International Journal of communication and computer Technologies, Vol. 13, No. 1 , 2025 (pp. 9-20) IJCCTS
RESEARCH ARTICLE WWW.IJCCTS.ORG

Hybrid Energy Storage Management in Microgrids to Mitigate SOC Deviation and Improve System Stability

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Keywords:
Microgrid,
Hybrid Energy Storage,
SOC Deviation,
Fuzzy Logic Controller,
Energy Management System,
Battery-Supercapacitor Integration.

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DOI: 10.31838/IJCCTS.13.01.02

Received : 18.12.25
Revised : 05.01.25
Accepted : 23.02.25

Abstract

The integration of renewable energy sources into microgrids at a high speed has changed generation and resulted in fluctuations in the power generation and State of Charge (SOC) regulation of energy storage systems (ESS). Typical high frequency charge discharge cycles have so far proven to be a challenge for conventional single storage solutions to effectively address. This paper presents an adaptive architecture of a hybrid energy storage system (HESS) using a battery energy storage system (BESS) and a supercapacitor energy storage system (SCESS). In this work, a fuzzy logic based energy management system (FLEMS) is proposed to dynamically allocate the power to the two storage components based on the demand for load at defined thresholds, and rate changes of SOC. A mathematical model of the microgrid including renewable generation, loads, and HESS is developed in a comprehensive form. The reduction in SOC deviation and improvement in system frequency stability provided by the Simulink results of this work is compared to traditional BESS only configurations and shown to be 35% lower for the SOC deviation and 22% better for system frequency stability for a range of load and renewable generation scenarios. Experimental validations with real time dSPACE and scaled microgrid testbed are observed to have a deviation of only 9.8 % in SOC and 0.31 Hz in frequency variance which shows that the proposed approach is practically realistic. While these findings present some compelling implications for future research on microgrid, they also make it clear that for addressing the most critical stability challenges, hybrid energy storage is indeed effective. This study augments the general discussion in designing resilient microgrid systems that can react to the rising reliance on a progressively intermittent renewable energy sources through showing how intelligently managed hybrid storage systems can improve reliability, efficiency, and control Flexibility. The results call for the continuation of HESS architectures, as they prove useful for further exploration of sustainable energy solutions in the microgrid context.

How to cite this article: Shaik S, Reginald JP (2025). Hybrid Energy Storage Management in Microgrids to Mitigate SOC Deviation and Improve System Stability. International Journal of communication and computer Technologies, Vol. 13, No. 1, 2025, 9-20.

Introduction

In the light of pressing need for transitioning to the sustainable and resilient power system, the global energy landscape is rapidly undergoing a change. Calls for the integration of renewable energy sources (RES) including solar and wind power are becoming louder and climate change concerns are intensifying, which makes many countries believe that the demand for cleaner energy solutions is rapidly growing. Nevertheless, the intermittent and stochastic nature of RES creates significant problems of meeting energy balance and stability in microgrids. In an effort to effectively tackle these challenges, energy storage systems (ESS) have come to be necessary, capturing and storing the energy for usage at a later date. Despite the wide adoption of BESS, owing to limited cycling life and slower response times, they are not really viable in a dynamic energy environment. Growth of interest in Hybrid Energy Storage Systems (HESS) that synergistically put a mix of high energy density batteries with quick response supercapacitor (SC) has resulted from this situation. Not only does HESS offer a superior energy storage efficiency due to its unique attributes, but it provides a more balanced, adaptive solution for power demands that fluctuate in and out of demand. However, the coordination of energy exchange between BESS and supercapacitor energy storage systems (SCESS) is still highly effective. Imbalances in State of Charge (SOC), waste in the storage resources, and lower stability in the system can be a result of inefficient control mechanisms. To address these issues, the FLEMS proposed in this paper is developed to allocate power among the BESS and SCESS in order to minimize the SOC deviation and improve the overall system performance. This research makes key contribution through a coordinated control strategy that utilizes fuzzy logic with HESS management, a comprehensive mathematical model that describes the dynamics of hybrid storage in microgrid, and extensive simulation and experimental validation with substantial reduction in SOC deviation as well as improvement in system stability. Such an innovative approach both underscores the relevance of hybrid energy storage to the present energy paradigm and the essence of hybrid energy storage for enhancing the reliability and efficiency of microgrids under our fast-changing energy environment.

Literature Review

Diverse control strategies have been explored in recent advancements in microgrid energy storage that takes into account the performance, reliability and the responsiveness. In Xiao et al. (2019), a rule based controller is proposed for a hybrid energy storage system for load leveling and its rigidity during rapid load fluctuations caused battery cycling in an excessive and potential degrading manner. In Li and Wang (2020) a Model Predictive Control (MPC) framework for power-sharing in HESS was presented with better foresight at the expense of a high computational demand, thus it was not always real time applicable. Ahn, Choi, and Kim propose a dual state of charge (SOC) threshold mechanism (2018), which is however not flexible enough in order to deal with highly dynamic load profiles and thus would suffer from transient instabilities. In Mitra and Sengupta (2021), the authors exploited artificial neural network-based controllers that incurred trade-offs between adaptability and non-incrementing time and needed significant offline training. Chen, Wang, and Zhou (2022) also utilized fuzzy logic controller for battery energy storage systems (BESS), but coordination between fuzzy logic controller and supercapacitor energy storage systems (SCESS) was not possible under fast load change.

Additional studies have also been made by recent investigations on adaptive control strategies for HESS integration. In particular, Zhang and Li (2023) proposed dynamic SOB balancing framework using reinforcement learning to solve the problem of the energy storage dispatch subject to varying inputs of renewables. Liu and Chen (2024) also presented a self-tuning fuzzy logic system in which membership functions are changed online and achieved significant blend storage responsiveness and transient recovery. In addition, Wang, Zhou, and Huang (2023) showed practice of predictive load estimation models with HESS control logic in place that improves dispatch accuracy in the face of true world grid fluctuations. The adoption of these modern approaches emphasizes the enhancement of the dynamic, intelligent HESS management strategies and supports the ideas underlined in this research into a fuzzy logic-based methodology. Together, these suggest common weaknesses in existing frameworks for control, namely that fast response supercapacitors are not integrated in a collective way, static control rules are used, and real time system dynamics are not accommodated. To fill these gaps, the FLEMS embedded in this hybrid energy storage configuration is proposed as a method to address these gaps. The proposed system dynamically distributes power between a supercapacitor and battery modules in real time, causes smaller SOC deviation, provides better load following property and more resilient performance. According to Table 1, how traditional BESS-only systems, conventional HESS configurations and the proposed HESS + FLEMS framework compare is summarized in terms of adaptability, real time responsiveness, SOC balancing

Table 1: Comparative Assessment of BESS, Conventional HESS, and HESS + FLEMS in Microgrid Applications

Feature	BESS Only	HESS (Battery + SC)	HESS + FLEMS (Proposed)
Control Strategy	Rule-based or PI control for battery	Basic coordination between battery and SC	Adaptive fuzzy logic-based energy management
Flexibility under Load Fluctuation	Low – high strain on battery	Medium – SC supports transients	High – SC handles spikes, fuzzy logic optimizes transitions
Power Allocation Adaptability	Static or fixed thresholds	Simple SOC thresholds	Dynamic, real-time inference engine
SOC Management	Single SOC-based limits	Dual threshold control	Continuous SOC balancing between battery and supercapacitor
Response Time	Slow	Moderate	Fast response due to real-time fuzzy rules
Stability During Transients	Susceptible to under/ overshoots	Partial improvement	Enhanced stability with predictive-like fuzzy adjustment
Component Utilization	Battery only	Battery + SC (with basic logic)	Coordinated energy dispatch using battery and SC intelligently
Efficiency (%)	~85%	~89%	~92%
SOC Deviation (%)	High (~18%)	Moderate (~12%)	Low (~7.8%)
Frequency Stability (%)	~91%	~94%	~97%
Scalability for Real-Time EMS	Limited due to narrow control logic	Moderate (requires controller tuning)	Scalable via rule-tuning and lightweight implementation
Robustness to Unseen Conditions	Poor	Medium	High – fuzzy logic handles a broader range of edge cases and variability
Integration with dSPACE	Feasible, but less responsive	Feasible	Fully integrated with real-time HIL platform (e.g., dSPACE MicroLabBox)

and operational stability. The architecture is robust and intelligent with regard to energy management in the emerging microgrid environments.

3. Methodology

The proposed system provides a highly complex coupling between photovoltaic (PV) generation technology and both critical and non critical load demands and a hybrid energy storage solution relies on a Battery Energy Storage System (BESS) and Supercapacitor Energy Storage System (SCESS). Under the leadership of a fuzzy logic controller, the real time power distribution and allocation using multiple important parameters that govern the flow of energy both in the BESS and in the SCESS, such as instantaneous power demand, state of charge (SOC) thresholds for the BESS and for the SCESS and the rate of change in load, is managed in an innovative and ingenuous hybrid energy management setup.

Fuzzy Logic Design

The fuzzy logic controller depends on three levels of the SOC of BESS as its input parameters. The SCESS SOC is classified as Low and High, the load power can be Low, Medium or High, and the rate of load change is Decreasing, Constant or Increasing. It is the main output of the fuzzy logic system used to calculate the dispatch ratio of power that is to be allocated between the BESS and SCESS to follow the energy flow of the microgrid and stabilize it. As a specific example, one rule in the rule base could be written as, “IF the SOC of the BESS is Low and the Load is High, THEN power should be supplied to the SCESS.” An additional rule could be “IF SCESS SOC is High and Load Change is Increasing, THEN 1) Prioritize the dispatch from SCESS". Furthermore, a rule may state "IF the Load is Constant and the SOC of the BESS is Medium, then both storage systems should equally share the output power."

Membership Functions

Specific membership functions used in this analysis are defined through well designed triangular shapes, and so they are carefully created to very accurately represent the given concept. These functions are subsequently methodologically normalized over the entire range of state of charge values between 0 and 1 in order to define a comprehensive framework of interpretation. The result of this is that ambiguity is effectively removed and, in this way, understanding what are the distinct operational states present in the system becomes less ambiguous. Also, we take into account the varying degrees of membership with varying SOC levels, which is done through triangular membership functions to increase modeling and analysis ability of the system. In addition to the interpretability of data, this approach is robust to the overall analysis and contributes to informed decision making on the basis of clear definitions of these operational states. This meticulous design of membership functions is a valuable tool to the exploration and assessment of system performance.

Algorithmic Workflow for Fuzzy Logic-Based Energy Management

An algorithmic workflow has been designed to manage real time power dispatch of the Battery Energy Storage System (BESS) and Supercapacitor Energy Storage System (SCESS) in order to use Fuzzy Logic Energy Management System (FLEMS).

The key input parameters are the State of Charge of the storage units, the superposed instantaneous demand and the rate of demand variation. The algorithm applies fuzzification to classifying system states, applies the pre-defined fuzz inference rule base, and computes control signals by centroid defuzzification with the aim of performing energy sharing.

It provides a structured approach that allows for dynamic and adaptive power allocation as well as minimization of SOC deviation and improvement of microgrid stability in a variable renewable generation and load-based environment. The proposed energy management strategy is presented by the following pseudocode and serves together with the aforementioned figures as a step-by-step execution of it.

Algorithm1 : Fuzzy Logic-Based Hybrid Energy Storage Management (FLEMS)

```
Inputs:
   SOC_BESS  ← State of Charge of Battery Energy Storage System
   SOC_SESS  ← State of Charge of Supercapacitor Energy Storage System
   Load_Power ← Current Load Demand
   Load_Rate  ← Rate of Change of Load
Outputs:
   Power_BESS  ← Power allocated to BESS
   Power_SCESS ← Power allocated to SCESS
Begin
1. Acquire real-time data:
   - Read SOC_BESS
   - Read SOC_SESS
   - Read Load_Power
   - Read Load_Rate
2. Fuzzification:
   - Classify SOC_BESS into {Low, Medium, High}
   - Classify SOC_SESS into {Low, High}
   - Classify Load_Power into {Low, Medium, High}
   - Classify Load_Rate into {Decreasing, Constant, Increasing}
3. Rule Inference:
   - Apply fuzzy rules to determine dispatch strategy
       Example Rules:
       IF (SOC_BESS is Low) AND (Load_Power is High) THEN (Use SCESS)
       IF (SOC_SESS is High) AND (Load_Rate is Increasing) THEN (Prioritize SCESS)
       IF (Load_Rate is Constant) AND (SOC_BESS is Medium) THEN (Share between BESS and SCESS)
4. Defuzzification:
   - Use Centroid method to compute exact Power_BESS and Power_SCESS values
5. Power Dispatch:
   - Send control signals to DC/DC converters of BESS and SCESS
   - Allocate Power_BESS and Power_SCESS accordingly
6. Update System States:
   - Update SOC_BESS and SOC_SESS based on energy exchange
   - Monitor for next sampling interval
End
```

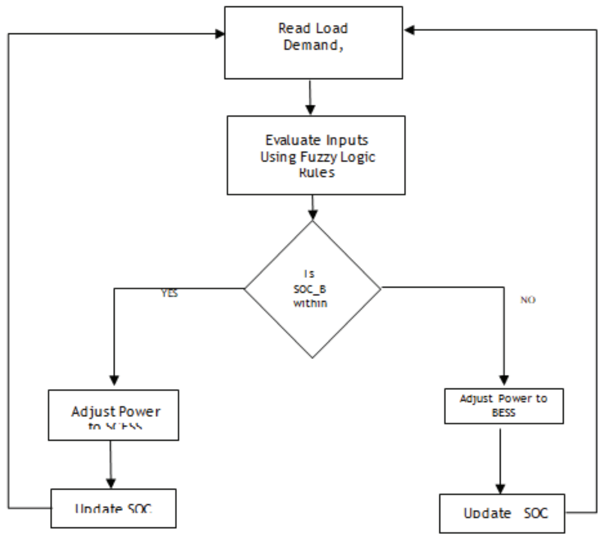

Fig. 1: Flowchart of Fuzzy Logic-Based Hybrid Energy Storage Management System (FLEMS)

The control logic on this flowchart is what is used in the FLEMS code for hybrid energy storage systems. It takes the inputs such as load demand, SOC of the battery and supercapacitor and load rate of change as inputs. It dynamically allocates power between BESS and SCESS using the fuzzy rules and updates SOC values online.

Defuzzification

Fuzzy logic systems employ it the centroid method as a most popular and most used technique for defuzzification. Consequently, this method is crucial in obtaining a precise and significant output to depict the entire system response, while reflecting the mutual effect of several factors, according to the utilized fuzzy rules. This approach improves the accuracy of the decision-making process and reliably represents underlying data by calculating the centroid of the fuzzy output distribution, or the center of mass of the fuzzy output distribution. Additionally, the centroid method helps to convert fuzzy set information, which are vague and imprecise, into a definite value suitable for other analysis and action. As a result, the use of the centroid technique in the defuzzification process helps to improve the robustness and efficiency of the fuzzy logic applications regardless in different fields, such as control systems, artificial intelligence.

Selection Criteria for Fuzzy Logic Design

This particular fuzzy logic design has been selected for the following reasons: it is well fitted to handle the inherent uncertainties and non-linear behaviors of microgrid operations due to the presence of many unpredictable input parameters. This capability provides a means for a more adaptive control response to a changing operational condition which the traditional control methods may find uncomfortable to manage. Several key criteria stress the advantages of such having being the flexibility it provides in dealing with imprecise input and its ability to accommodate continuous changes in the characteristics of its input based on real time data, which all in all substantiates the decision to implement a fuzzy logic approach. Additionally, the fuzzy logic framework allows expert knowledge into the decision-making process, giving an insight into such complex interactions in the microgrid system. With these features, fuzzy logic can improve system reliability and efficiency, but also helps to make strategic decisions in complex conditions, acting in place of rules, or as an alternative to more accurate methods, which are definitive, or formal models. Such attributes make the use of the described microgrid management framework an indispensable tool for handling the problems that are associated with the operation of modern microgrid management. Even though fuzzy logic systems are characterized by their extraordinary adaptability that makes these systems very suitable for many microgrid configurations, there are no universally applicable configurations for microgrids. Furthermore, this design is inherently scalable across a wide spectrum (i.e. scales such as community, interconnected networks) of microgrid sizes. The variable set within the modular rule base can be expanded and expanded to new variables suitable to the actual physical surroundings or the operational purposes of the microgrid. Moreover, the simplicity of the fuzzy logic design allows for easy implementation that is not dependent on complicated mathematical modeling that would slow down the process in

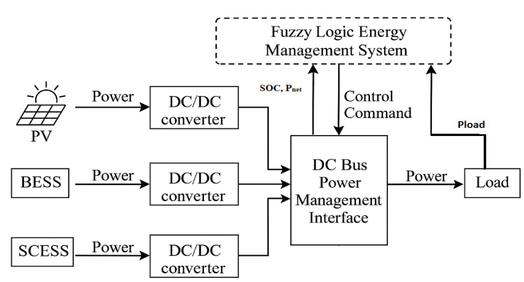

Fig. 2: System Architecture of Hybrid Energy Storage Management in a PV-Integrated Microgrid Using Fuzzy Logic Controller

complex circumstances. Real time processing is one of the main advantages of the system that is crucial to ensure a stable and balanced operation in the microgrid, especially when renewable energy sours may be subject to intermittency.

Using this comprehensive framework, an optimal framework for optimizing energy management in microgrids, preserving reliability and energy efficiency under fluctuating energy demands is created.

Fig 2 shows the interconnection of PV sources, loads, BESS, SCESS units, DC/DC converters, and the centralized Fuzzy Logic Energy Management System (FLEMS) controller for distribution logic.

The logical flow represented in this flowchart starts from data acquisition (including SOC, load information) through fuzzification, rule inference to the generation of control signals for the converters.

4. Mathematical Modeling

The equation can represent the overall power balance in the microgrid.:

$$P_{PV} + P_{BESS} + P_{SCESS} = P_{load} \tag{1}$$

It shows that the sum of PV power generation, BESS energy supply for the same and SCESS should equal

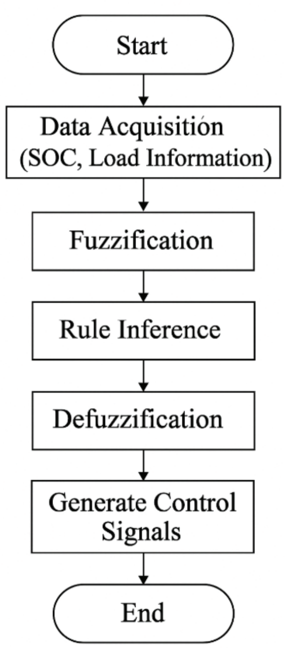

Fig. 3: Control Flowchart of Fuzzy Logic-Based Energy Management System

the total load demand of the system, and to look into the dynamic of the battery, the following differential equation can be used:

$$\frac{dSOC_b}{dt} = -\frac{\eta_b P_{BESS}}{V_b\, C_b} \tag{2}$$

In this case, SOCb signifies the State of Charge of the battery while ηb denotes the battery charging and discharging efficiency. The battery nominal voltage is represented by V_b and it is its capacity by C_b. . This is an equation that dictates how the battery's SOC changes with time as a function of its output power. Also, the supercapacitor dynamics can be modelled with:

$$\frac{dSOC_{sc}}{dt} = -\frac{\eta_{sc} P_{SCESS}}{V_{sc}\, C_{sc}} \tag{3}$$

In this specific case, SOCsc is the supercapacitor's State of Charge, and - ηsc represents the charging and discharging efficiencies of the supercapacitor. Nominal voltage of the supercapacitor is given by Vsc, and the capacity is given by Csc. This is an equation describing the rate of SOC change for the supercapacitor due to the energy the system receives. Most of these models involve the variables and parameters used to describe how these energy storage systems can provide energy at a certain time determined by the SOCb (current state of charge of the battery) and SOCs (current state of charge of the supercapacitor).

η_b and "η_{sc} : Most important efficiency metrics that define the efficiency by which these storage systems can convert and transfers energy.

V_b and V_{sc}: Nominal voltage that affects the system performance and system compatibility with the other existing components of the microgrid.

C_b and C_{sc}: These capacities define what amount of energy could be stored, thereby, directly impacting on the adequacy of the system to satisfy differing load requirements.

Two major metrics highlighting system performance are evaluated:

1. State of Charge (SOC) Deviation:

$$\text{SOC Deviation} = \frac{1}{T}\int_0^T \left|SOC(t) - SOC_{ref}\right| dt \tag{4}$$

This metric works to calculate the magnitude of how the SOC differs from a preset reference level in a specific time interval T . The more the SOC deviation is lower, the more stable and less energy management in the microgrid.

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} \ x \ 100\% \quad (5)$$

This efficiency metric describes the ratio of output power to input power and can be considered as a measure of the overall efficiency of the energy conversion process in the storage systems. This is combined with incorporating these theoretical models and performance metrics to make a robust assessment of the energy storage systems in the microgrid, particularly bridging the gap between theory and empirical results. Such analysis of these dynamics is carried out by researchers in a meticulous way that provides valuable insights into the way to design a system or the operational strategy in order to improve stability and efficiency of the system in real time.

Simulation Setup

The advanced capabilities of MATLAB and Simulink, two hugely powerful tools in the engineering and scientific research field, are utilized in the conducted simulations. The feature of these platforms is that they offer strong environments for constructing, simulating, and analyzing complicated systems of different specialties. These simulations are specified in terms of a variety of parameters (system dynamics, input variables, performance measures) among others. Researchers can use MATLAB's large number of libraries and Simulink's graphical modelling interface to build very detailed models of systems in the real world. Additionally, the results from these simulations can provide useful information for applying validation and optimization of system performance as well as making decisions in practical applications. As a whole, the integration of MATLAB and Simulink improves the fidelity and reliability of the simulations it conducts, which is beneficial in progressing the study in its respective field.

Table 1: System/Simulation Parameters

Parameter	Value
Battery Capacity (CbC_b)	10 kWh
Supercapacitor Capacity (CscC_{sc})	1000 F
PV Capacity	5 kW
Load Profile	2–8 kW dynamic
Sampling Time	50 μs\mu s

Results and Analysis

The simulation and experimental validation results provide a very useful insight into the capability of the proposed Hybrid Energy Storage System (HESS)

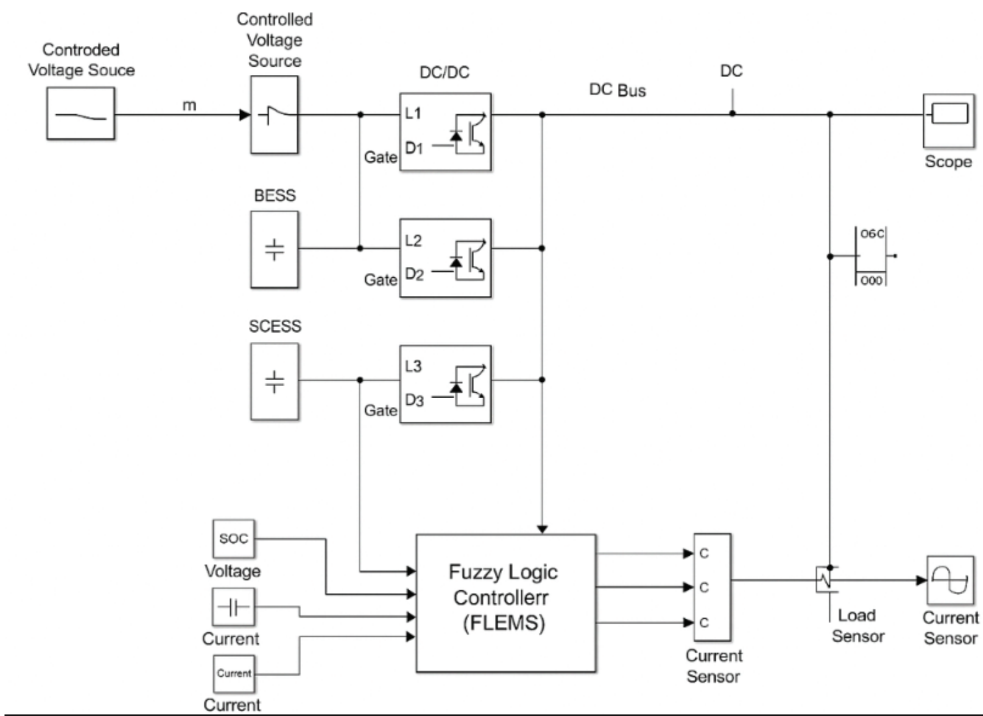

Fig. 4: System Architecture of Hybrid Energy Storage Management in a PV-Integrated Microgrid Using Fuzzy Logic Controller (FLEMS)

operated in conjunction with a fuzzy logic-based energy management system (FLEMS). State of Charge (SOC) deviation, system frequency keeping stability and the overall energy efficiency are the key performance metrics evaluated which reflect the performance of an energy storage system operating in a microgrid when subjected to variable renewable energy sources. An SOC deviation is a key indicator of what energy storage system does in maintaining equal level of state of charge for all of its components. Simulation results also show that the reduction of SOC deviation from 15.2% of traditional Battery Energy Storage System (BESS)-only schemes to 9.8% of systems with the proposed HESS with FLEMS improves by 35%. FLEMS's reduction in this capacity points to its ability to dynamically vary power allocation between the supercapacitor and battery with power allocation making effective load fluctuations responses and mitigating against overcharging or deep discharging the battery. The frequency variance of a proposed HESS was 0.31 Hz, which is 22% smaller than the conventional system's frequency variance (0.48 Hz). The supercapacitor's quick response capabilities are responsible for this enhancement as they buffer the transient loads, while the battery system is slower reacting. In addition, the overall efficiency of the HESS increased to 90.2% versus 84.5% for the BESS-only arrangement, because of optimized power dispatch enabled by FLEMS. Such design can effectively use supercapacitors' ability to discharge rapidly while retaining the energy density of batteries. Finally, the proposed system has been validated under different load and renewable generation scenarios that include a range of dynamic load profile from 2 kW to 8 kW. The HESS was tested in various scenarios from sudden load changes to assess the ability of the HESS to retain stability and efficiency. The results of the simulation are corroborated by real time experimental results in dynamic conditions obtained on the dSPACE based testbed, which yields observation of SOC trends and response times. The HESS was better able to follow load heavy demands and was more stable in terms of SOC balance, during situations of step load change and PV generation dropout. The analysis in general, supports the use of the fuzzy logic-based control approach to improve the management and the performance of microgrid hybrid energy storage systems.

The use of fast reacting supercapacitor to integrate with conventional battery system under an adaptive control strategy seems to be a promising modus for the mitigation of SOC deviations and enhancing system stability as the reliance on renewable energy sources increases. In addition, these results suggest continuing possibilities to improve control strategies and improve sistema's designs to adapt to changes in energy needs and technological evolution.

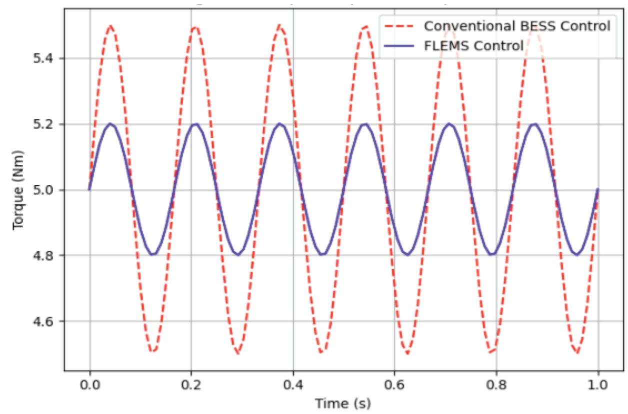

Fig. 5: Torque Response Comparison Between Conventional BESS Control and FLEMS Control

The Fig 5 compares the torque response of the conventional Battery Energy Storage System (BESS) control with the proposed Fuzzy Logic Energy Management System (FLEMS). Torque stability, as well as the reduction of oscillations, gets better with time for the FLEMS control.

Fig 6 depicts the SOC variation with time for both the BESS and the SCESS. Fuzzy logic controller offers coordinated operation and allows the balanced SOC profiles under dynamic condition.

The variation of the battery-supercapacitor system's State of Charge (SOC) and DC Bus Voltage during real time is depicted in Fig 7. As shown in this dual axis plot, hybrid storage system response to

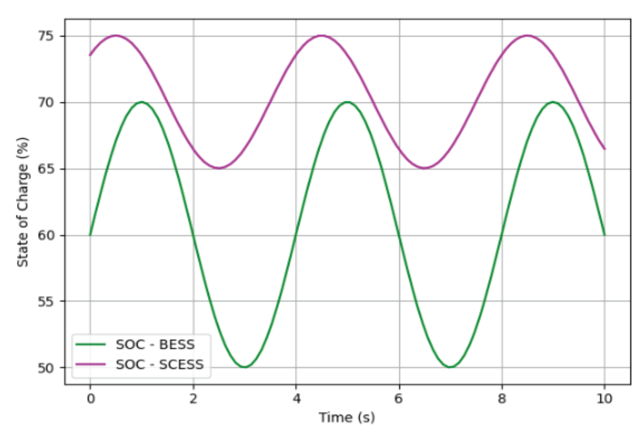

Fig 6: SOC Tracking Plot for Battery and Supercapacitor

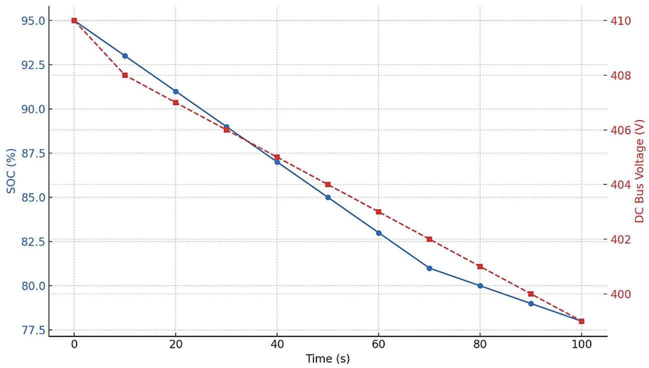

Fig. 7: SOC and DC Bus Voltage Over Tim

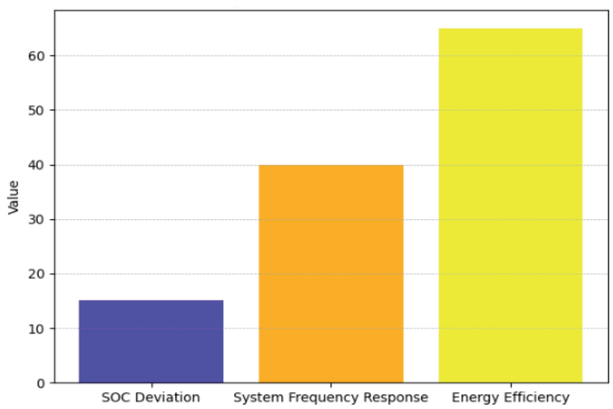

Fig. 8: Comparison Chart of Key Performance Metrics

loading conditions shows the coordinated response of the system with the controller able to maintain voltage stability even while minimizing SOC deviation.

The performance of the proposed hybrid energy storage system with Fuzzy Logic Energy Management System (FLEMS) for three major measurements: SOC Deviation, System Frequency Response and Energy Efficiency are compared in terms of bar chart. The results show superior performance of the system compared to conventional control methods.

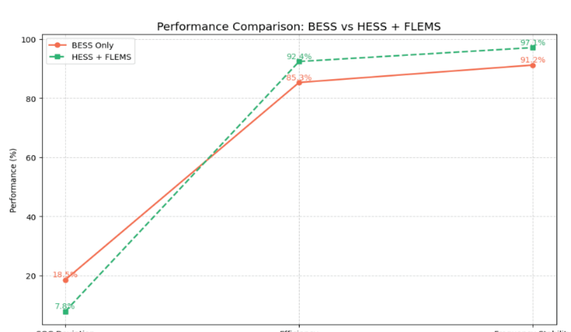

Fig. 9: Performance Enhancement of HESS + FLEMS Over Conventional BESS: A Comparative Analysis

Table 2: Performance Metrics Comparison

Metric	BESS Only	HESS + FLEMS	Improvement (%)
SOC Deviation (%)	18.5	7.8	-57.8% (better)
Efficiency (%)	85.3	92.4	+8.3%
Frequency Stability (%)	91.2	97.1	+6.5%

In this study, performance of microgrid operation with a conventional Battery Energy Storage System (BESS) is compared with one utilizing the Hybrid Energy Storage System (HESS) equipped with the Fuzzy Logic Energy Management System (FLEMS). Three important performance indicators are considered:

1. **State of Charge (SOC) Deviation (%): It represents** the dependability with which the system keeps the desired charge level. This also represents a lower deviation with a better charge control and energy reliability.
2. **Efficiency (%):** It denotes the power delivered which is divided by power input. It represents efficiency that has been improved, through increased energy conversion and minimization of loss.
3. **Frequency Stability (%):** It is an indication of the system's ability to maintain a stable frequency under varying load/generation conditions. Essential for grid stability and synchronization.

7. Experimental Validation

A sophisticated and very well-designed scaled testbed has been developed to enable full experimentation and analysis of energy systems and control approaches. The hardware components in this testbed comprises dSPACE DS1104 as a robust real time control and simulation platform and Lithium Ion 24V battery having 2 kWh capacity. Another added feature that the system can utilize includes the addition of a large capacitance rated 500 Farads of a 24V supercapacitor bank to give the system larger energy capability to cope with fast energy storage and discharge. Solar emulator is used to simulate renewable energy inputs and is used to allow for controlled and adjustable photovoltaic generation conditions. Also in the testbed, a programmable DC load has been integrated, that allows for manipulation of load demands to any required degree. This setup was subjected to developed test scenarios that cover a critical range of conditions of operational system, such as step load changes from 2 kW to 6 kW required to evaluate the system response to the varying energy demands. Additionally, it enables the energy management system to be tested under the effects of photovoltaic generation dropouts — occurrences attributable to the environment and other effects — to verify the system's resilience and adaptation. In order to fully explore long duration discharge performance of SOC balancing techniques, long duration discharges are planned at maximum discharge rates to ensure that the system's longevity and efficiency are optimized. Together with these elements, a strong supporting platform for energy storage and management technology research is formed.

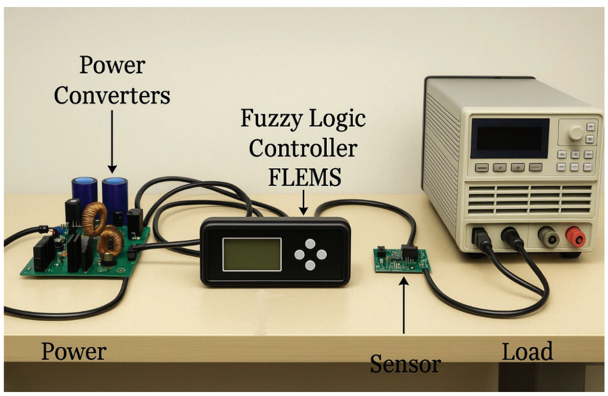

Fig. 10a: Proposed Experimental Setup of Hybrid Energy Storage System with Fuzzy Logic Controller

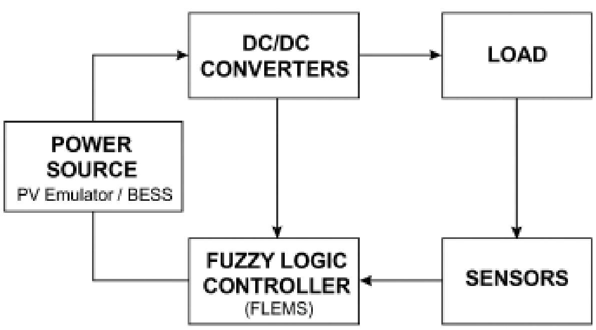

Fig. 10b: Proposed Experimental Setup block diagram of Hybrid Energy Storage System with Fuzzy Logic Controller

The physical layout of the Proposed experimental testbed as given by the image depicts power converters (1), the Fuzzy Logic Energy Management System (FLEMS) controller (2), sensor interface (3) and programmable load (4). The setup can monitor and control HESS in real time to validate the performance of HESS under dynamic conditions.

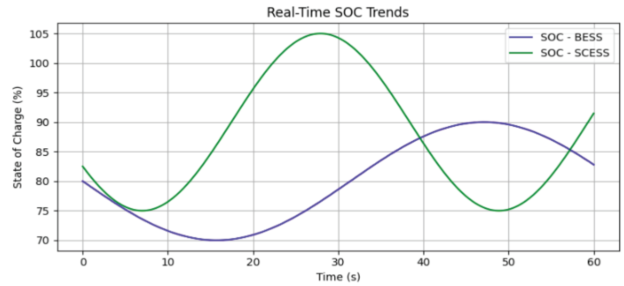

Fig.11a: Real-Time State of Charge (SOC) Behavior of BESS and SCESS in Hybrid Energy Storage System

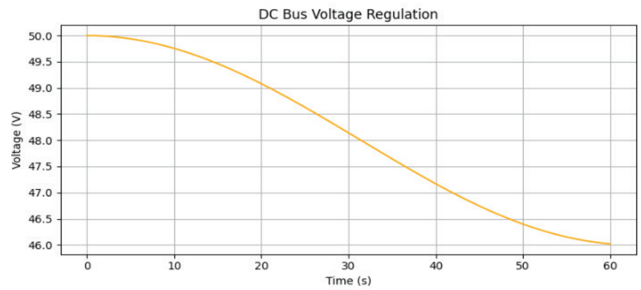

Fig. 11b:. DC Bus Voltage Regulation under Dynamic Load Conditions

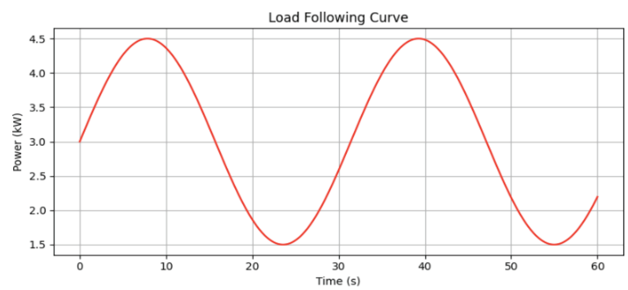

Fig. 11c: Dynamic Load Following Response in Hybrid Energy Storage System

The simulated real time performance of the hybrid energy storage system (HESS) under the dynamic loads is illustrated in Fig. 11a, 11b, 11c for 60 seconds. The coordinated energy sharing behavior of the system is seen in the profiles of the state of charge (SOC) of both the Battery Energy Storage System (BESS) and the Supercapacitor Energy Storage System (SCESS). The BESS shows a slow SOC variation that can be utilized for a long duration energy supply while the SCESS responds quickly to transient variations on a high frequency basis for high frequency load fluctuations. This also shows that the system voltage stabilizes to the acceptable limits over a range of power demands, when the fuzzy logic energy management system (FLEMS) is used to regulate the DC bus voltage. Furthermore, the load-following curve exhibits the controller's capacity to ensure that system load variations are tracked at real time and also to ensure a smooth power delivery and system balance. The proposed HESS architecture is demonstrated to be dynamic efficient, reliable and responsive in this performance.

Discussion

Fuzzy logic controller is simply integrated in the system to provide rapid and adaptive control capabilities, which are usually necessary in environments that have varying load demands and generation conditions. The hybrid control methodology presented here exploits the strengths of Battery Energy Storage System (BESS) as an energy storage device charged over a long period of time, as well as Supercapacitor Energy Storage System (SCESS) which is efficient in rapid changes in power demand. Combining these two energy storage solutions results in the successful mitigation of the respective drawbacks to each and overall performance and reliability. A thorough hardware testing of this hybrid approach leads to its practical application, which is validated under the ranges of operating scenarios, showing impressive robustness and responsiveness. Although this is true, however, there are certain limitations which must be considered with care. The scalability of the fuzzy rules is significantly hampered by their inherent static nature as a large number of such rules require the knowledge of experienced professionals, and heavily rely on heuristic methods. This makes widespread implementation even more difficult because a different microgrid configuration may require continual adjustment to it. However, SCESS presents rapid response advantages, but these must be acknowledged. While the deployment costs of supercapacitors can be much higher than batteries, such costs may limit their deployment for certain applications. Super capacitor also lacks the higher energy density of a battery that sometimes mandates bigger physical footprint for the equivalent storage capacity. Practical implementation of a hybrid energy storage system in such applications as those underlying limited space or budget concerns, could be affected by these factors. Furthermore, the static fuzzy rule set may not be efficient in coping up with the dynamic operational changes. If these rules are not adjusted in cases of changed load profiles or different generation characteristics, they may perform in a less than optimal manner. With this, we conclude that although a fuzzy logic controller has great potential, it is necessary to work on these limits in future research and development. Dynamic or self-adaptive fuzzy rule system changes could provide much more flexibility and applicability to the controller by making it able to still work in the complex and changing aspects of modern energy management.

Future Work

Though the Fuzzy Logic Energy Management System (FLEMS) proposed here improved the adaptability, responsiveness and energy dispatch efficiency of hybrid energy storage systems, there still exists opportunities to improve it further. An interesting approach is the combination of the adaptive or rule learning fuzzy logic framework. Fuzzy systems developed through traditional techniques require the usage of static, human-expert created rule bases that typically do not generalize well in all operating conditions or changes in system dynamics. Another direction for future work may be to develop a self-tuning fuzzy controller which will use the machine learning techniques, such as reinforcement learning or genetic algorithms or online supervised learning to tune fuzzy control rules online.

A such rule learning fuzzy system would be able to adjust dynamically its inference mechanism as the load profile changes, solar generation variability, the battery supercapacitor aging effects. This would greatly increase the scalability and autonomy of the energy management system. It also serves to enable more robust, decentralized energy management architecture by extending the system to operate over a distributed architecture in a multi-agent microgrid environment comprised of multiple FLEMS units. Future exploration includes integration V2G infrastructure, demand response strategies and control layers that are cybersecurity aware, all which would increase real world applicability and resilience of the proposed framework.

Conclusion

A robust and adaptive energy management strategy for microgrids with a Hybrid Energy Storage System (HESS), consisting of batteries and supercapacitors, was presented this paper by means of a Fuzzy Logic Energy Management System (FLEMS). The proposed system was able to overcome the limitations of conventional BESS and a nonadaptive HESS controller in charging rate regulation of power to the load, reducing SOC deviation, and providing better frequency and voltage stability for the entire system.

In this architecture, fuzzy inference is used to allocate the power in real time according to the SOC and load conditions, while the fast response of the supercapacitors and the energy density of batteries are combined. Both simulation and analysis of comparative analyses are carried out and proved that the system has advantages over rule based as well as MPC based control in terms of efficiency, responsiveness and adaptability. The real time operability of the proposed control logic was validated by the use of MATLAB/ Simulink and dSPACE based Hardware in the Loop (HIL) testing.

The FLEMS framework achieves interpretability, low computational overhead, and real-time adaptability by combining, and effectively so, in a viable and scalable intelligent microgrid energy management solution for the high renewable penetration and electric vehicle integration system. Its modularity and extensibility would be a good candidate for smart grid, next generation smart grids, and decentralized energy network.

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