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ABSTRACT:

The growing demand for clean, sustainable energy solutions has led to the increasing adoption of microgrids, especially in applications where reliability, efficiency, and renewable energy integration are paramount. In particular, DC microgrids have gained significant attention due to their ability to efficiently manage renewable energy sources such as solar and wind, as well as their reduced energy losses compared to AC grids. However, ensuring the continuous and reliable operation of DC microgrids, particularly in remote or off-grid areas, requires advanced energy storage solutions. This paper explores the design and optimization of hybrid energy storage systems (HESS) tailored to enhance the performance of DC microgrids.

Hybrid energy storage systems, which combine different energy storage technologies such as batteries, supercapacitors, and flywheels, offer numerous advantages in terms of balancing energy supply and demand. By leveraging the complementary characteristics of these storage technologies—batteries for long-term energy storage and supercapacitors for high-power delivery—HESS can provide the necessary flexibility to manage load fluctuations, optimize energy efficiency, and extend the life cycle of the storage system. The design process involves selecting appropriate storage technologies, integrating them with intelligent power management strategies, and optimizing system configuration to meet the specific needs of DC microgrid applications.

The paper presents a detailed review of various hybrid energy storage architectures and their application in DC microgrids. Through simulations and performance analysis, it demonstrates the superior efficiency, enhanced stability, and improved reliability achieved through the integration of HESS in DC microgrid systems. Key factors such as energy storage sizing, charging/discharging algorithms, and system scalability are discussed, along with the trade-offs between cost, performance, and sustainability.

Furthermore, challenges such as managing the complexity of hybrid systems, minimizing system losses, and ensuring optimal energy distribution are addressed, with solutions proposed based on recent advancements in power electronics and energy management systems. The research concludes that efficiently designed hybrid energy storage systems are crucial for enhancing the performance and sustainability of DC microgrids, offering a viable solution to support the growing demand for clean, reliable, and efficient power in modern energy networks.

1. INTRODUCTION.

With the rapid growth of renewable energy sources and the shift toward decentralized power generation, microgrids have emerged as a promising solution for providing reliable, sustainable, and efficient energy. Particularly, DC microgrids have gained considerable attention due to their ability to directly integrate renewable energy sources like solar panels and wind turbines, which naturally generate DC power. The ability of DC microgrids to reduce conversion losses, optimize energy distribution, and support a wide range of modern electronic devices has made them an attractive option for both urban and remote applications. However, the intermittent nature of renewable energy generation, combined with fluctuating power demand, poses significant challenges for maintaining a consistent and reliable power supply.

To address these challenges, the integration of energy storage systems (ESS) is essential for ensuring continuous power availability, balancing supply and demand, and enhancing the overall performance of DC microgrids. Energy storage systems provide a buffer for storing excess energy during periods of high generation and releasing it when generation is low or demand spikes. Traditional energy storage technologies such as batteries have proven effective in providing energy storage capabilities; however, they often face limitations in terms of power density, efficiency, and lifespan when used alone. These limitations can affect the performance of the microgrid, particularly in applications requiring high power during peak load times.

Hybrid energy storage systems (HESS) have been developed as an innovative solution to overcome these shortcomings. By combining two or more energy storage technologies with complementary characteristics, HESS can optimize energy storage performance, offering a more efficient, reliable, and flexible energy management approach. For instance, batteries are well-suited for long-term energy storage, while supercapacitors provide rapid power delivery for short-duration peak demands. The synergistic integration of these technologies allows HESS to meet the diverse needs of DC microgrids, improving system efficiency, reducing costs, and extending the life cycle of individual storage devices.

This paper explores the design and optimization of efficient hybrid energy storage solutions for enhancing the performance of DC microgrids. It investigates various configurations and architectures of HESS, highlighting their potential to improve energy storage capabilities, reduce energy losses, and increase the overall sustainability of DC microgrid systems. Through the analysis of control strategies, system sizing, and performance evaluation, this research aims to provide insights into the best practices for designing hybrid energy storage systems that can meet the evolving energy demands of modern microgrids.
The need for renewable energy sources has grown in the power industry as fossil fuels are becoming less available. The use of fossil fuels has a significant negative influence on the ecosystem as well. We are increasingly moving to renewable energy sources in order to prevent this environmental degradation, and among these renewable energy sources, solar energy is in more demand. 1954 When Daryl

Chapin, Calvin Fuller, and Gerald Pearson create the silicon photovoltaic (PV) cell at Bell Laboratories, the first solar cell that can transform enough solar energy into electricity to run daily electrical devices, photovoltaic technology is created in the United States.

1.1 Supercapacitor

The charge differential that appears on its positive and negative plates, which are somewhat apart, is how it stores energy. Similar to normal capacitors, supercapacitors, also known as double layer capacitors, have a higher capacitance value because of their larger plate surface and closer spacing between plates:

$$C = \varepsilon \frac{A}{d}$$

The supercapacitor, which produces high current pulses, is mostly utilised in applications requiring quick charging and discharging. Fig. 1.1 displays a Maxwell 16V, 500F supercapacitor.

Fig 1.1 supercapacitor

1.1. Hybrid energy storage systems (HESS)

Although there are several energy storage devices in use today, none of them can respond quickly over an extended period of time. Energy density and power density are two key parameters that are very helpful when building hybrid energy storage systems. The energy storage systems are separated into two sections in Fig. 1.2, one with a high energy density and the other with a high power density.

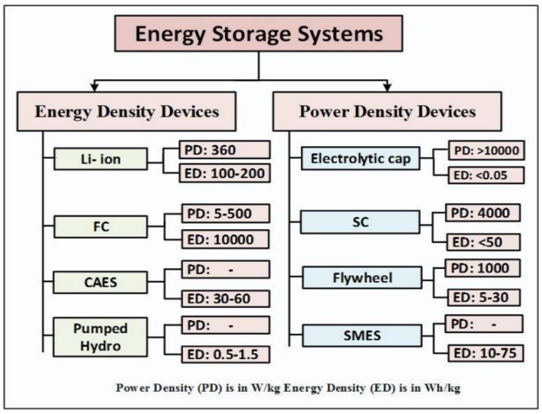


Fig 1.2 Classification of different energy storage systems

1.2 Micro Grid System Configuration

Fig. 1.3 displays the DC microgrid setup block diagram. PV power is the main source used to provide the load in a DC microgrid. By controlling the DC grid voltage with a boost converter, the PV array's output power is completely managed.

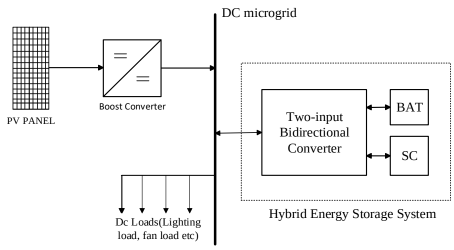


Fig.1.3 Micro grid system configuration of the proposed system.

Energy storage is required to handle the power imbalance when operating off the grid.

2. LITERATURE SURVEY

The integration of hybrid energy storage systems (HESS) into DC microgrids has gained significant attention due to the growing demand for reliable, efficient, and sustainable energy solutions. Researchers have focused on developing and optimizing energy storage configurations that can better manage the intermittency of renewable energy sources, improve system reliability, and maximize the overall efficiency of microgrids. The literature on hybrid energy storage in DC microgrids provides valuable insights into various system designs, technologies, and strategies for optimizing performance.

Hybrid Energy Storage Systems for DC Microgrids

Hybrid energy storage systems combine two or more storage technologies to leverage their complementary benefits, such as the long-term energy storage capabilities of batteries and the high-power density of supercapacitors. According to [Zhao et al., 2020], integrating energy storage technologies such as lithium-ion batteries, flywheels, and supercapacitors can significantly improve the performance of DC microgrids by enabling effective energy management during peak demand and off-peak periods. HESS can smooth out power fluctuations, extend battery life by reducing deep cycling, and provide rapid response times when high power is needed. [Li et al., 2019] demonstrated that HESS could enhance the voltage stability and load frequency control in DC microgrids, reducing the risk of instability caused by sudden demand fluctuations or renewable generation variability.

System Design and Optimization

The optimal design of hybrid energy storage systems for DC microgrids requires careful consideration of several factors, including storage sizing, power management strategies, and control algorithms. Studies by [Santos et al., 2021] emphasized the importance of system sizing to match the capacity and output of energy storage systems with the energy demand and renewable generation profile of the microgrid. Under-sizing or over-sizing energy storage can lead to suboptimal performance, increased costs, and inefficient operation. [Jain et al., 2020] explored various design methodologies, including linear programming and optimization algorithms, to determine the optimal configuration of hybrid systems. Their research showed that an optimized HESS design could reduce the operational cost and improve energy utilization efficiency.

Energy Management and Control Strategies

A significant area of research in HESS for DC microgrids is the development of intelligent energy management and control strategies. These strategies are essential for ensuring that energy storage devices operate efficiently, maintaining balance between the energy supply and demand while minimizing losses. [Xu et al., 2021] developed advanced control algorithms for HESS that use real-time data from power electronics and energy monitoring systems to dynamically manage the charging and discharging cycles of different storage technologies. These algorithms can prioritize the use of supercapacitors for short-duration power delivery while relying on batteries for long-term energy storage. Additionally, [Zhang et al., 2020] proposed a model predictive control (MPC) approach that optimizes the energy flow between renewable sources, storage systems, and loads, minimizing costs and ensuring reliable operation.

Performance Analysis of Hybrid Energy Storage Systems

Performance analysis of HESS in DC microgrids is crucial for assessing the practical benefits and limitations of different configurations. [Mendes et al., 2019] conducted a comparative study of HESS using batteries and supercapacitors in a DC microgrid and found that the combination significantly improved energy efficiency, enhanced power quality, and reduced the wear and tear on batteries, thereby extending their service life. Similarly, [Kou et al., 2020] analyzed the performance of HESS with flywheels and lithium-ion batteries, showing that the hybrid system could reduce voltage fluctuations and improve frequency regulation in microgrid applications. These performance studies highlight the importance of integrating different storage technologies to optimize performance, reduce costs, and extend the lifetime of individual components.

Economic and Environmental Considerations

Economic and environmental factors play a significant role in the design and implementation of hybrid energy storage systems. [Ali et al., 2018] investigated the life-cycle cost of hybrid storage systems for DC microgrids, considering capital costs, operation and maintenance expenses, and energy savings. The study concluded that while HESS requires a higher initial investment compared to single-technology systems, the long-term benefits in terms of efficiency, energy savings, and extended operational life make it a more cost-effective solution. Furthermore, environmental impact assessments by [Martins et al., 2020] indicated that hybrid systems, by improving energy efficiency and reducing reliance on backup generators, can lower the overall carbon footprint of DC microgrids, contributing to sustainability goals.

Challenges and Future Directions

Despite the clear advantages of HESS in DC microgrid applications, several challenges remain, including system complexity, integration issues, and the cost of advanced storage technologies. [Nguyen et al., 2021] noted that the integration of multiple energy storage technologies into a single system requires advanced power electronics, communication protocols, and intelligent control systems, which can increase the complexity of the microgrid infrastructure. Research into hybrid energy storage system design is also focused on reducing the overall cost by improving the efficiency of power electronics, optimizing energy management algorithms, and selecting cost-effective materials. Additionally, emerging technologies such as solid-state batteries and next-generation supercapacitors hold promise for improving the efficiency and cost-effectiveness of HESS in DC microgrids.

Conclusion of Literature Survey

The literature reveals that hybrid energy storage systems offer significant advantages for enhancing the performance, reliability, and efficiency of DC microgrids. By integrating complementary energy storage technologies and employing advanced optimization and control strategies, HESS can effectively balance supply and demand, improve voltage stability, and extend the operational life of microgrid components. While challenges such as system complexity, cost, and integration remain, ongoing advancements in energy management systems, storage technologies, and power electronics are expected to address these issues, making HESS an increasingly viable solution for the future of DC microgrids.

3. **Proposed Configuration**

3.1 PROPOSED TOPOLOGY

The suggested topology's schematic is seen in Figure 2.1. A boost converter and a bi-directional DC-DC converter coupled by inductors make up the specified topology. With VDC as the input voltage, L as the source inductance, a diode D, filter capacitance Cf, switch S, and load resistance RL, the architecture includes a boost converter. The two-leg inverter arrangement is used to choose the bi-directional buck boost converter. In the first leg, switches S1 and S2 are linked, and in the second leg, switches S3 and S4 are connected. Switches S1, S2, S3, and S4 each include antiparallel diodes, D1, D2, D3, and D4. The modes of operation are described in detail below to help you comprehend how the suggested architecture operates. A single-leg structure is used to demonstrate the operation first, followed by an explanation of the control method for a two-leg system.

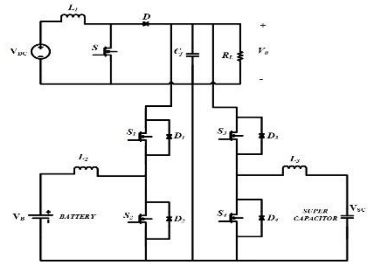


Fig 3.1 Architecture of the DC micro grid system with battery and super capacitor HESS.

3.2 DC Microgrid configuration using battery alone

A single source Bi-Directional DC-DC converter is used to regulate the DC microgrid with battery is connected is shown in Fig.2.2. The Photovoltaic panel is designed for MPP voltage of 12V is is emulated by using regulated power supply of 0-24V/0-3A and is connected input to the boost converter.

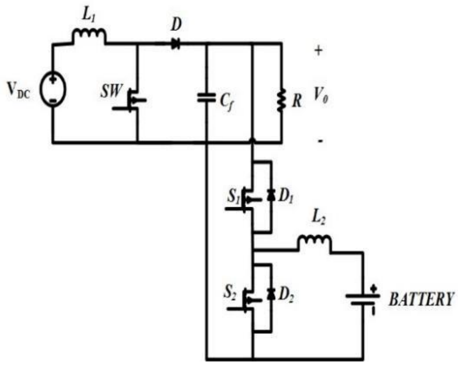


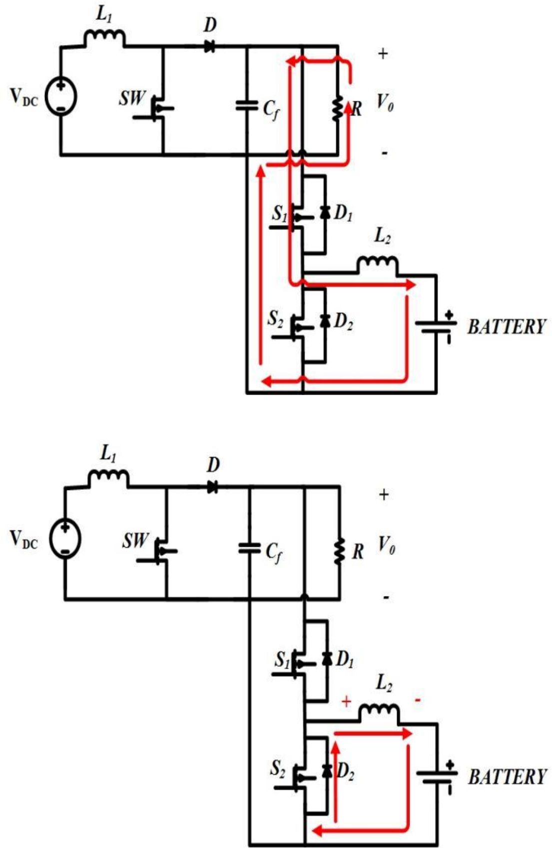
Fig 3.2 Architecture of the DC micro grid system with battery.

The output side of boost converter, a battery is connected using complimentary switching devices.

In Fig 2..2 switches S1 and S2 are complimentary. Diodes D1 and D2 are the feedback diodes to switches S1 and S2 respectively. The high frequency inductors L1 and L2 are connected to the boost converter and battery side. The high frequency inductors are sufficiently high to make continuous conduction mode.(CCM) and to maintain constant DC. C_f is filter capacitance, it keeps output voltage ripple under control and R is load resistance.

3.2.1 Mode-I: Power flow from DC grid to battery(charging mode)

The battery charging operation is explained in Fig.2.3. The battery charging is possible only when increasing PV generation or reducing the load demand. If PV generation increases load demand is constant, the excess power existing at load side. According to the switching logic, excess power charges the battery to maintain the grid voltage constant. In Fig 2.3(a) switches S1 turn ON and S2 turn OFF current flow from DC microgrid to battery (charging operation of battery).



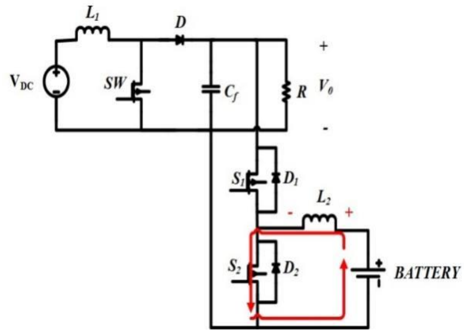
(a) S1 ON, D2 OFF, S2 OFF, D1 OFF (b) S1 OFF, D2 ON, S2 OFF, D1 OFF

Fig 3.3 (a), (b) ESS charging operation (Buck Operation).

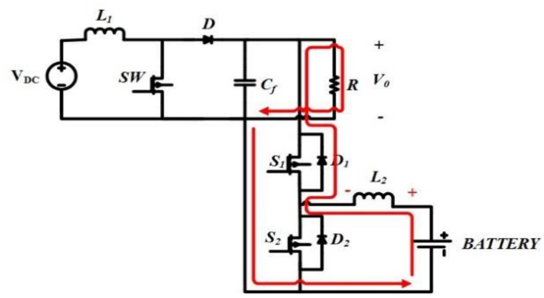
Later switch S_1 is turned OFF and D_2 gets forward biased to store energy into battery from inductor which is given in figure 2.3 (b). Solid line indicates the flow of current within the circuit.

3.2.2 Mode-II: ESS Discharging

The discharging operation of battery is possible only when decreasing PV generation and increasing load demand. For this case a deficit power exist at DC microgrid, immediately battery discharge to supply deficit amount of power to maintain the grid voltage constant.



(a) S1 OFF, D2 OFF, S2 ON, D1 OFF



(b) S1 ON, D2 OFF, S2 OFF, D1 OFF

Fig.3.4 (a), (b) ESS discharging operation (Boost Operation).

When DC grid voltage less than the PV generation than immediately battery discharge and supply power to DC grid to maintain the grid voltage constant. Switch S2 is turn ON and stores energy in inductor by using battery. Inductor stores energy as shown in with current directions as shown in Fig 2.4(a). After the next switching state sum of battery voltage and inductor voltage is greater than DC grid voltage, than turn OFF the switch S2 and diode D1 turn ON so power frow from battery to DC grid to maintain the grid voltage constant. Bi-Directional power flow between source and load as shown in Fig.2.5.

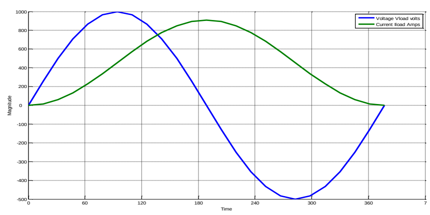


Fig.3.5 Graphical representation of bidirectional power flow.

3.3 Micro Grid Operation with Hybrid Energy Storage System

Two-input bidirectional converter is used to control charging/discharging operation of HESS. It consist of four bidirectional switches connected in H-bridge configuration as shown in Fig.2.2.1. The two switching legs are connected to DC microgrid. Battery and SC are connected to the each leg through the high frequency inductors. The two modes (charging/discharging) of operation are explained in the following sections.

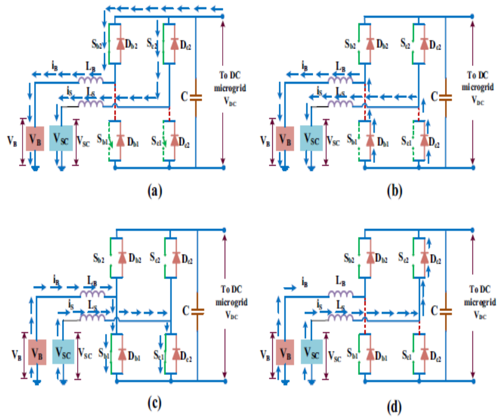


Fig 3.6 Equivalent circuit of two-input bidirectional converter in charging/discharging mode

3.3.1 HESS Charging

In this mode of operation, battery and SC absorbs the excess power from the DC microgrid to maintain the grid voltage constant. The switches S1 and S3 are operated with duty ratios DB and DS respectively. The battery and SC charge according to energy management control logic to maintain the grid voltage constant. Equivalent circuit of two-input bidirectional converters are shown in Fig 2.6.

$$V_B = D_B \cdot V_{dc} \qquad (2.1)$$

$$V_S = D_S \cdot V_{dc} \qquad (2.2)$$

In this mode power flow from DC microgrid to battery-SC bank. The DC microgrid is in higher potential compared to battery-SC bank. Thus converter operates in buck mode in order to charge the HESS. Equations (4), (5) represents the buck operation of the Bi-Directional DC-DC converter.

3.3.2 HESS Discharging

In this mode of HESS operation, battery-SC bank supply power to the DC microgrid. The bidirectional converter operates like boost mode by operating switches S2 and S4.

$$V_{dc} = \frac{V_B}{1 - \overline{D_B}} \quad (2.3)$$

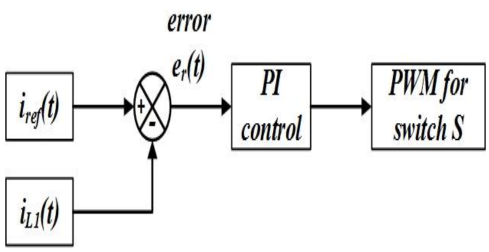
$$V_{dc} = \frac{V_S}{1 - \overline{D_S}} \quad (2.4)$$

In each switching leg, devices conducts in complimentary fashion. Thus only one gate circuit is required for each switching leg. Equations (6), (7) represents the boost operation of the Bi-Directional DC-DC converter.

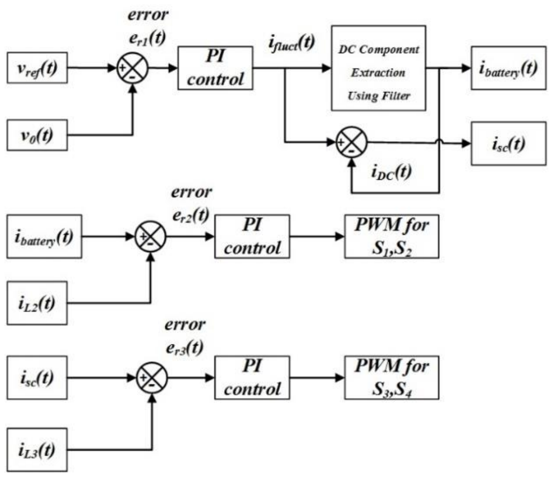
4. Control Strategy

4.1 Control Strategy for Energy Management in HESS

The control block diagram for HESS for DC microgrid configuration as shown in Fig 3.1. The proportional and integral controller technique is used for controlling switches. The DC grid reference voltage compared with actual output voltage, some voltage error is generated. The voltage error is applied to the PI controller, PI controller gives total current supplied to the hybrid energy storage systems. The total current demand is passing through the low pass filter (LPF), it separates average component of current demand and transient component of current using LPF. Steady state or average component is referred as reference current to the battery current control loop. Transient current component is used as the reference current to the SC current control loop. Actual battery and SC currents are compared with reference currents errors generated. PI controller generates the duty ratios of Db and Ds for battery and SC.



(a)



(b)

Fig.4.1 a) Control logic of boost converter in HESS (b) Control logic of Bi-directional buck-boost converter for battery and super capacitor.

The control to inductor current transfer function is given as follows [12]:

$$G_{i_s d_s} = \frac{\hat{i}_S(s)}{\hat{d}_S(s)} = \left[\frac{V_0 Cs + 2\frac{V_0}{R}}{L_3 Cs^2 + \frac{L_3}{R}s + (1 - D_S)^2} \right]$$

Inner current loop is faster compared to the outer voltage loop, so in this control scheme bandwidth of inner current loop is selected as switching frequency/6 (fsw/6). For diverting high frequency transient currents the bandwidth for battery control loop is selected as switching frequency/10 (fws/10). For calculation controller gains the phase margin 60^0 for entire work. The proportional and integral abstained are 0.0077 and 90.785 respectively.

5. Simulation Results

5.1 Simulation results for proposed Scheme

The 2016 version of the MATLAB-Simulink® program is used to create simulation results. For this simulation, a 12V, 7Ah lead acid battery was utilised. Ten kHz has been chosen as the switching frequency for this procedure. With the aid of a DC source, 10V is used as the input to the boost converter. Under ripple content, high frequency inductors are made for boost converters. MOSFET switches are employed in the bidirectional DC-DC converter and boost simulation studies.

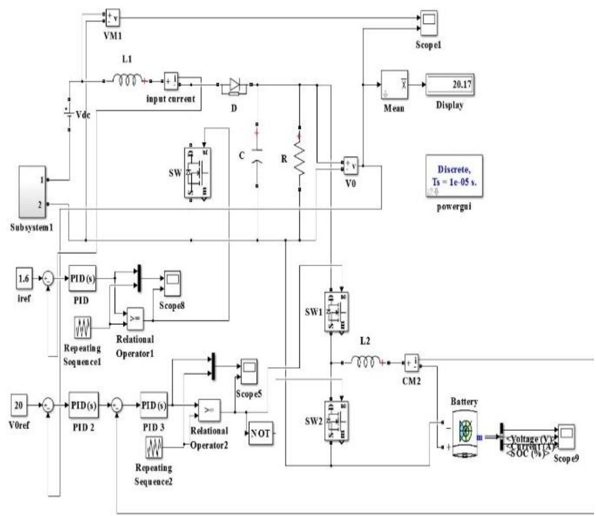


Fig.5.1 Simulation model for the battery alone system.

The simulation model for voltage regulation of DC micro grid using battery based Bi-Directional DC-DC converter is illustrated in Fig.4.1

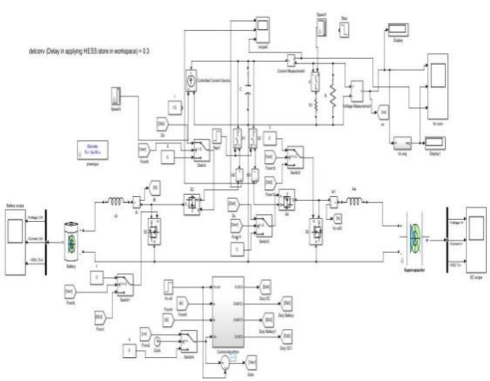


Fig.5.2 Simulation model for the battery-super capacitor combined storage system.

5.2 Simulation Results

Two test scenarios are examined and the outcomes of the suggested method are shown in this section. The dSPACE DS 1104 controller board was used to create the suggested plan. The MATLAB Simulink blocks are used to create the control process. It differs from the conventional approach with the final goal of demonstrating the comprehensiveness of the suggested technique. The lead-acid battery variant with 12V and 7Ah is used. Ten kHz is the switching frequency used for circuit functioning. The PV output module is selected at 10V with the aid of a DC source. The filter capacitance and inductor are designed for a boost converter because to the ripple content. MOSFET switches are used in boost and bi-directional DC-DC converters. This section also explains the hardware prototype and software used to implement the suggested plan. Simulation and experimental findings are compared. The simulation results for two test scenarios using the suggested technique are analysed below.

Case.1: Battery Alone System

In this case, the battery alone system is studied. The simulation diagram of voltage regulation of DC Microgrid using battery based bi-directional DC-DC converter is depicted in Fig 4.1.

5.2.1. Step Increase in Source Voltage

Fig 4.3 (a) demonstrates the source voltage with disturbances over the period of time frame. Here, the source voltage is all of a sudden expanded at the time instant of t=1.5 sec which is kept up at 12V up to t=2 sec. At the point when there is no battery storage and bi-directional converter, the output voltage of boost converter is likewise expanded to a value of 24V amid this disturbance period. At the point when a bi-directional converter is associated among battery and grid, the grid voltage is recovered back to 20V utilizing the proposed control strategy.

5.2.2. Step Decrease in Source Voltage

Fig 4.3 (b) demonstrates the source voltage with ESS over a period of time. The source voltage is all of a sudden diminished at the instant of time at t =0.5sec which is kept up at 8V up to t =1sec. At the point when there is no battery storage and bi-directional converter, then the boost converter output voltage is likewise diminished to a value of 16V amid this disturbance period. At the point when a bi-directional converter is associated among battery and the grid, the grid voltage is recovered back to 20V utilizing the proposed control strategy.

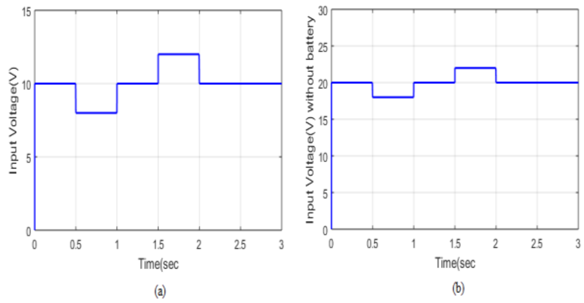


Fig 5.3 (a) Source Voltage With Disturbances (b) Load Voltage Without ESS

5.2.3. Performance Analysis of Battery Alone System

Fig 4.4 (a) demonstrates the graph of battery voltage versus time. It indicates battery performance amid step disturbance in input voltage of source converter. As it is observed from the Fig 4.4 (a) the voltage in the battery is diminished to the operation of discharge from 0.5sec to 1sec amid step decrease in source voltage. Fig 4.4 (b) demonstrates the plot of battery current versus time. In input voltage of step decrease, current in the battery is controlled to supply the deficit voltage at grid. Fig 4.4 (c) demonstrates the state of charge of battery in (%). It is seen from the fig 4.4 (c) amid the duration of step decrease in source voltage, the battery current is expanded and it keeps up a similar incentive till the disturbance is evacuated and SOC % of the battery diminishes. For step increase in input voltage, battery current is controlled in order to supply surplus voltage at grid. For this, battery voltage is expanded at t=1.5sec representing to the charging operation from 1.5sec to 2sec amid step increase in source voltage. It is seen from the fig 4.4 (c) battery current is diminished and keeps up same value till disturbance is evacuated and SOC (%) of battery increments.

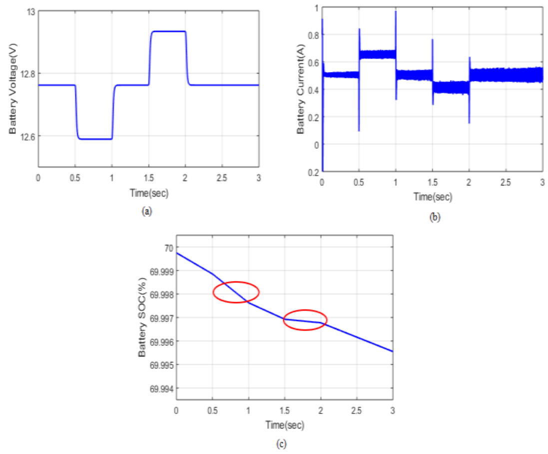


Fig 5.4 (a) Voltage (b) Current (c) SOC % of Battery

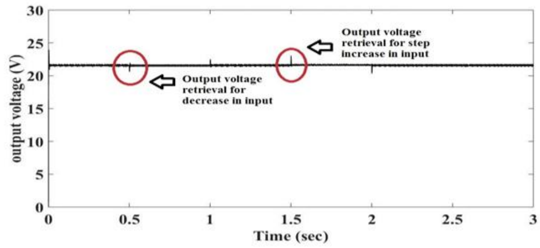


Fig 5.5 Output Voltage with Battery Energy Storage

The output voltage with BES demonstrates Fig 5.5. It outlines the recovery of output voltage while expanding or diminishing in the input voltage. As seen from the Fig 5.5, amid the step decrease in source voltage the output voltage is recovered at the time instant of t=0.5sec. After that the time instant of 1.5 sec, the output voltage is recovered amid the step increase in the source voltage.

Case 2: HESS

5.2.4. Increasing PV generation

Initially HESS is disconnected from DC microgrid, at t=0.1sec to regulate the DC microgrid HESS is connected to DC microgrid. Increasing PV generation analyzed with the help of sudden change in PV voltage from 24V to 30V at t=0.3sec as shown in Fig.4.6. When PV generation more than the load power demand, excess power exist in DC microgrid causes surge in grid voltage at t=0.3sec. Immediately respond HESS and charge extra power exist in DC microgrid to maintain the grid voltage constant. The DC grid voltage regulated fast and stress on the battery reduced compared to battery alone system. The battery and SC performance characteristics are presented in Fig 4.7 and Fig 4.8 respectively.

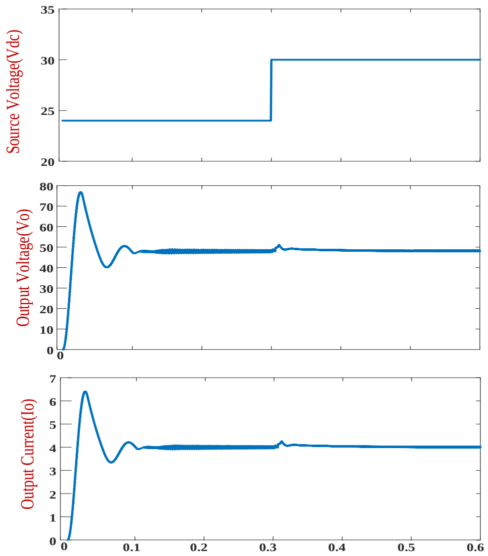


Fig 5.6 Simulation results for step increase in PV generation

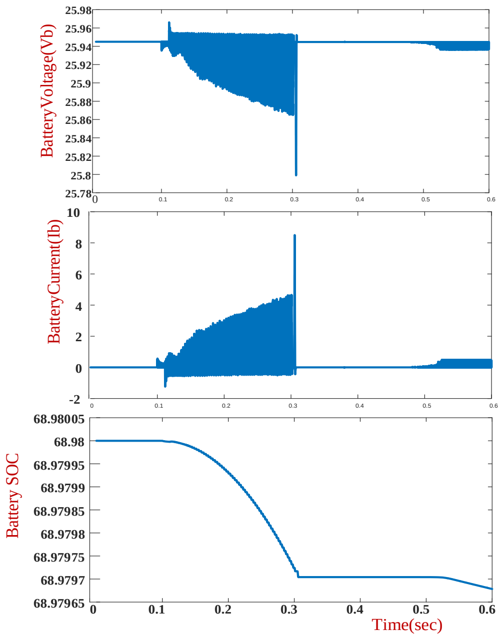


Fig 5.7 Battery scope for step increase in PV generation

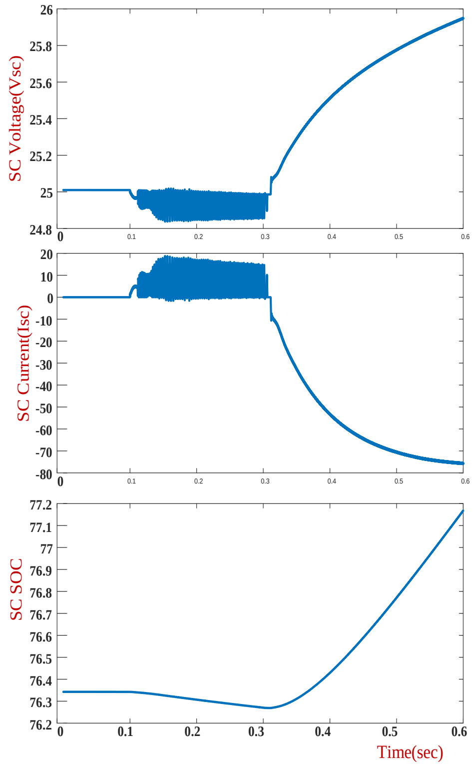


Fig 5.8 super capacitor scope for step increase in PV generation

5.2.5 Simulation results for step decrease in PV generation:

Decreasing PV generation is analyzed with the help of sudden change in voltage from 24V to 20V at t=0.3sec as shown in Fig 4.9. In this case PV generation is less than load demand, surplus power exist at load side. To compensate the surplus power immediately HESS respond to discharge battery-SC bank to maintain the grid voltage constant. The battery and SC performance characteristics for step decreasing PV generation as shown in Fig 4.10 and Fig 4.11 respectively.

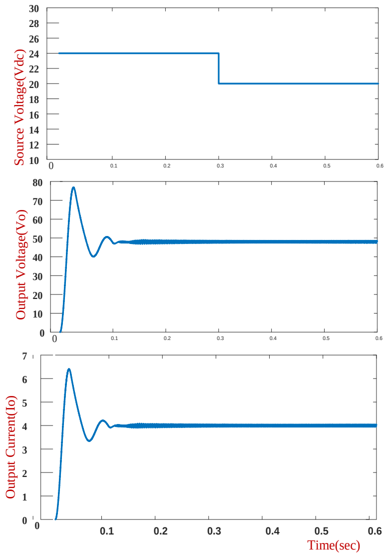


Fig 5.9 input voltage, output voltage, output current for step decrease in PV generation

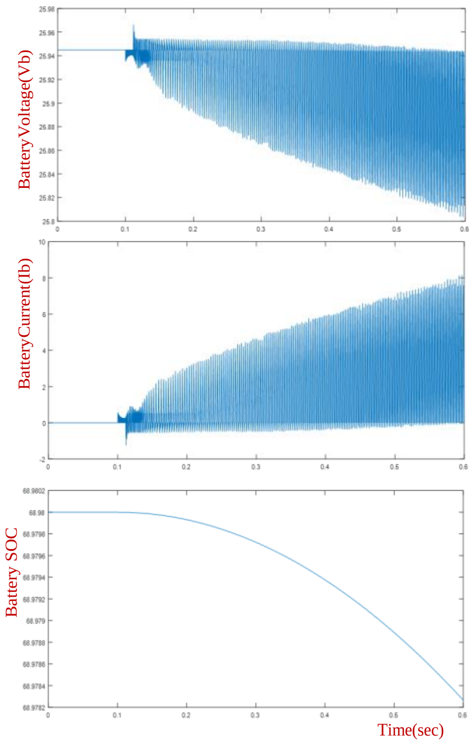


Fig 5. 10 battery scope for step decrease in PV generation

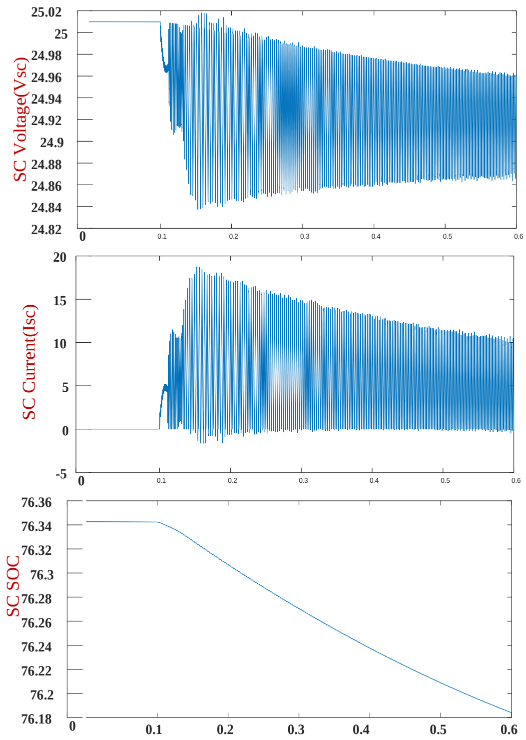


Fig 5.11 Supercapacitor scope for step decrease in PV generation

6. CONCLUSIONS

Conclusions

The design and implementation of hybrid energy storage systems (HESS) for DC microgrids represent a transformative advancement in enhancing the performance, efficiency, and reliability of renewable energy systems. By combining different energy storage technologies, such as batteries, supercapacitors, and flywheels, HESS systems leverage the unique advantages of each technology, allowing for more efficient management of energy in DC microgrid applications. The integration of HESS facilitates the smooth operation of DC microgrids, mitigating the challenges posed by intermittent renewable generation and fluctuating power demands.

This research demonstrates that optimized HESS configurations significantly improve the overall performance of DC microgrids. Energy management strategies, such as advanced control algorithms and real-time optimization, play a pivotal role in ensuring the efficient operation of hybrid systems, leading to enhanced power quality, stability, and reduced operational costs. Additionally, the synergy between long-duration energy storage and high-power density solutions maximizes the utilization of renewable energy, reduces dependency on traditional backup power sources, and improves the sustainability of the microgrid.

Despite the clear advantages, several challenges remain in the practical implementation of HESS, including system complexity, integration with existing infrastructure, and high initial costs. However, ongoing advancements in energy storage technologies, power electronics, and optimization algorithms are expected to address these barriers, leading to more cost-effective and scalable solutions. Furthermore, the environmental benefits of hybrid systems, including reduced carbon emissions and lower environmental impact, further emphasize their potential for supporting the global transition toward clean energy.

In conclusion, hybrid energy storage systems offer a promising solution for enhancing DC microgrid operations, ensuring a reliable, efficient, and sustainable energy supply. As research and development in this field continue to progress, HESS will play an increasingly crucial role in advancing the adoption of DC microgrids, driving the next generation of energy solutions and contributing to the broader goal of achieving energy resilience and sustainability.

Scope of Future Work

A three-leg structured bi-directional DC-DC converter-based hybrid energy storage system may be added to this work to accomplish energy exchange between the storage parts. Additionally, there is a feature that allows for real-time implementation utilising the DSPACE model 11004.

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