Variable Frequency Filtering Approach For SoC-Oriented Energy Management in Battery–Supercapacitor DC Microgrid Systems

V. Rajasekhar
PG. Student
Department of Electrical & Electronics Engineering
JNTUH, Kukatpally
Hyderabad, India.
vishlavathrajasekhar@gmail.com

Dr. Malaji Sushama M. Tech, Ph. D
Sr. Professor
Department of Electrical & Electronics Engineering
JNTUH, Kukatpally
Hyderabad, India.
m73sushama@jntuh.ac.in

***Abstract*— More and more photovoltaic (PV) systems are being added to DC microgrids. This has resulted in issues with power output that does not always work, voltage variations on the DC bus and battery degradation. The use of batteries with supercapacitors in an HESS is suitable due to the ability to control energy more efficiently. Batteries meet long-term power requirements whilst super capacitors smooth sudden power changes. This work shows an EMS based on SoC for a battery–supercapacitor HESS in a DC microgrid that is not connected to the main power grid. The proposed solution proposes to use a VFLPF to adjust the frequency for power sharing according to the configuration of the two storage parts in the SoC. The EMS allows flexible control when there is extra or less power by controlling the flow of energy, keeping the battery safe from too much current stress, and making better use of the supercapacitor. With a full-active HESS configuration with a bidirectional DC–DC converter, dependent and inflexible power control is believed to be avoided. The proposed scheme helps to better control the DC bus voltage, reduce the transient voltage deviation, increase the dynamic response and extends battery life. Simulations and tests done in real time using MATLAB show that this method works better than traditional fixed-frequency filtering methods. It provides smoother variation of battery current, reduces voltage oscillations, and optimizes energy utilization when renewable generation and load vary.**

Index Terms* — *DC Microgrid, Photovoltaic System, Hybrid Energy Storage System, State of Charge, Energy Management Strategy, Variable Frequency Low-Pass Filter, Battery–Supercapacitor System, Bidirectional DC–DC Converter.

I. INTRODUCTION

Increased use of PV system as RESs. This has hastened the development of DC microgrids (DCMGs) that use RESs, current DC loads, and energy storage devices. DC microgrids facilitate easier distribution of green energy, and more efficient energy conversion. They also worked on decreasing the power conversion processes. With the increasing need for "green" sources of energy, efficient energy management is required for stable operations while generation and load are variable [1]. ESSs can assist with power imbalances in isolated DC microgrids, help stabilize the DC bus voltage and provide reliability when the green energy supply is variable [2].

BESSs can store a significant amount of energy for a relatively long period of time, which is why many people decide to invest in them. Fast power shifts, however, put strains on the current and result in reduced battery life [3]. To avoid these issues, HESSs that use batteries and SCs are popular. The supercapacitor compensates for the high power density and rapid response to changes in power demand [14] and the battery provides the power regularly. Battery-Supercapacitor combinations enhance the transient performance, battery life and energy utilization of DC Microgrids [11].

Different configurations of the HESS (inactive, semi-active and full-active) have been studied, with optimization of power sharing. Semi-active structures offer more control options, but could potentially experience more storage device problems. In the full-active HESS system, a bidirectional DC–DC converter is used for each of the battery and supercapacitor. This makes it easier to control the power [12]. Changing operating conditions, however, make it difficult to keep the voltage in the dc bus and to distribute the power evenly among the storage units.

In traditional energy management, LPF separates low frequency energy and high frequency energy, and most of the control systems employ LPF. These techniques are easy and effective, however, the setting of filtering parameters may result in delayed reaction, inadequate power sharing and large voltage fluctuations on the DC bus [7]. Various advanced control strategies such as fuzzy logic, optimization and clever control have been proposed as ways to enhance the performance of HESS. These techniques, however, are hard to implement and require a lot of parameter tuning [10]. For robust power sharing, battery protection and efficient transient reaction, Adaptive energy management techniques accounting for battery and supercapacitor SoC conditions are crucial [8].

Three aspects are proposed: 1) energy management strategy based on SoC, which dynamically adjusts the power sharing between the batteries and supercapacitors in various working conditions; 2) variable frequency low pass filtering to better suppress the fluctuation of DC bus voltage and improve the transient response of the system; 3) optimization of battery performance while achieving maximum power utilization of the supercapacitor for dynamic power compensation, to reduce excessive charge and discharge stress.

II. LITERATURE SURVEY

Hybrid Energy Storage Systems (HESSs) have become an effective solution for improving energy management and operational stability in DC microgrids with high penetration of renewable energy sources. By combining batteries and supercapacitors, HESS architectures provide complementary characteristics in which batteries support long-duration energy requirements while supercapacitors compensate for rapid power fluctuations and transient disturbances. Several studies have focused on improving coordinated power sharing, converter regulation, and storage utilization to maintain stable DC bus operation under dynamic loading conditions [2].

Recent developments have explored advanced control methods for improving HESS performance. Decentralized and coordinated power allocation strategies have been introduced to improve energy sharing among storage units while reducing dependence on centralized control structures [8], [12]. These approaches enhance operational flexibility and improve voltage stability; however, maintaining balanced energy utilization under varying renewable generation and load conditions remains challenging.

To improve dynamic response and storage coordination, predictive and intelligent control techniques have also been investigated. Model Predictive Control (MPC)-based approaches provide effective energy scheduling and improved transient regulation through predictive decision-making [9]. Likewise, fuzzy logic and intelligent energy management methods have demonstrated improved handling of nonlinear operating conditions and adaptive storage control [10], [13]. Although these approaches improve system responsiveness, they often increase implementation complexity and require extensive tuning of control parameters.

Several studies have emphasized improving converter-level coordination and voltage regulation for battery–supercapacitor systems in isolated and grid-connected DC microgrids. Hybrid controller-based approaches and disturbance rejection control methods have shown improvements in power splitting, DC bus stabilization, and converter performance [5], [7]. In addition, integrated renewable–storage architectures have demonstrated enhanced regulation capability and more efficient utilization of storage resources [4], [11]. Accurate modeling and analysis of battery–supercapacitor interaction have further highlighted the importance of considering storage dynamics and state-dependent behavior during energy allocation [14].

Energy management strategies based on adaptive coordination have received increasing attention because of their ability to respond to changing operating conditions. Recent studies have explored autonomous coordination mechanisms and flexible power management techniques for maintaining stable operation during fluctuations in renewable generation and load demand [6], [15]. These methods improve storage cooperation; however, many existing solutions continue to rely on fixed control parameters or predefined power-sharing rules that may reduce adaptability under highly dynamic conditions.

Despite these advances, several limitations remain. Existing methods frequently emphasize either converter control, optimization complexity, or fixed-frequency energy separation, while limited attention is given to dynamically adapting power sharing according to the real-time state of charge (SoC) of both storage elements. Moreover, achieving rapid transient response, minimizing battery stress, reducing DC bus oscillations, and improving energy utilization simultaneously remains an open challenge.

To address these limitations, this work proposes a SoC-oriented energy management strategy for battery–supercapacitor HESS in a standalone DC microgrid using a Variable Frequency Low-Pass Filter (VFLPF) approach. The proposed method dynamically adjusts power allocation according to storage conditions, improves transient compensation, reduces battery current stress, enhances DC bus regulation, and enables more efficient utilization of hybrid energy storage resources.

III. Materials And Methods

The proposed work aims at developing an adaptive energy management strategy for a HESS consisting of battery and supercapacitor energy storage devices coupled with a separate DC microgrid. The framework aims to simplify the sharing of power in storage units, taking into account the conditions under which the units are in the SoC and the varying work conditions. We will examine a full active HESS configuration where the battery and supercapacitor are connected to the DC bus with bidirectional DC–DC converters that can independently manage their power. A variable frequency low-pass filtering method is used to get around the problems with fixed-frequency filtering by changing the power split on the fly based on the storage conditions. The energy management plan is designed to enhance the safety of the batteries, optimise the supercapacitors and maintain a stable DC bus voltage in the event of large variations in the load and production from renewables. How vital adaptive tactics are to make microgrids function better is demonstrated by new smart energy management methods that rely on real-time embedded control. The use of digital-based energy management models provides more options to enhance monitoring and decision making in hybrid DC microgrids. Optimization-based energy management techniques facilitate the effective collaboration of green energy sources, storage units and varying loads.

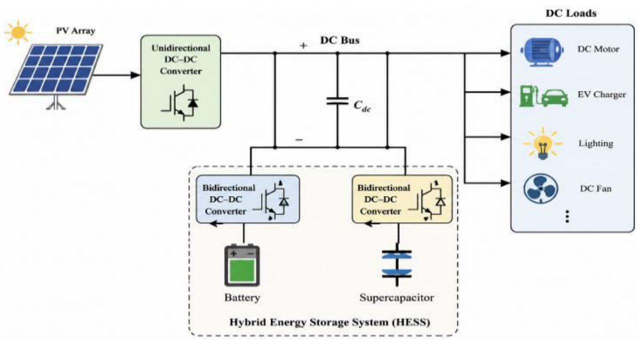

Fig.1 Structure of HESS-based DC Microgrid

The proposed HESS-based DC microgrid architecture is illustrated in Fig. 1. The photovoltaic (PV) array serves as the primary renewable energy source and is connected to the common DC bus through a unidirectional DC–DC converter. The Hybrid Energy Storage System (HESS) consists of a battery and a supercapacitor, each interfaced to the DC bus via an independent bidirectional DC–DC converter, enabling flexible charging and discharging operations. The DC bus supplies power to various DC loads such as DC motors, EV chargers, lighting systems, and other DC appliances. This configuration enables efficient power sharing, enhanced DC bus voltage regulation, and improved transient response under varying renewable generation and load conditions.

A) Hybrid Energy Storage Configuration and Power Flow Management

The first phase of the process will be to develop a battery–supercapacitor combined energy storage system that is selfcontained and can operate in standalone DC microgrid. Combining these two forms of storage is believed to overcome the disadvantages of battery and supercapacitor storage alone. The supercapacitor will absorb any sudden surges in the DC load and buffer fluctuations in available green energy sources, while the battery will meet the average demand of the DC load. It is configured fully active with both battery and supercapacitor connected to the DC bus with separate bidirectional DC–DC converters. This allows charging and discharging to be controlled separately, making it easier for the power trading of storage components. The power flow control mechanism checks the status of renewable energy production, load demand, battery condition and supercapacitor status on a continuous basis. Given these working parameters, the energy flow is divided among energy storage devices to maintain the power flow and prevent the battery from getting overworked. The coordinated operation of storage elements ensures good transient compensation behaviour, stability of the DC bus, and utilisation of more of the stored energy in a range of operating conditions.

B) State-of-Charge-Based Energy Management Strategy

The energy management plan is created based on the battery and supercapacitor's SoC information that allows for more flexible sharing of power. The SoC values are continually tested to determine how best the individual storage parts can function. To protect the battery, it's important to avoid overcharging and heavy discharging, and the supercapacitor should only be used when it has enough energy. High SoC of the battery allows it to meet the load demand and store additional green energy via controlled charging operation. As battery SoC decreases, the control method reduces the stress of the battery, such that the supercapacitor operates harder under short-term conditions. The SoC-based decision process facilitates seamless integration of the long term and short term energy storage with ease. The new technique differs from earlier ones that assign a fixed amount of energy to be shared, in that it allows energy sharing to be variable depending on what the storage conditions are at any one instant. This method enhances the charge-discharge performance of batteries, storage capacity reliability and maintains the isolated DC micro-grid running without any disturbances in case of change in the demand load and green energy generation sources.

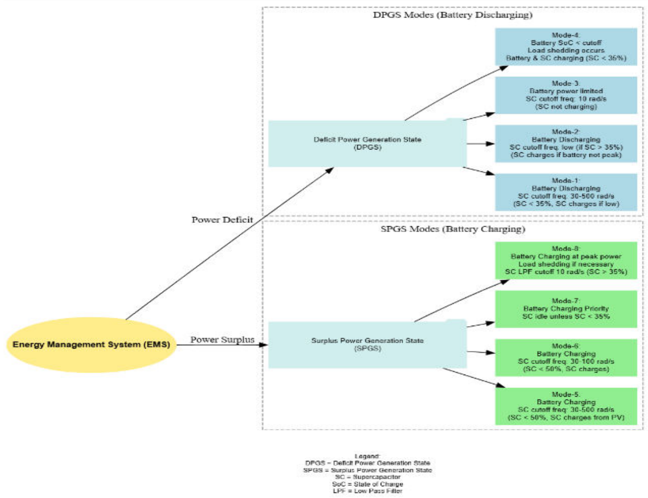

Fig.2 EMS-Based Adaptive Power Flow and Storage Management Strategy

Fig. 2 illustrates the EMS-based adaptive power flow and storage management mechanism used in the proposed HESS. The controller dynamically distributes energy between the battery and supercapacitor according to SoC conditions, enabling efficient power allocation, reduced battery stress, and improved energy utilization under varying operating conditions.

C) Variable Frequency Low-Pass Filter-Based Power Separation

There are issues with the use of fixed-frequency filters in the power separation device that are overcome with a variable frequency low pass filter. By traditional means a constant cutoff frequency is employed to split the low frequency power components from the high frequency power components. This will lead to slower response of the battery and less efficient use of the supercapacitor when the conditions evolve. The variable frequency filtering method dynamically adjusts the maximum frequency according to the operation of the hybrid storage system. The adjustment process is influenced by the SoC of the battery and supercapacitor. This enables the system to modify the power-sharing attributes as needed, in real-time. If this is a sudden change, then the lower frequency changes are handled by the battery and the higher frequency changes are handled by the supercapacitor, which is used to assist with the corrections. This adaptable filtering system lowers battery current changes that aren't needed and makes the storage system faster to respond. The dynamic frequency adjustment leads to smoother changes in power, reducing oscillations in the DC bus voltage, and increases the microgrid stability when production and load levels change rapidly.

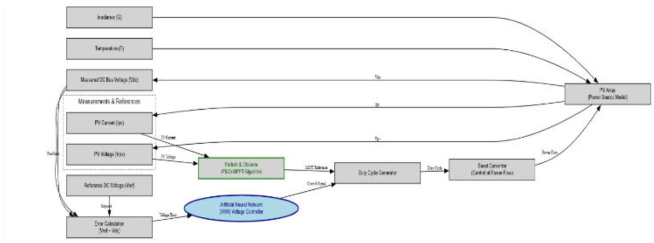

Fig.3 Adaptive Control for PV MPPT ANN Controller

Fig. 3 shows the adaptive PV MPPT control mechanism implemented using ANN to regulate photovoltaic power extraction. The controller continuously adjusts operating conditions to improve maximum power tracking efficiency and support stable DC microgrid operation.

D) Bidirectional DC–DC Converter Control and DC Bus Regulation

The reversible DC–DC converter devices controlling power flow between the energy storage devices and the DC bus need to be monitored. The battery and supercapacitor are individually controlled by converter control for precise charging and discharging. The energy management strategy defines the reference numbers for the controller of the converter to control current flow. The super capacitor converter "takes up" short time events quickly and the battery converter takes care of the slow and stable power exchange. As the main sign of system reliability, DC bus voltage is constantly checked. The contribution of the storage components is adjusted for any difference with the standard voltage. The coordinated operation of the converter ensures that the changes in the renewable power and changes in the load are well matched. This voltage control method will decrease voltage overshoot and undershoot, improve transient response and increase the DC microgrid's inertial response. The control structure is designed around a Bi-directional converter that enables flexible energy exchange and reliable operation under different microgrid operating scenarios.

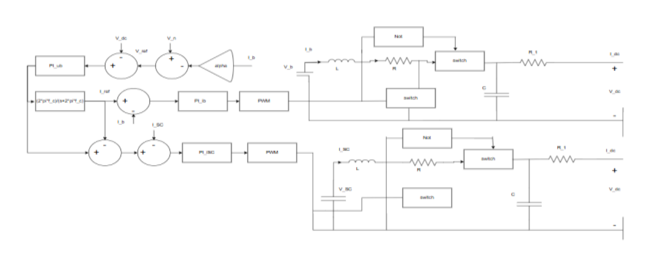

Fig.4 Battery and Supercapacitor Dual Converter Control System

Fig. 4 presents the dual converter control architecture used for battery and supercapacitor coordination. Independent bidirectional converter control enables flexible charging and discharging while maintaining DC bus voltage regulation and improving transient response performance.

E) Simulation and Real-Time Validation Framework

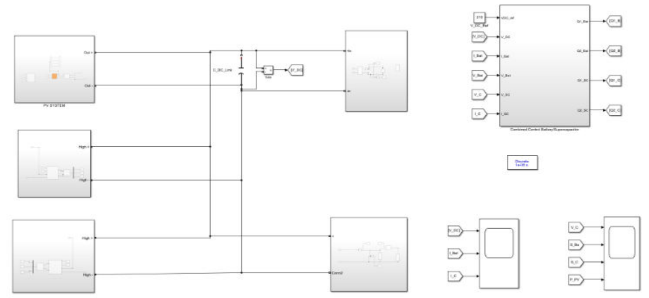

Fig.5 Simulink Model of the Proposed Battery–Supercapacitor HESS Control System

Figure 5 presents the MATLAB/Simulink implementation of the proposed SoC-oriented energy management strategy. The model integrates the photovoltaic (PV) system, battery, supercapacitor, common DC bus, and the combined control subsystem. The controller continuously monitors the DC bus voltage and storage states to regulate the bidirectional DC–DC converters for coordinated power sharing. Output scopes are used to observe battery current, supercapacitor current, DC bus voltage, and PV power during dynamic operating conditions. This implementation serves as the simulation platform for validating the proposed energy management strategy under varying renewable generation and load conditions.

Real-time digital validation and MATLAB / Simulink-based simulation are used for performance evaluation to see how well the new energy management method works. Several possible working situations are looked at, such as changes in the amount of power generated by photovoltaics, sudden changes in the load, and various storage SoC conditions. The simulation framework tests the robustness of the system to various system dynamics such as DC bus voltage control, battery current dynamics, supercapacitor dynamics, and power sharing dynamics. The outcomes are contrasted with usual fixed-frequency filtering-based methods to find ways to boost dynamic performance. Real-time validation is used to make sure that the control method works in real-world situations. In general, the test is focused on the ability of the battery to absorb sudden electricity demands, to be able to relieve stress on the battery and to store energy. The new method is expected to improve the performance of the DC microgrid system, reduce voltage fluctuations, smoothen energy transitions, and extend battery life. When simulations are combined with real-time tests, the adaptive energy management approach for hybrid energy storage applications is comprehensively tested.

IV. Results And Discussions

The results of the performance evaluation demonstrate the adaptive energy management solution superior dynamic behavior to conventional control approaches in various operating conditions. The processor is capable of controlling the voltage on the DC bus with reduced voltage drop-out, overshoot and settling time during load changes. In the normal method, the voltage variation of the DC bus is reduced from ±8-10 V to ±2-5 V, which indicates a good voltage stability and disturbance blocking capacity. The faster settling response is more responsive in handling transients if the load demand and green power is rapidly changing. The less the battery current is jumping up and down when it charges and discharges, the fewer changes will occur. This decreases stress on the battery and prolongs its usage. The supercapacitor was able to regulate short term power fluctuations by reducing the current spikes and improving the amount of energy it stored.

If there is not enough supercapacitor SoC, the method maintains the stability of the system by distributing the power more effectively, and reduces the current ripple of the batteries by approximately 60%. The smaller voltage ripple and faster settling reaction demonstrate better transient compensation. More improvements can be observed when the supercapacitor SoC is high, such as reducing the voltage surge, steady state error, and coordination of the stored energy. The developed control method is able to maintain a DC microgrid reliable and efficient under varying conditions. It does so by enhancing MPPT tracking, reducing oscillations in the power and increasing the efficiency of energy management.

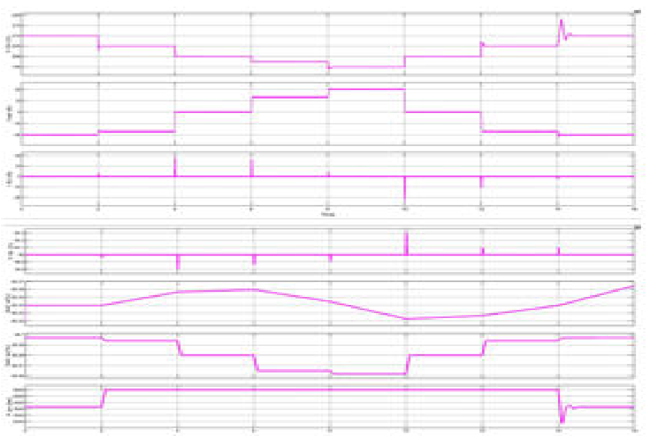

Fig.6 Performance Analysis with Variable Load Demand with ANN

For the case where the load changes, the study on the effectiveness of the HESS-based DC microgrid with the ANN controller is depicted in Fig. 6.

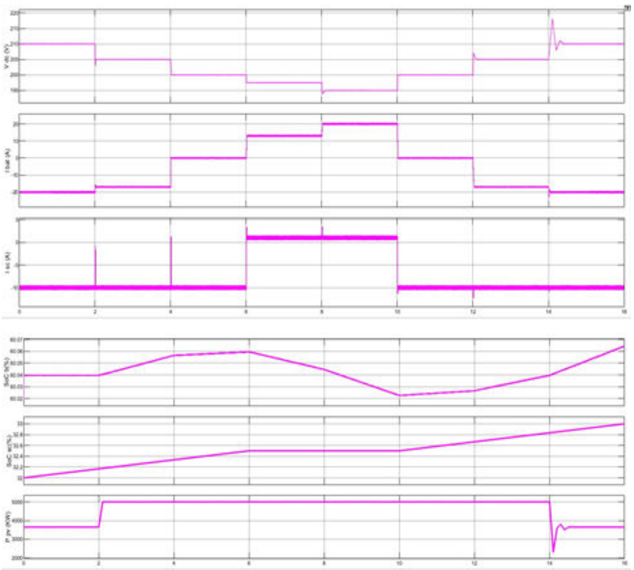

Fig.7 Performance of Proposed Strategy in Low SoC OF SC

Fig. 7 shows the performance of the proposed HESS control strategy under low supercapacitor SoC conditions. The adaptive controller maintains stable operation by reducing battery current fluctuations and improving power distribution efficiency.

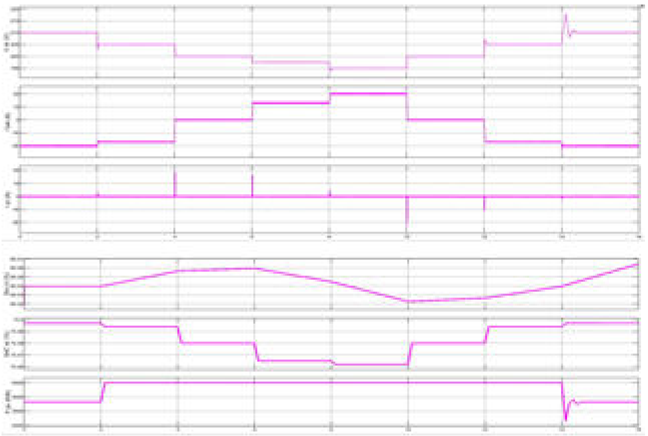

Fig.8 Performance of Proposed Strategy in High SoC of SC

Fig. 8 illustrates system performance under high supercapacitor SoC conditions. The proposed strategy achieves smoother power transitions, improved voltage regulation, and enhanced coordination between storage units.

V. Conclusion

The findings demonstrate the success achieved in managing the energy successfully with the use of a variable frequency low-pass filter in a DC microgrid system, which is not connected to the main grid. The adaptive control mechanism controls power sharing between the battery and supercapacitor depending on their SoC conditions and the resources available are maximized. The new strategy can decrease the slow reaction time of the battery controller when the supercapacitor SoC level is low, and can prevent the battery from overworking when its SoC level is low. During dynamic operating situations, the battery discharge rate slows down. This enhances the charge–discharge performance and extends the battery life. The approach to energy management also increases the stability of the DC bus voltage and significantly reduces overshoot and undershoot of the transient. This occurs when the demand for load and the amount of renewable power generation varies rapidly. The voltage changes are less, leading to a higher effective virtual inertia and dynamic stability for DC microgrid. This adaptive frequency change approach offers superior transient response, power transition smoothness and reliability than conventional fixed-frequency filtering techniques. This is shown by MATLAB simulations and real-time digital validation using the Opal-RT OP5700. The results demonstrate the ability to ensure stable operation, better energy distribution and better performance of the storage system in a microgrid under changing conditions when using the proposed method.

In complex operating conditions, the use of intelligent learning based optimization techniques can improve the adaptive decision making in the future. For better energy scheduling, ML and reinforcement learning algorithms can be used to predict renewable production, changes in load, and storage behavior in real time. Incorporating tests for battery health can provide insights into battery life and help maintain proper battery conditions. Complex communication-based control architectures can be developed to facilitate different kinds of DC microgrids and distributed energy resources to operate together. In real-world applications, hardware deployment with a significant portion of renewable energy, charging solutions for EVs and smart grid components can demonstrate how the theory applies. Further, energy management systems can be enhanced with cybersecurity capabilities and fault-tolerant control strategies to make them more reliable and resilient for future applications.

References

[1] A. T. Hoang, V. V. Pham, and X. P. Nguyen, “Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process,” J. Cleaner Prod., vol. 305, Jul. 2021, Art. no. 127161.

[2] M. Panda, D. V. Bhaskar, and T. Maity, “Coordinated power sharing among multiple subgrids in a photovoltaic-battery based DC microgrid,” Energy Sources A: Recovery, Utilization, and Environmental Effects, vol. 44, no. 2, pp. 5358–5380, Jun. 2022.

[3] X. Lin, R. Zamora, and C. A. Baguley, “A fully filter-based decentralized control with state-of-charge balancing strategy for battery energy storage systems in autonomous DC microgrid applications,” IEEE Access, vol. 9, pp. 15028–15040, 2021.

[4] N. Kim, C. Roy, and B. Parkhideh, “PV-BESS DC-series integration for regulated DC systems,” IEEE Trans. Power Electron., vol. 39, no. 8, pp. 10380–10389, Aug. 2024.

[5] Z. Li, B. Wang, L. Xian, M. Zhang, and Q. Xu, “Decentralized active disturbance rejection control for hybrid energy storage system in DC microgrid,” IEEE Trans. Ind. Electron., vol. 71, no. 11, pp. 14232–14243, Nov. 2024.

[6] A. C. Raveendran and U. B. Manthati, “Dynamic power sharing assisted hybrid controller for PV fed isolated DC microgrid,” IEEE Syst. J., vol. 17, no. 1, pp. 1087–1097, Mar. 2023.

[7] C. R. Arunkumar and U. B. Manthati, “A hybrid controller assisted voltage regulation and power splitting strategy for battery/supercapacitor system in isolated DC microgrid,” IEEE Trans. Energy Convers., vol. 38, no. 3, pp. 1544–1553, Sep. 2023.

[8] Z. Wang, P. Wang, W. Jiang, and P. Wang, “A decentralized automatic load power allocation strategy for hybrid energy storage system,” IEEE Trans. Energy Convers., vol. 36, no. 3, pp. 2227–2238, Sep. 2021.

[9] S. Chen, Q. Yang, J. Zhou, and X. Chen, “A model predictive control method for hybrid energy storage systems,” CSEE J. Power Energy Syst., vol. 7, no. 2, pp. 329–338, Mar. 2021.

[10] H. Maghfiroh, O. Wahyunggoro, and A. I. Cahyadi, “Energy management in hybrid electric and hybrid energy storage system vehicles: A fuzzy logic controller review,” IEEE Access, vol. 12, pp. 56097–56109, 2024.

[11] P. K. Behera and M. Pattnaik, “Hybrid energy storage integrated wind energy fed DC microgrid power distribution control and performance assessment,” IEEE Trans. Sustain. Energy, vol. 15, no. 3, pp. 1502–1514, Jul. 2024.

[12] M. Zhang, Q. Xu, C. Zhang, L. Nordström, and F. Blaabjerg, “Decentralized coordination and stabilization of hybrid energy storage systems in DC microgrids,” IEEE Trans. Smart Grid, vol. 13, no. 3, pp. 1751–1761, May 2022.

[13] M. Panda, D. V. Bhaskar, and T. Maity, “A fuzzy-based coordinated power management strategy for voltage regulation and state-of-charge balancing in multiple subgrid-based DC microgrid,” Int. Trans. Electr. Energy Syst., vol. 2022, pp. 1–17, Apr. 2022.

[14] Narasimha, S., & Sushama, M. A CONTROL METHOD FOR BUCK-BOOST VOLTAGES USING MULTILEVEL INVERTERS FOR APPLICATION OF HYBRID ELECTRIC VEHICLE.

[15] Reddy, C. L., Kumar, P. S., Sushama, M., & Babu, N. S. (2015, November). A five level cascaded H-bridge multilevel STATCOM. In 2015 IEEE Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics (PrimeAsia) (pp. 36-41). IEEE.

V. Rajasekhar received the B.E. degree in Electrical and Electronics Engineering from Vasavi College of Engineering, Hyderabad, affiliated with Osmania University, in 2018 and is pursuing the MTech. degree in Electrical Power Engineering from UCESTH, Jawaharlal Nehru Technological University Hyderabad. He has over five years of combined industrial and academic experience, including roles as a Trainee Engineer, Tron Associate, and Assistant Professor. His research interests include power systems, DC microgrids, renewable energy integration, hybrid energy storage systems, electric vehicle charging infrastructure, and AI/ML applications in electrical engineering. He is proficient in MATLAB, LabVIEW, and Python, and is a GATE 2024 qualified candidate and recipient of the Best Faculty Award 2024.

Dr. Malaji Sushama received the B.Tech. degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University in 1993, the MTech. degree in Electrical Power Systems in 2003, and the Ph.D. degree in Power Quality from JNTU Hyderabad in 2009. She is currently a Sr. Professor in the Department of Electrical and Electronics Engineering at Jawaharlal Nehru Technological University Hyderabad, Hyderabad, India. With over 24 years of teaching and 12 years of research experience, she has published numerous international journal and conference papers. Her research interests include power quality, power systems, renewable and green energy, power electronics, neural networks, fuzzy logic applications, FACTS controllers, and harmonic analysis.