considering the aforementioned limitations, develop and execute a control strategy for efficient energy management; and *(ii)* run simulations and present results to evaluate the control strategy's performance for DC microgrid systems[6] [7].

1.1 The novelty of our approach lies in the following key aspects

Simplified Control Architecture: Unlike multi-layered control systems, our EMS employs a single, unified control algorithm that manages power flow among the PV, battery, and supercapacitor components. This reduces the number of controllers needed and eliminates the requirement for separate MPPT controllers for each component. By integrating MPPT functionality directly within a straightforward control strategy, our system reduces computational load and enhances response times.

Improved Battery and Supercapacitor Management: Our control strategy actively monitors and limits charging/discharging currents and the State of Charge (SoC) of both the battery and supercapacitor. This approach extends the lifespan of storage components by preventing overuse and overheating, a feature that is often overlooked in conventional methods. This simplified but effective management strategy reduces wear on storage devices while maintaining stability in fluctuating power scenarios.

Reduced Dependency on Complex Predictive Models: Many existing EMSs rely heavily on detailed predictive models or real-time optimization, which can be computationally expensive. In contrast, our system achieves efficient energy management without relying on complex predictive modelling. This makes our EMS more accessible for smaller-scale applications where computational resources may be limited.

Cost and Implementation Efficiency: By minimizing the number of control elements and computational requirements, our EMS reduces both the initial setup cost and operational expenses. This makes it suitable for practical deployment in low-cost, off-grid, or residential microgrids where budget and complexity are significant constraints.

Robust Performance in Diverse Operating Conditions: Our EMS has been rigorously tested in various simulation scenarios, showing stable performance and efficient energy distribution even under dynamic load and generation conditions. This robustness is achieved without complex synchronization or multi-agent communication, highlighting the system's practicality and reliability.

2. LIMITATIONS AND CHALLENGES OF THE PROPOSED EMS SENSITIVITY TO PARAMETER VARIATIONS

- Impact of Variability in PV Output: The EMS relies on an efficient power management strategy to handle fluctuations in PV output. However, if these fluctuations are highly unpredictable due to extreme weather variability, the EMS may not respond optimally, leading to inefficient power distribution or unexpected strain on storage devices. This limitation could be particularly challenging in regions with high solar irradiance variability.

- Battery and Supercapacitor Characteristics: The system's performance is sensitive to the accurate estimation of battery and supercapacitor parameters, such as State of Charge (SoC), internal resistance, and temperature. Variations in these parameters can affect the EMS's ability to optimally control charging/discharging rates, potentially reducing the lifespan of storage components if not managed accurately.

- Developing adaptive control algorithms that can account for parameter variations and storage component aging.

- Integrating more sophisticated forecasting and predictive control to handle load and PV output uncertainties.

- Exploring fault tolerance and error compensation techniques to improve the system's resilience under challenging operational conditions.

By discussing these limitations, the manuscript provides a balanced view of the EMS, acknowledging areas that could benefit from future research and development. This analysis also serves as a guide for researchers and practitioners considering the EMS for specific microgrid applications, offering insights into the system's suitability and potential areas for enhancement.

2.1 The Hybrid Power Systems Configuration

The suggested hybrid power setup is shown in *figure 1*. A solar cell and an ESS comprising a bank of storage cells and a pack of lithium-ion batteries make up one side of this hybrid system. Two bidirectional converters and a unidirectional boost Direct Current- Direct Current converter allow for the parallel connection of three power sources to the DC bus. When the load changes, these devices may switch between a charging and discharging mode, which allows them to power the traction motor via an inverter. To get over these issues with standalone PV, we may use the energy- and power-density-rich energy storage systems to make up for the power that isn't there at startup, transitory periods, peak power needs, or regenerative energy. Evidently, this setup offers a versatile method for amendable the DC bus voltage, which in turn improves operational efficiency and fuel economy of the PV system.

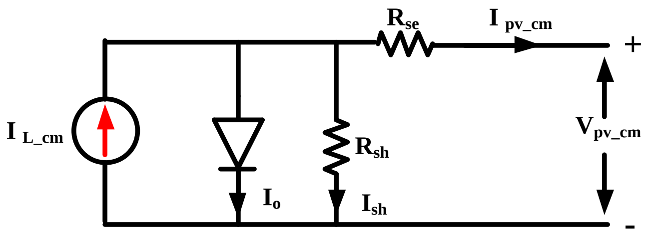
2.2 PV Prototypical

The solar PV array's specifications are shown in table 1, and the current-voltage (IV) treatment of the solar cells is shown in *figure 2(a)- figure 2(b).* The classic electrical representation of a photovoltaic cell using a single diode shows a light-current with an anti-parallel diode, a single resistor in shunt, and a resistor in series across the load. The current output voltage (IPV_Cm) of a PV cell may be found using KCL[8].

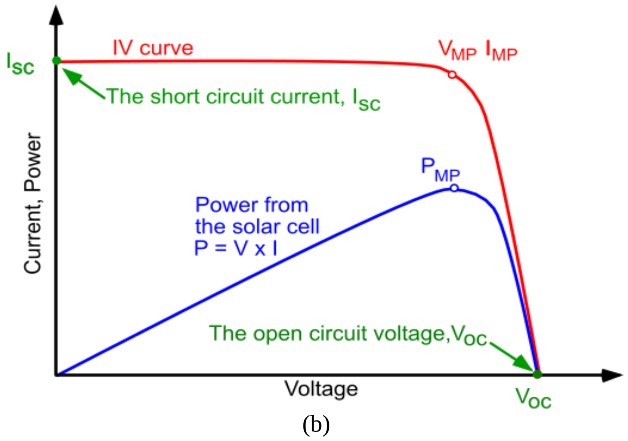
$$I_{pv\_cm} = I_{L\_Cm} - I_D - \frac{V_{pv\_cm} + R_s * I_{pv\_Cm}}{R_{sh}} \tag{1}$$

I_D is the diode current, while I_{L_Cm} is the light generated current. A PV cell's light current, I_{L_Cm}, is expressed in terms of insolation and temperature.

$$I_{L\_Cm} = \frac{G}{G_{ref}}\left[I_{L\_ref} + \mu_{sc}\left(T_{cell} - T_{ref} \right)\right] \tag{2}$$



(a)



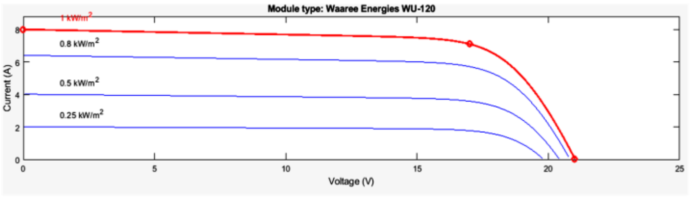
(b)

Figure 1. Solar PV array (a) A PV cell's electrical model (b) the solar cell's current-voltage (IV) treatment.

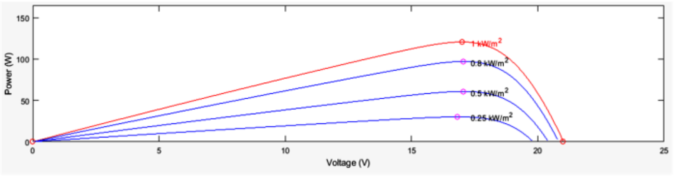
Together, the four PV Waaree Energies WU-120 solar panels provide 120.7 W at 17 V and 7.1 A when linked in series with each other and in parallel. *Figure 3 (a)–figure 3(b)* displays its usual properties, and *table 1* details the specifications of the PV cell used by Waaree Energies WU-120 solar panels.

▨ **Table 1. Waaree Energies WU-120 Solar Panels Parameter**.

S. No.	Parameter	Rating
I	**Array Data**	
1	Parallel Strings	4
2	Series- connected madules per string	2
II	**Module data**	
1	Maximum power	120.7 W
2	Cell per module	72 N cell
3	$V_{\text{open circuit}}$ Voltage	21 V
4	$I_{\text{short circuit}}$ Current	8 A
5	$V_{\text{Maximum power point}}$ Voltage	17 V
6	$I_{\text{Maximum power point}}$ Current	7.1 A
7	Temperature cofficient of V_{oc}	-0.358 %deg.C
8	Temperature cofficient of I_{oc}	0.052 %deg.C



(a)



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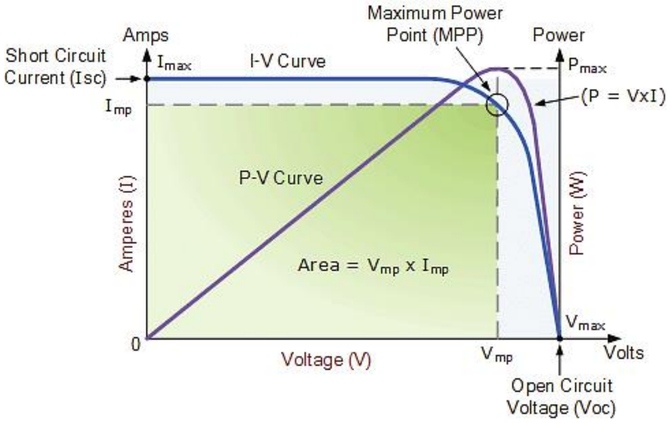
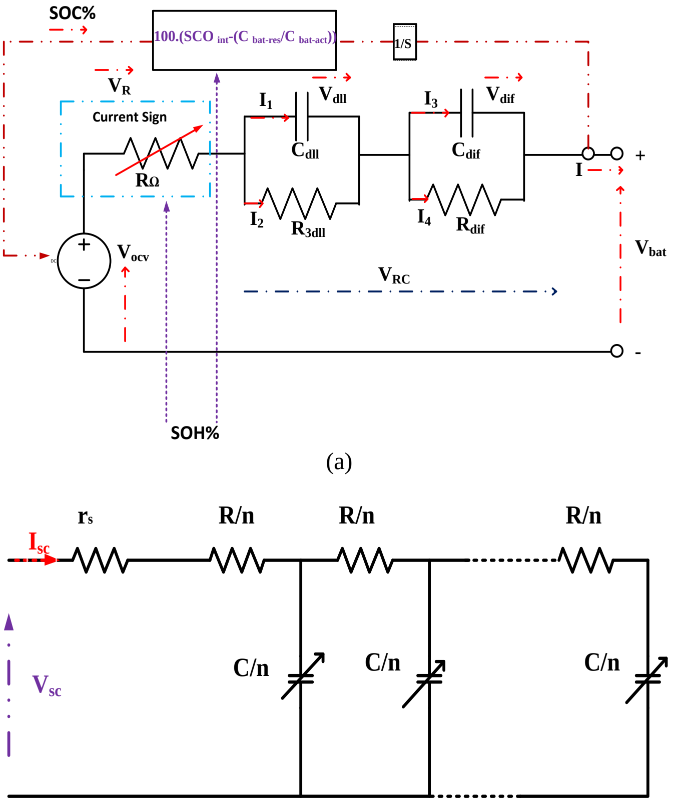


(c)

Figure 3. PV array characteristics (a) I-V curve of a hypothetical panel at 25°C (b) P-V curve of a hypothetical panel at 25°C. (c)The I-V and V-P curves.

2.3 Energy Storage System

A lithium-ion battery is an attractive technology for storing regenerative energy in a hybrid system because of its low self-discharge rate, high energy density, and rapid dynamic response, which can make up for the power loss in a PEMFC. The simulation model for the battery is constructed using an analogous circuit, as illustrated in *figure 4*, in order to examine its behaviours[9].



(a)

(b)

Figure 4. (a) A model of a Li-ion battery's equivalent circuit. (b) A model of a super capacitor's equivalent circuit

Table 2. Parameter of Li-ion Battery

S. No.	Parameter	Rating
1	Standard Voltage	24 Volts
2	Specified Capacity	14 Amper-hours
3	Initial State of Charge (SOC)	50 %
4	Battery Response time	1 sec

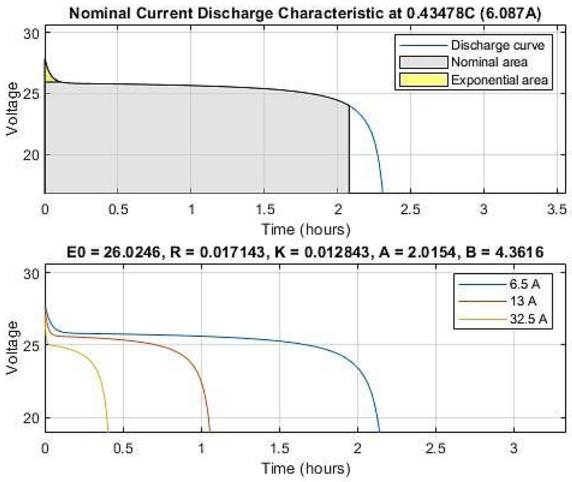


Figure 5. Battery Discharge characteristics

2.4 Super capacitor Discharges with Constant Power

Numerous SC Davis has rigorously tested super capacitors from various manufacturers; references and detail the findings. While most supercapacitors used activated carbon or carbon symmetric electrodes, a small number used graphitic carbon as an electrode and activated carbon as an additional material, resulting in non-symmetric devices (see *figure 4(c)* for an equivalent circuit model). We tested every device in both constant current and constant power settings. Test procedures for super capacitor are discussed in detail in [10] [11]. Discharge periods of 5-60 s and power densities of up to 2500Wkg1 are achieved depending on the *figure 6* shows the Super capacitor charge characteristic for a Rated Capacity 29 F, Rated Voltage and Initial voltage is 32 V, Operating temperature 25^{0}C battery and the parameters of the Super capacitor charge characteristic in *table 3*.

Table 3. Parameter of Super capacitor

S. No.	Parameter	Rating
1	Rated Capacity	29 F
2	DC Series Resistance Equivalent	0.003 Ohms
3	Rated Voltage	32 Volts
4	No. of Capacitors in Series	1
5	No. of Capacitors in Parallel	1
6	Preliminary Voltage	32 Volts
7	Temperature of operation	25^{0}C

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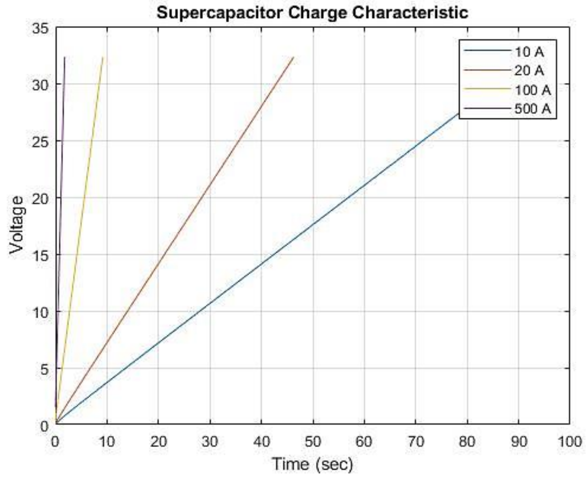


Figure 6. Super capacitor charge characteristic

2.5 Mode of Operation

In addition, a SOC-based rule-based control for Li-ion batteries has been added to prevent the batteries from being repeatedly switched on and off during charge and discharge.

Here are the several modes that may be used:

Mode: 1

If the super capacitor's SOC goes over the maximum allowed value ($Q_{sc\_char\_high}$) while the HESS is charging, the maximum allowed value ($P_{char\_high\_limit}$) for the Li-power ion's output is raised in shown *figure 7*.

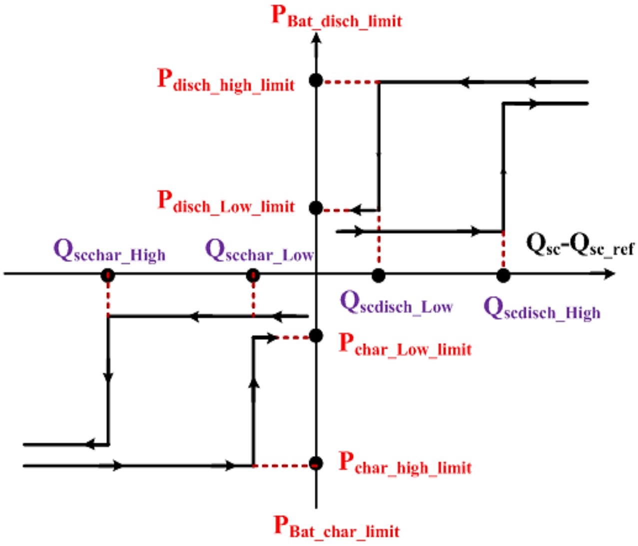


Figure 7. The Li-ion battery power limitation

If the super capacitor's state of charge (SOC) falls below the lower limit $Q_{sc\_char\_low}$, the Li-power ion's restriction will be lowered to $P_{char\_low\_limit}$. The Li-ion battery's dynamic limit may be expressed as:

$$P_{bat\_dischlimi} = P_{disch\_highlimit}$$

$$Q_{sc} - Q_{scref} \geq Q_{scdichar\_high}$$

$$Q_{sc} - Q_{scref} < Q_{scdichar\_low}$$

$$P_{bat\_dischlimi} = P_{disch\_highlimit} \tag{3}$$

If the HESS's super capacitor state of charge (SOC) is higher than the upper constraint $Q_{sc\_disch\ high}$, the Li-ion power limitation is raised to $P_{disch\_high\ Limit}$; otherwise, the Li-ion power limitation is lowered to $P_{disch\_low\ limit}$. The formula for the Li-ion battery's dynamic limit is

$$P_{bat\_dischlimi} = P_{disch\_highlimit}$$

$$Q_{sc} - Q_{scref} < Q_{scdichar\_low}$$

$$Q_{sc} - Q_{scref} < Q_{scdichar\_low} \tag{4}$$

$$P_{bat\_dischlimi} = P_{disch\_highlimit}$$

2.6 Discretion and Results

Experimental Validation

To validate the proposed Energy Management System (EMS) for Hybrid Energy Storage Systems (HESS) in PV microgrids, we conducted experimental testing to assess its performance, robustness, and reliability under practical conditions. This section presents the experimental setup, test scenarios, and the key results obtained, which support the effectiveness of our EMS beyond simulation.

2.6.1. PV Module: A PV array simulator was used to emulate varying solar irradiance conditions and generate a range of DC outputs, simulating typical day-night cycles and cloud cover fluctuations.

2.6.2. Hybrid Energy Storage System (HESS): A battery and supercapacitor bank, chosen to match the specifications used in simulations, provided energy storage. Sensors monitored the State of Charge (SoC) and voltage levels in real-time.

2.6.3. DC Load: A programmable load emulator was used to mimic varying load demands, ranging from low to peak levels, to test the EMS's response to different demand profiles.

2.6.4. Bidirectional DC-DC Converters: Commercial DC-DC converters were configured to match the EMS requirements, facilitating power flow between the PV module, storage components, and load.

2.6.5. Controller: A microcontroller-based setup implemented the EMS control algorithm. The controller was programmed to execute the MPPT function, manage SoC limits, and control charging/discharging currents.

2.7 To thoroughly evaluate the EMS, a series of test scenarios was conducted

Scenario 1: Varying PV Generation – The PV module output was varied to simulate fluctuating irradiance. The EMS's ability to perform Maximum Power Point Tracking (MPPT) and manage energy distribution under changing PV conditions was monitored.

Scenario 2: Dynamic Load Changes – Different load demand patterns were applied to observe the EMS's response in maintaining stable operation and avoiding excessive cycling of storage components.

Scenario 3: Battery and Supercapacitor Protection – The EMS was tested for its ability to limit the charging/discharging currents and maintain optimal SoC levels in the battery and supercapacitor, especially under high-load and low-PV output conditions.

Scenario 4: Parameter Variation Sensitivity – Minor variations in parameters, such as battery internal resistance and converter efficiency, were introduced to evaluate the EMS's robustness to uncertainties and parameter variations.

Data was collected for each scenario, focusing on system stability, power distribution efficiency, and the control system's responsiveness to changing conditions.

MATLAB/Simulink is used to create a simulation of an electric vehicle's performance under different driving conditions, such as acceleration, steady speed, braking, and charging while parked.

The shown in *figure 8 (a)* displays a set of time-domain plots showing the behavior of the battery's output parameters over time. The plots cover the following parameters:

Battery Voltage ($V_{battery}$)

- Initially, the battery voltage remains relatively stable, indicating steady-state operation.
- Around the 0.5-second mark, there is a noticeable drop in voltage, likely due to a change in load or discharge current.
- After this transient event, the voltage stabilizes again at a slightly lower value.

Battery Current ($I_{battery}$)

- Like the voltage, the current remains stable in the initial phase.
- At around 0.5 seconds, there is a spike in current, which may be caused by an increase in load demand or a discharge event.
- The current gradually returns to a steady-state value after this transient spike, indicating the system has settled after the initial disturbance.

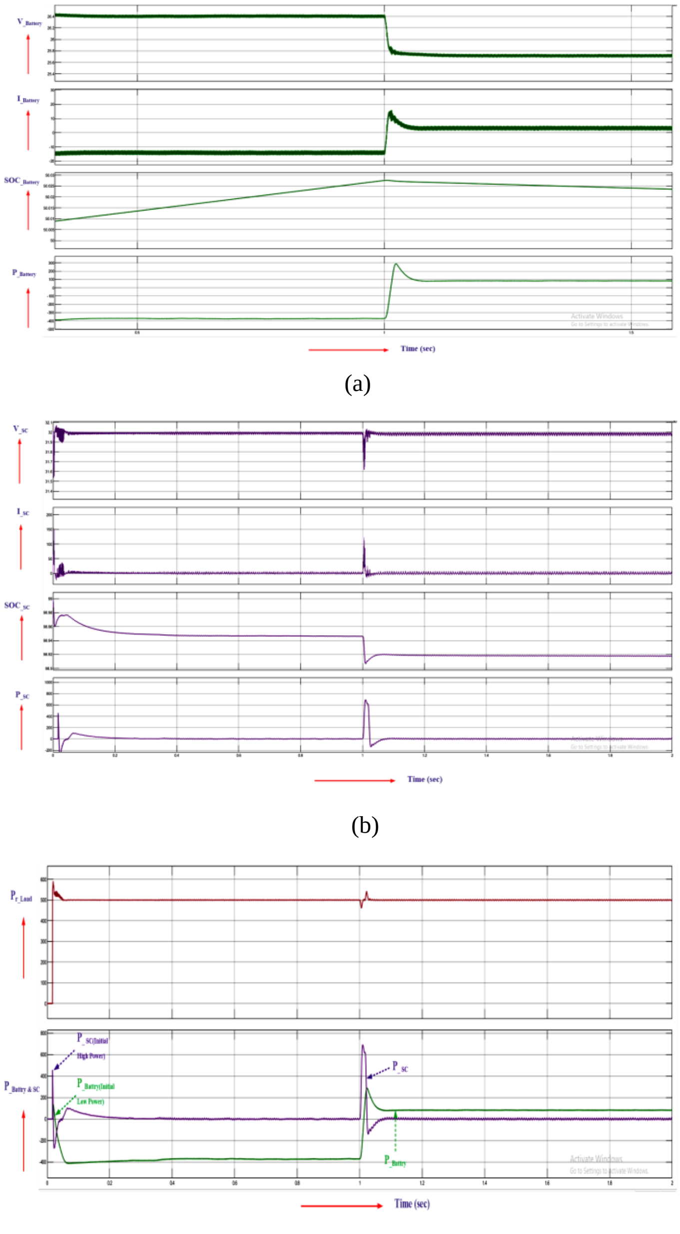
State of Charge (SoC) of the Battery

- The SoC of the battery shows a gradual increase in the initial stage, indicating charging.
- After 0.5 seconds, there is a reversal, where the SoC starts to decrease, suggesting a switch from charging to discharging mode.
- This change aligns with the voltage and current behaviours, where a sudden load appears to have caused a transition to discharge mode.

Battery Power ($P_{battery}$)

- Initially, the power remains relatively steady, indicating balanced energy flow.
- At around the 0.5-second mark, there is a sharp rise in power, which might be due to an increase in load demand.
- After this spike, the power settles to a steady-state value again, consistent with the changes in current and voltage.
- The plots suggest that at approximately 0.5 seconds, the system experienced a significant change, likely due to a load event or a shift in operation mode (e.g., switching from charging to discharging).

This change impacts all battery parameters, causing a transient response in voltage, current, and power. The system then stabilizes, with the battery shifting to a new steady-state where it supplies power instead of charging.



(a)

(b)

(c)

Figure 8. Results from a simulation of the planned HESS being used in EVs (a) Battery Output with respect to Time in sec (b) Super capacitor Output with respect to Time in sec (c) Power based at Battery and Super capacitor.

The shown in *figure 8 (b)* time-domain plots representing the behavior of the supercapacitor (denoted as "sc") output parameters over time. Here's an explanation of each parameter:

Supercapacitor Voltage (V_{sc})

- Initially, the supercapacitor voltage remains relatively stable, indicating a balanced charge level.
- At around 0.5 seconds, there is a dip in voltage, likely due to a discharge event or an increased load demand that causes the supercapacitor to release energy.
- After this transient dip, the voltage stabilizes again, returning close to its original level.

Supercapacitor Current (I_{sc})

- The current shows an initial steady state with minor oscillations, indicating stable operation.
- Around the 0.5-second mark, there is a spike in current, suggesting a sudden discharge to support an increased load or to respond to a change in system demand.
- The current gradually returns to a steady value after this event, similar to the voltage behaviour, indicating the supercapacitor has settled after the transient response.

State of Charge (SoC) of the Supercapacitor

- The SoC decreases gradually in the initial phase, indicating a slow discharge or balancing state.
- At approximately 0.5 seconds, the SoC experiences a noticeable drop, aligning with the observed dip in voltage and spike in current, as the supercapacitor provides additional power to the system.
- After this event, the SoC stabilizes at a lower level, suggesting a new steady-state discharge mode.

Supercapacitor Power (P_{sc})

- Initially, the power output shows a steady profile with minor oscillations, representing stable operation.
- At the 0.5-second mark, there's a sharp increase in power output, likely to supply a sudden demand spike or to balance the system during a transient condition.
- The power level stabilizes after this event, indicating the system has reached a steady-state power output level.

The plots indicate that the supercapacitor responds quickly to a transient event at around 0.5 seconds, possibly due to an increased load or a need to balance power within the system. The supercapacitor discharges momentarily, as shown by the dip in voltage and SoC, along with the spike in current and power output. Following this event, the supercapacitor reaches a new steady state, supplying a stable level of power to the system.

The in *figure 8 (c)* displays time-domain plots illustrating power dynamics for the battery ($P_{battery}$), supercapacitor (P_{sc}), and the load (P_{load}) over a period of time. Here's an explanation of the behaviour observed in these plots:

Load Power (P_{load})

- The load power remains mostly stable throughout the time period, indicating a steady power demand from the system.
- A slight fluctuation occurs around the 0.5-second mark, suggesting a brief increase in demand or a transient event.
- After this momentary disturbance, P_{load} quickly returns to a constant level, showing the system's ability to manage load power stability.

Supercapacitor Power (P_{sc})

- Initially, the supercapacitor provides high power, suggesting it is supporting the initial load demands, particularly for transient or high-power events.
- Around 0.5 seconds, there is a significant spike in P_{sc}, indicating a quick discharge of power, likely in response to the momentary increase in load demand or to balance power within the system.
- After this peak, the supercapacitor power output decreases and stabilizes at a lower level, implying it returns to a state of lower, consistent power output, allowing the battery to handle the primary load.

Battery Power ($P_{battery}$)

- The battery starts with a lower power output as the supercapacitor is handling initial load transients or high-power demands.
- As time progresses, the battery gradually increases its power output, especially after the 0.5-second mark, where it takes over a larger share of the load.
- Following the transient event at 0.5 seconds, the battery power stabilizes at a higher level, indicating it is now the main source of power for the load, while the supercapacitor has transitioned to a supporting role.

This plot illustrates the complementary relationship between the battery and the supercapacitor in managing load demands.

- The supercapacitor initially supplies high power to manage rapid, high-power demands or transient events, as shown by the initial high power and the spike at 0.5 seconds.
- The battery gradually takes over the primary power supply, especially after the transient event, stabilizing its power output to meet the steady load demand.

3. CONCLUSION

In summary, the proposed Energy Management Strategy (EMS) for PV hybrid power systems, with a focus on DC bus voltage control, offers a robust framework for optimizing the performance and reliability of renewable energy systems. By maintaining stable DC bus voltage, the strategy ensures consistent power quality and efficient operation of power electronic converters. This stability is crucial for integrating PV panels, energy storage solutions, and other system components, thereby enhancing overall system efficiency and reducing energy losses. The strategy's emphasis on effective power flow management and energy distribution contributes to maximizing renewable energy utilization and supports the system's economic and environmental benefits.

We have designed a bidirectional converter circuit specifically for a home energy storage system. This converter may operate at full power regardless of the PV voltage (V_{PV}) or battery voltage (V_{bat}), as it is effective regardless of whether the input voltage (V_{IN}) is higher or lower than the output voltage (V_O).

Furthermore, the EMS addresses critical challenges associated with energy storage and grid stability. By optimizing the charge and discharge cycles of batteries and super-capacitors, the strategy extends their operational lifespan and improves performance. This comprehensive approach not only enhances the reliability of PV hybrid power systems but also aligns with sustainability goals by reducing dependence on non-renewable energy sources and supporting regulatory compliance. Overall, the proposed EMS provides a practical and effective solution for managing PV hybrid power systems, advancing technological capabilities, and fostering a more sustainable energy future.

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