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EFFICIENT ENERGY MANAGEMENT IN DC MICROGRIDS USING A HYBRID BATTERY–SUPERCAPACITOR STORAGE SYSTEM

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Abstract **-** As renewable energy sources have grown considerably in recent years, efficient storage of this type of energy and intelligent management of the power system in DC microgrids has become a hot topic. Battery-based energy storage systems suffer from their limited life cycle, sluggish responses to fluctuating loads and low efficiency. The proposed next-generation Hybrid Energy Storage System (HESS) via a cascaded multiport converter is designed to surmount these impediments for their amalgamation in an array of DC microgrid applications. This work proposes a solar photovoltaic source, battery, and supercapacitor system for reliable and efficient energy management. Dynamic control strategy of power-sharing among multiple energy sources based on microcontrollers according to load and system situation. The supercapacitor quickly responds to sudden loads while the battery supports stable long-term energy output. This cascaded multiport converters enhance power conversion efficiency, and can provide effective coordination among various energy storage parts. Voltage and current sensors measure system parameters continuously to maintain safe operation under normal conditions. The solution provides better energy efficiency, lowered battery stress, higher system reliability and enables seamless integration of renewable energy sources in DC microgrids. These results demonstrate that the system provides a scalable and low-cost solution for next generation smart grid and distributed energy applications.

Keywords - Hybrid Energy Storage System (HESS); DC Microgrid; Cascaded Multiport Converter; Renewable Energy Integration; Supercapacitor; Battery Energy Management; Smart Grid.

I. INTRODUCTION

The transition towards clean and renewable energy remains a growing trend in today's world. The DC microgrid is being recognized as an efficient architecture for renewable energy sources, energy storage systems and DC loads integration innovate compared to conventional AC infrastructures due to its higher efficiency, fewer conversion stages and lower costs. This presents a major challenge for stable power supply and energy management in DC microgrids, given the intermittent nature of renewable resources. Energy storage systems (ESSs) are essential solutions to these challenges as they help alleviate the discrepancies between power generation and consumption, enhance power quality, and improve system reliability[1].

Conventional DC microgrid systems usually have battery storage systems that are independent of each other. Though batteries offer comparatively good energy density and long term energy storage, it has various drawbacks including slow dynamic response, limited life cycle and deterioration as a result of frequent charge discharge cycles. In order to defeat these shortfalls, Hybrid Energy storage Systems (HESS) has been of great interest over the past few years. A hybrid system will normally integrate batteries with supercapacitors in which the battery provides the steady-state energy and the supercapacitor provides quick response to the load surges. This complementary action enhances the general efficiency of the system, decreases battery tension, and expands the lifespan of the energy storage units [2][3].

Power electronic converters are important in the management of power in-flow and outflow of the renewable sources, stored and consumed power. Multiport converters have become a potentially useful alternative to other converter topologies in that they can support the combination of energy sources and storage tools within a single energy conversion framework. Multiport converters Cascaded Multiport converters allow the sharing of power efficiently, fewer components, and easy management of energy in hybrid storage structures. They are also efficient in conversion and scaling of systems in DC microgrids [4][5].

In this regard, this paper suggests a hybrid energy implementation concept of a cascaded multiport converter of DC microgrid systems. The proposed system combines the solar photovoltaic source, battery, and supercapacitor to attain an effective energy distribution and constant power delivery. A control plan that involves a microcontroller dynamically maintains the flow of power between various sources of energy based on the conditions of the load. The suggested architecture will help to increase the energy efficiency, system reliability, and adaptability to integrate renewable energy effectively in the contemporary DC microgrids [6][7].

II. LITERATURE REVIEW

The high rate of development of renewable energy infrastructure strengthened the role of effective energy storage technologies in contemporary power networks. The popularity of DC microgrids is also increasing because they offer a way to combine renewable energy sources, storage devices and DC loads into fewer conversion steps as well as better efficiency. Nevertheless, renewable energy sources like solar and wind are intermittent in nature, which give rise to variations to power generation and difficulty in ensuring constant voltage and power equilibrium in microgrids [1]. In order to resolve these problems, the solution that will be necessary is the adoption of advanced energy storage technologies to stabilize the power supply and enhance the reliability of the systems.

BESS were traditionally used in microgrids in order to save surplus energy and provide power during peak periods. Batteries have a great energy density and longtime storage thus they are applicable in maintaining consistent flow of energy. The battery systems, however, are not without a number of limitations that include slowness in responding to sudden changes in load, low cycle life and deterioration of performance with repeated cycle of charge-discharge [2]. The above challenges have prompted researchers to consider the concept of hybrid energy storage system (HESS) which involves the integration of several storage technologies to improve the functionality of the system.

Hybrid energy storage Systems normally combine supercapacitors and batteries in order to take advantage of the complementary traits of the two products. Batteries have high energy density, which can be used in long-term energy supply and supercapacitors have high power density and response capability to compensate transient loads. The combination of both allows energy management to be done efficiently, the strain on batteries is minimized and the overall storage system life is enhanced [3][4]. It was observed in the studies that battery-supercapacitor hybrid systems can greatly enhance the voltage stability and power quality within DC microgrids whenever there is sudden variation in loads and occasional variation in the renewable generation [5].

A number of researchers have come up with a number of control strategies and system architectures so as to optimize the working of hybrid energy storage systems. Indicatively, sophisticated energy management algorithms are devised that can manage the power transfer between batteries and supercapacitors depending on the load dynamics and state of charge [6]. Sophisticated control methods including fuzzy logic control, model predictive control and adaptive algorithms have also been explored to improve the energy distribution and the system stability in renewable energy based microgrids [7].

Power electronic converters are essential to combine various sources of energy, storage systems in hybrid energy systems. Multiport DC-DC converters have been of particular interest since they are able to interface multiple sources of power into a single power conversion unit. These converters minimize the number of components, enhance efficiency as well as allow flexible power control in micro grid applications [8]. The cascaded multiport converter architectures also take the capability of the energy systems to a greater heights of power sharing and dynamically controlling power between the renewable sources and storage units.

Moreover, there are a few studies focused on the performance of photovoltaic (PV)-based DC microgrids, which are combined with a hybrid energy storage system. These systems usually use two-way DC-DC converters to operate charge and discharge of storage devices as well as provide constant DC bus voltage. Simulation and experimental evidence proves the fact that hybrid storage system attains significant reduction of DC-link voltage variation and the overall stability of the microgrid in changing load conditions [9][10].

Recent studies have also been aimed at enhancing the economic viability and efficiency of hybrid energy storage systems. Optimization has been used to establish the optimum sizing of batteries and supercapacitors to ensure that the cost is minimized and maximize the system operation. These measures enhance the effective energy use and increase the economic feasibility of microgrids based on renewable energy [11].

In addition, improved data based and model driven control systems are advanced to improve the performance of the hybrid energy storage system in the DC microgrids. These methods rely on real-time control of voltage, current and

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load variables to dynamically control the power flow and system stability [12]. The realization of smart control and high efficiency power converters has enhanced the reliability and scalability of microgrids based on hybrid storage greatly.

Although these improvements are made, some issues still exist in the area of creating an efficient hybrid energy storage architecture such as the best converter topology, the efficient control strategy, and scalability of the system. Thus, there is an increasing demand in better energy management systems and converter architectures that can effectively incorporate renewable energy sources with hybrid storage devices. In this connection, this suggested cascaded multiport converter-based hybrid energy storage system is supposed to increase the efficiency of energy use, minimize power losses, and improve the stability of AC microgrids in terms of operation [13]-[20].

III. PROBLEM STATEMENT

The progress of renewable energy sources like solar and wind becoming a part of the modern power systems has created the concept of DC microgrids as an effective approach to power distribution and control. Nevertheless, renewable energy sources are direct intermittent and unpredictable and this leads to variations in power generation and difficulty in having a steady power supply to the loads that are connected to them. Old fashioned DC microgrid systems are usually supported by battery based energy storage systems to store surplus energy and provide supplementation during periods of peak demand. Despite its high energy density and the ability to store energy over a long period of time, batteries have low response time to sudden changes in the load, have short lifecycle, and its performance reduces as a result of repeated charge/discharge cycles.

Besides, traditional energy storage systems cannot effectively respond to the changes in the transient load and rapid changes in power, and as a result, cause the instability of the voltage, low system efficiency, and stress on battery storage units. Lack of efficient power management mechanism also causes the loss of energy and inefficiency in the use of renewable energy resources.

Thus the problem is to have a more sophisticated hybrid energy storage architecture that is capable of effectively incorporating renewable energy sources in combination with various storage devices and then has efficient energy management and constant power supply. The suggested system focuses on these issues with the implementation of a Hybrid Energy Storage System (HESS) on the basis of the cascaded multiport converter that connects a solar panel, battery, and supercapacitor together. The proposed method will enhance energy efficiency, stability of power, decrease stress on batteries and guarantee reliability of operations of microgrids on DC microgrids under different load conditions.

IV. PROPOSED SYSTEM

This proposed system proposes the implementation of a Hybrid Energy Storage System (HESS) with a cascaded multiport converter incorporated to ensure efficient control of power in the DC microgrid. This system will be a mixture of renewable energy production and hybrid energy storage to enhance power stability, efficiency and reliability. The key elements of the suggested system are a solar photovoltaic (PV) panel, battery storage, supercapacitor, cascaded multiport DC-DC converter, microcontroller based control unit, voltage and current sensors, and load interface. The proposed architecture is aimed at controlling the dynamical flow of the energy between various sources and storage devices and keeping the DC bus voltage constant.

In the design suggested, the solar PV panel will serve as the main source of renewable energy and will produce electric energy using sunlight. Created DC power is fed into the system by the cascaded multiport converter. The converter facilitates effective exchange of power among the solar source, battery, supercapacitor and the load. The battery forms the primary energy storage unit which provides energy throughout periods of low solar generation, or when the load requirement is higher than the supply of solar energy. Nevertheless, it is not only batteries that can react fast to a sudden change in load. To eliminate this constraint, a supercapacitor is incorporated into the system to supply quick transient power backup. The supercapacitor responds immediately to abrupt load changes and absorbs or provides intermittent changes of power, hence lessening the strain on the battery.

The suggested system is that of a Hybrid Energy Storage System (HESS) incorporated using a cascaded multiport converter to manage the power efficiently in the DC micro grid applications. The system integrates the power generation technology using renewable source with the hybrid storage of the energy to enhance the power stability, efficiency, and reliability. The key elements of the suggested system are a solar photovoltaic (PV) panel, battery storage, the supercapacitor, cascaded multiport DC-DC converter, microcontroller-controlled unit, voltage, and current sensors, and load interface. The aim of the proposed architecture is to dynamically control the flowing of the energy among various sources and storage devices to ensure a constant DC bus voltage.

The solar PV panel in the proposed structure will serve as the main source of renewable energy and will supply electrical power using the sunlight. The cascaded multiport converter provides the generated DC power to the system. The converter facilitates effective transfer of power between solar source, battery, supercapacitor and load. This battery is the primary energy storage component, which supplies energy in a sustained form in the absence of solar generation or when load demand is above the solar generation, or vice versa. Nonetheless, batteries are not sufficient in responding rapidly to spikes in loads. In order to eliminate this shortcoming, a supercapacitor has been included in the system to offer quick transient power supply. The supercapacitor has a fast response to the abrupt change of loads and absorbs or provides short-term fluctuations of power, thus eliminating stress on the battery.

Relay switching module and protection circuits are also provided to guarantee safe working of the system in the abnormal conditions like overvoltage, overcurrent or low voltage of the battery. The suggested control strategy increases the use of energy, reliability of the systems and long battery life by avoiding unnecessary charge-discharge cycles.

4.1 System Architecture

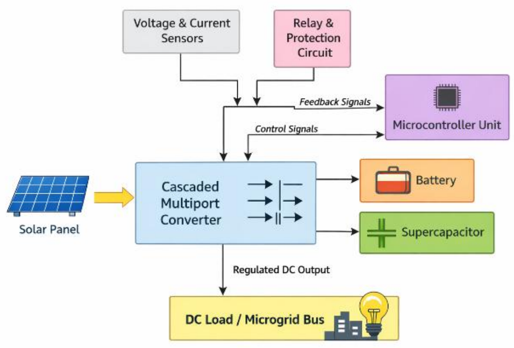

Figure 1. Hybrid Energy Storage System diagram

Proposed system will have a number of functional units which collaborate to maintain efficient energy control in DC microgrid.

Solar Panel: Solar photovoltaic panel is a solar panel which changes solar energy into electrical energy and is the main source of power in the system.

Cascaded Multiport Converter: This converter combines various sources and storage of power. It balances voltage, allows the flow of energy between the load, solar panel, battery, supercapacitor and controls it.

Battery Storage: The battery holds any extra power created by the solar panel and provides power when there is lack of renewable sources. Supercapacitor: The supercapacitor offers high-power density and quick load response to the changes in the load, which enhances stability of the whole system.

Microcontroller Unit: The microcontroller is the controller of the whole system as it processes sensor data and provides control signals to the converter and switching devices. Voltage and Current Sensors: These sensors are used to continuously monitor system parameters in order to include real-time monitoring and intelligent control. Relay Switching Module: The relay module decides on the right energy sources and offers the protection by separating components in case of fault conditions.

DC Load / Microgrid Bus: The regulated DC output is supplied to the load or DC microgrid bus, ensuring stable power delivery.

The proposed system architecture is practical to include renewable energy generation with the hybrid form of the energy storage technologies in order to attain efficient energy management, the best power quality, and increased reliability in DC microgrid systems. The Cascaded multiport converter and smart-control-plan allows ideal exploitation of solar power as well as reduces energy wastage and the life span of energy storage apparatus.

V.METHODOLOGY

The proposed system uses a Hybrid Energy Storage System (HESS) coupled with a Cascaded Multiport Converter to make effective use of renewable energy in a DC microgrid. The system is a combination of solar photovoltaic source, battery storage and supercapacitor to maintain a constant power output at different load and generation conditions. The methodology is devoted to the power-generation, energy-storage coordination, converter operation, and intelligent control strategy.

1. Converter Operation Modes

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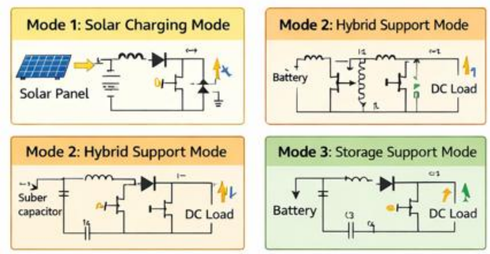

Figure 2. Converter operation modes of the proposed hybrid energy storage system.

The cascaded multiport converter operates in **three main modes** depending on energy availability and load demand.

Mode 1: Solar Charging Mode

In the case when there is solar energy and the load demand is moderate, the solar PV panel will provide power to the load and charge the battery and supercapacitor.

The boost converter attached to the solar panel has a resultant voltage: $v_{out}\, \frac{v_{in}}{1-D}$

Where

V_{in}= Solar panel voltage

D = Duty cycle of the switching Transistor MOSFET

The current in the inductor is: $I_L = \frac{v_{in}\, X\, D}{L-f_s}$

Where

L = Inductor value

fs= Switching frequency

Mode 2: Hybrid Support Mode

Once the load demand becomes sudden, the battery and the supercapacitor collaborate to provide power.

The power that is delivered to the load is a total of.

$$P_{load} = V_{dc} \times I_{dc}$$

The hybrid storage power sharing is

$$P_{load} = P_{battery} + P_{supercapacitor}$$

Battery current: $I_b = \frac{P_{battery}}{V_b}$

Supercapacitor current: $I_{sc} = \frac{P_{sc}}{V_{sc}}$

This makes sure that transient loads are responded to quickly and there be less stress on the battery.

Mode 3: Storage Support Mode

When the solar energy is not available (during the night or when the clouds cover the sky), the battery is the main source of power, and the supercapacitor fills in the sudden fluctuations in loads.

Energy stored in the battery is: $E_b=V_b \times I_b \times t$

Energy stored in the supercapacitor is: $E_{sc} = \frac{1}{2}\, cv_{sc}^2$

Where

C= Capacitance of supercapacitor

V_{sc} = Supercapacitor voltage

2. Power Management Control Algorithm

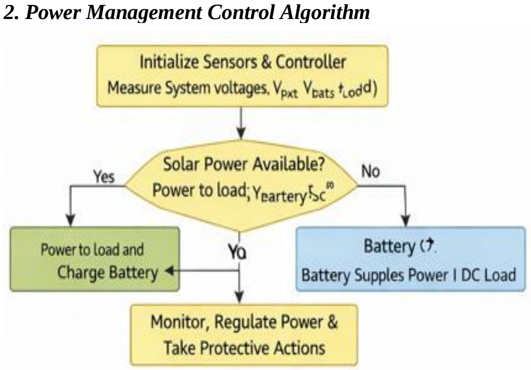

Figure 3. Power Management Control Flow

The system is controlled via a microcontroller-based algorithm of the energy management that controls the flow of power.

Step 1: Initialization

The controller initializes sensors and measures:

- Solar panel voltage V_{pv}
- Battery voltage V_b
- Supercapacitor voltage V_{sc}
- Load voltage V_{load}

Step 2: Solar Availability Check

If $P_v > P_{load}$

then the load is provided by solar power which recharges the storage devices.

Step 3: Load Increase Condition

If $P_{load} > P_v$ then

$P_{load}=P_v+P_{battery}+P_{supercapacitor}$

Step 4: Continuous Monitoring

The controller continuously updates the converter duty cycle to regulate the DC bus voltage:

$$V_{dc}=V_{ref}$$

Where V_{ref} is the reference DC bus voltage.

3. Cascaded Multiport Converter Circuit

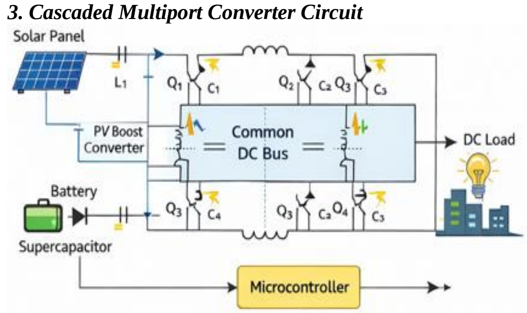

Figure 4. Cascaded multiport converter circuit diagram for hybrid energy storage integration.

The converter consists of:

- MOSFET switches Q_1,Q_2,Q_3,Q_4
- Inductors L_1,L_2
- Capacitors C_1,C_2,C_3,C_4
- Common DC bus

Inductor Design

$$L = \frac{v_{in}\,(1 - D)}{\Delta I_L\, X\, f_s}$$

Where

ΔI_L = Inductor ripple current

Output Capacitor Design

$$C = \frac{I_o\, X\, D}{\Delta V_o\, X\, f_s}$$

Where

ΔV_o= Output voltage ripple

System Efficiency

$$\eta = \frac{P_{out}}{P_{in}}$$

Where

$P_{in}=V_{in} \times I_{in}$

$P_{out}=V_{out} \times I_{out}$

VI.RESULTS AND DISCUSSION

Simulation and hardware analysis were used to determine the performance of the proposed Hybrid Energy Storage System (HESS) that employed Cascaded Multiport Converter. This system was tested with various operating conditions that include solar charging mode, hybrid support mode and storage support mode. Stability of DC bus voltages, converter switching waveforms, current sharing between battery and supercapacitor, system efficiency were a few key performance parameters that were analyzed.

1. Converter Switching Waveforms

The operation of the cascaded multiport converter was studied using op-amp gate pulse, inductor current and output voltage waveforms of a switch.

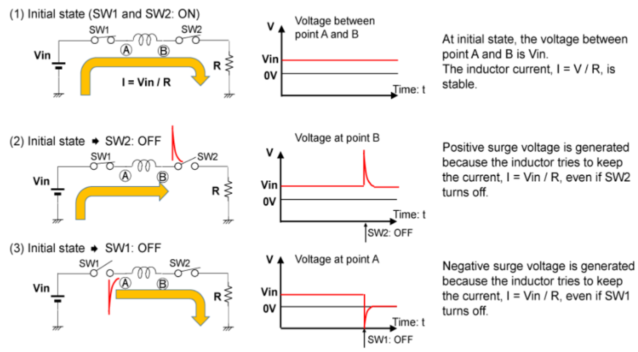

Figure 5. Switching operation and inductor transient voltage in the converter circuit.

Observations

- The microcontroller produces the gate pulses that control the duty cycle of the switches of the MOSFET.
- The waveform of current through the inductor is triangular, which is a sign of continuous conduction mode (CCM) operation.
- The capacitors filter out the ripple in output voltage waveform and cause the waveform to remain constant.

The output voltage ripple can be calculated as:

$$\Delta V_o = \frac{I_o \; X \; D}{C \; X \; f_s}$$

Where

I_o = Output current

D = Duty cycle

C = Output capacitance

f_s = Switching frequency

2. DC Bus Voltage and Load Response

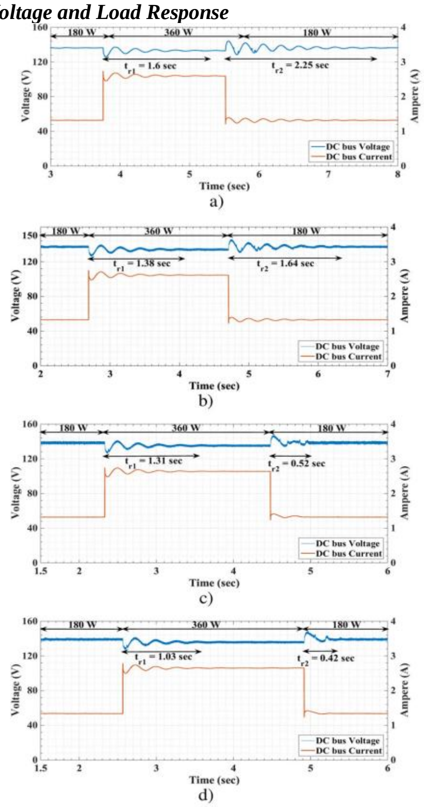

Figure 6. DC bus voltage and current response under different load variations

The DC bus voltage stability was also tested at sudden increase or reduction of the load.

Observations

- As the load demand rises, the supercapacitor responds by providing high current immediately thus keeping the DC bus voltage steady.
- The battery provides a constant power once the transient situation has been stabilized.
- The DC bus voltage remains close to the reference value V_{ref}.

Voltage regulation can be expressed as:

$$\text{Voltage Regulation} = \frac{V_{no\_load} \; X \; V_{full\_load}}{V_{full\_load}} \; X \; 100$$

A lower voltage regulation percentage indicates better system performance.

3. Battery–Supercapacitor Power Sharing

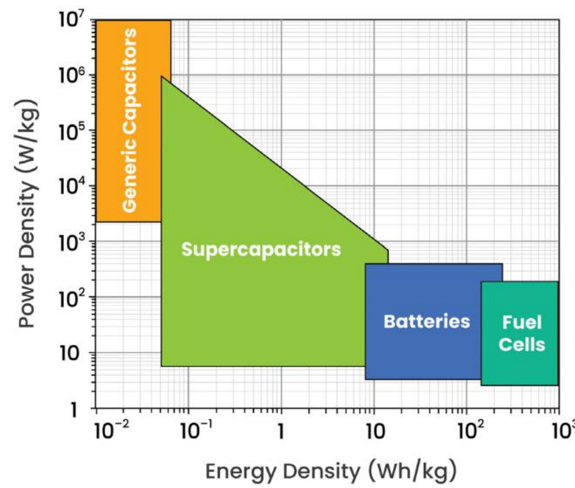

Figure 7. Load variation performance graphs

The hybrid storage system allocates the power between the supercapacitor and the battery based on the load dynamics.

Observations

- The supercapacitor provides high peak current in sudden changes in loads.
- The battery is used to supply constant power at steady state operation.
- This hybrid system will substantially decrease the stress on the battery and increase life duration.

Total load power is

$$P_{load} = P_{battery} + P_{supercapacitor} + P_{solar}$$

Energy stored in the supercapacitor is:

$$E = \frac{1}{2} \; X \; CV^2$$

4. Performance Comparison Table

Parameter	Conventional Battery Storage	Proposed Hybrid Energy Storage
Energy Sources	Battery only	Solar + Battery + Supercapacitor
Response Time	Slow	Very Fast
Voltage Stability	Moderate	High
Battery Stress	High	Reduced
Power Conversion Efficiency	85–88%	92–95%
Transient Load Handling	Poor	Excellent
System Reliability	Medium	High

Discussion

The findings reveal that the proposed hybrid energy storage system is far better in performance in DC microgrid than the conventional systems based on batteries. The addition of a supercapacitor enables high rate response in transient response and results in the system being able to respond to sudden changes in the load without voltage instability. The cascaded multiport converter is effective in synchronizing power between renewable energy sources and storage devices as well as keeping the DC bus voltage at a consistent level.

Moreover, the hybrid architecture lowers the load on the battery by distributing peak power loads with the supercapacitor, and therefore, increases battery life and overall system performance. The converter also minimizes switching losses and enhances the use of energy in the micro-grid. On the whole, the offered system offers the effective, stable, and scalable solution to the renewable energy integrated DC microgrid usage.

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VII.CONCLUSION

In this paper, the authors have provided a Hybrid Energy Storage System (HESS) with a cascaded multiport converter to manage power efficiently in DC microgrids. The suggested system will be a combination of a solar panel, battery, and supercapacitor to provide reliability in supplying power that is needed at different load levels. The converter architecture allows good distribution of energy and constant DC bus voltage.

Its findings indicate that the hybrid system is more efficient in energy, more stable in voltage, and better at transient response than the traditional battery-enhanced storage systems. A combination of supercapacitor helps to minimize the stress of the battery and to improve the reliability of the systems. Thus, the suggested solution can be implemented to offer a cost-effective and scalable system to operate DC microgrids utilizing renewable energy.

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