A fuzzy logic approach to sustainable energy management in standalone microgrids

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ABSTRACT

The fast development of worldwide energy consumption, driven by industrial growth and increasing dependence on fossil fuels, has led to higher carbon emissions and degradation of the environment. In response, renewable energy sources, such as solar, wind, and hydroelectric power, offer cleaner and sustainable replacements with insignificant carbon emissions. This paper examines the role of artificial intelligence (AI)-based techniques, particularly fuzzy logic, in developing energy management system. A fuzzy logic-based energy management system is proposed for a renewable-powered microgrid that incorporates a hybrid energy storage system. Fuzzy logic-based energy management, due to its capability to manage uncertainty and complexity, offers viable solutions for improving the generation and distribution of energy within microgrid systems. This system is compared to a dynamic cascaded dual-loop proportional-integral (PI) controller-based energy management system in standalone mode. The comparative analysis emphasizes the ability of fuzzy logic-based energy management to improve the efficiency and sustainability of microgrids. The research aims to advance the creation of more intelligent and dependable energy solutions that integrate renewable resources and enhance energy management practices.

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1. INTRODUCTION

In recent years, globalization has led to an important increase in global energy consumption. As the world transitions from an agricultural-based economy to an industrialized society, energy consumption has become more intensive, resulting in higher carbon emissions [1]. The shift towards industrialization has further escalated the demand for energy, often relying on fossil fuels, which contribute to environmental degradation. In contrast, renewable energy sources, such as solar, wind, and hydroelectric power, offer environmentally friendly alternatives [2]. These sources are naturally renewable and generate minimal environmental harm, making them a sustainable option for future energy needs.

Since 2004, the renewable energy capacity has grown-up at remarkable rates, with yearly rises ranging from 10% to 60% across different renewable technologies. By 2010, renewable energy accounted for nearly one-third of the newly constructed power generation capacity, signaling a strong trend toward cleaner energy solutions. According to a 2011 forecast by the International Energy Agency (IEA), solar power alone could become the principal source of universal electrical energy within the next fifty years, highlighting the potential of renewable energy in determining the future of the energy segment [3], [4]. As global attention shifts toward long-term energy security and sustainable practices, the need for accurate energy modeling and effective planning becomes increasingly important [5], [6]. The fluctuating nature of energy demands and renewable energy sources poses challenges for microgrids in meeting energy requirements. To address these issues, an energy management system (EMS) is essential. The EMS takes into account hybrid systems, demand-side management (DSM), non-renewable energy sources, and energy storage systems (ESS) [7], [8]. These models help to project the future energy landscape and assess the feasibility of different energy solutions. In this context, advanced computational techniques, particularly those based on artificial intelligence (AI), have emerged as crucial tools in energy management. AI-driven approaches, such as fuzzy logic, neural networks, and evolutionary algorithms, have been employed in energy modeling to optimize energy production and distribution [9]. These technologies are widely used for tasks such as site evaluation, installation of photovoltaic and wind farms, maximum power point tracking (MPPT) in solar and wind systems, and optimization under conflicting criteria [10]. The energy management system is essential for maintaining microgrid (MG) stability, safety, and efficiency, helping to balance energy supply despite unpredictable factors like fluctuating renewable energy sources (RES) and varying electricity demand. EMS implementations are classified based on control strategies, including linear and nonlinear programming, meta-heuristic algorithms, stochastic and robust programming, model predictive control, and artificial intelligence (AI) methods [11].

Conventional energy management system (EMS) techniques utilize a variety of optimization and programming methods. Iterative techniques offer adaptability to changing conditions but require significant computational resources and are highly sensitive to initial settings [12]. While linear programming offers reliable solutions, its application becomes challenging in systems with nonlinear behavior. Predictive analysis techniques are well-suited for dynamic environments, but they often come with high computational demands. Mixed-integer linear programming provides greater flexibility for managing discrete variables; however, it can be resource-intensive, especially when applied to large-scale microgrids [13]. Robust optimization approaches are effective in handling system uncertainties, but they require accurate estimation of probability distributions to perform optimally. Likewise, stochastic programming is valuable in uncertain scenarios, although it may not always produce the most optimal outcomes [13].

On the other hand, artificial intelligence-based energy management influences innovative computing methods to enhance compliance and supervision. Neural networks provide adaptive learning, making interpretation complex, and it involve wide-ranging data for training. The above-discussed algorithms are well-suited for tackling complex nonlinear problems but demand high computational data and are sensitive to parameter adjustments [14]. Among various techniques discussed above, fuzzy logic control (FLC) has achieved significant attention due to its capability to handle uncertainties and indefinite data in complex nonlinear systems without requiring detailed mathematical modelling [15]. Numerous studies have focused on fuzzy-based energy mam designs for both grid-connected and isolated microgrids for battery-alone systems and fuel cell-based energy storage systems [16]-[19]. In the research related to grid-connected systems integrated with photovoltaic (PV) and wind turbine (WT) generators, battery energy storage systems (ESS), electric vehicles (EVs), and dynamic electricity pricing have been examined. These fuzzy-based EMS models regulate battery state of charge (SOC) to minimize electricity costs by using weather and market data for improved efficiency. Another study designed a fuzzy-based energy management system aimed at ensuring safe and economical MG operation while enhancing the lifespan of hybrid energy storage systems (HESS) [20].

Fuzzy logic is one of the most capable AI-based methods for energy management. It offers an influential background to handle the uncertainty and complexity in microgrid systems by converting imprecise data into precise, computable parameters [21]. This nature of fuzzy logic enables the development of robust energy management systems that are capable of handling uncertain conditions. Fuzzy logic-based models have been progressively used in the microgrid to produce practical and operative solutions for energy planning and management [22].

This paper's main objective is to present a fuzzy logic-based energy management system for a renewable energy-powered microgrid integrated with hybrid energy storage systems. Additionally aims to utilize a super capacitor energy storage system not only for transient power requirement and the proposed system is assessed against a dynamic cascaded dual-loop proportional-integral (PI) controller-based energy management system in standalone mode [23]. The study presents a comparative assessment to showcase how fuzzy logic can effectively optimize energy management and boost the operational efficiency of microgrids that incorporate hybrid energy storage. By exploring this approach, the research aims to support the development of intelligent, resource-efficient energy systems that utilize renewable sources while ensuring consistent performance and long-term sustainability.

2. SYSTEM CONFIGURATIONS

PV based direct current (DC) microgrid is implemented with a battery and super capacitor hybrid energy storage system. PV system is integrated into a microgrid using a boost converter implemented with a perturb and observe MPPT algorithm [24]. The DC microgrid is designed to supply a DC load. Supercapacitor and battery are connected in parallel to the DC bus via DC-DC bidirectional converters. Battery and supercapacitor models available in MATLAB Simulink are utilized [25], [26]. Control switching pulses for battery and super capacitor DC-DC converters are generated from a fuzzy-based energy management system. The proposed microgrid system is shown in Figure 1.

The main aim of the proposed energy management strategy is to maintain the DC link voltage constant at 400 V. The voltage control loop, which consists of a PI controller, generates a reference DC link current by comparing the actual DC link voltage with the reference DC link voltage signal and taking the difference as the input. This DC link current, SOC of battery, and SOC of supercapacitor are given as the input to the fuzzy logic controller-based energy management system. A fuzzy energy management system based on the available Idcref, SOC of the battery, and super capacitor generates an output current control signal. Using this control signal, reference current signals for the battery and super capacitor current controller were generated as shown in Figure 2. The generated reference signal and available actual battery current are compared, and the difference is given to the battery current controller to generate switching pulses for the battery DC-DC bidirectional converter. Similarly, control switching pulses were generated for the supercapacitor DC-DC bidirectional converter.

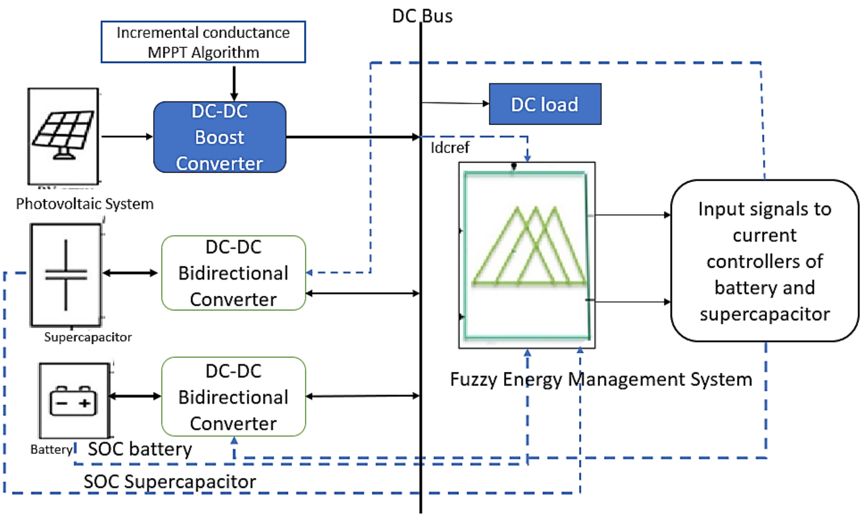

Figure 1. Proposed microgrid system with fuzzy energy management system

2.1. Energy management control technique

Fuzzy-based energy management generates the control output based on the SOCs of battery and supercapacitor SOCsc and available DC link current. The main objective of this fuzzy-based energy management control algorithm is to maintain a constant DC link voltage. The presented fuzzy energy management algorithm is shown in Figure 2. The DC link reference current is given as input, which is obtained from a PI controller, as shown in the control strategy. This DC link current represents the total current requirement from the grid, and Idcref is also the sum of the supercapacitor reference current and battery reference current, under balanced conditions as given in (1) and (2).

$$I_{dcref} - I_{batref} - I_{scref} = 0 \quad (1)$$

Where I_{dcref} is the total DC link current reference, I_{batref} is the reference current for battery controller, and I_{scref} is the reference current for a super capacitor. The DC link voltage remains constant by modelling the DC bus as in (2).

$$C\frac{dv_{dc}}{dt} = i_{scref} + i_{batref} + i_{pv} - i_{load} \quad (2)$$

DC link current input of fuzzy system (Mamdani) is defined by two membership functions, positive and negative. The allowable range variation of DC link current is -5 to 5. SOCbat input is defined by three membership function as low, medium, and high and the range of SOC of the battery is 0-100% similarly super capacitor SOC is also defined by three membership functions as low, medium, and high and the range of SOC considered here is 0-100% and the details of the same is given in the Table 1.

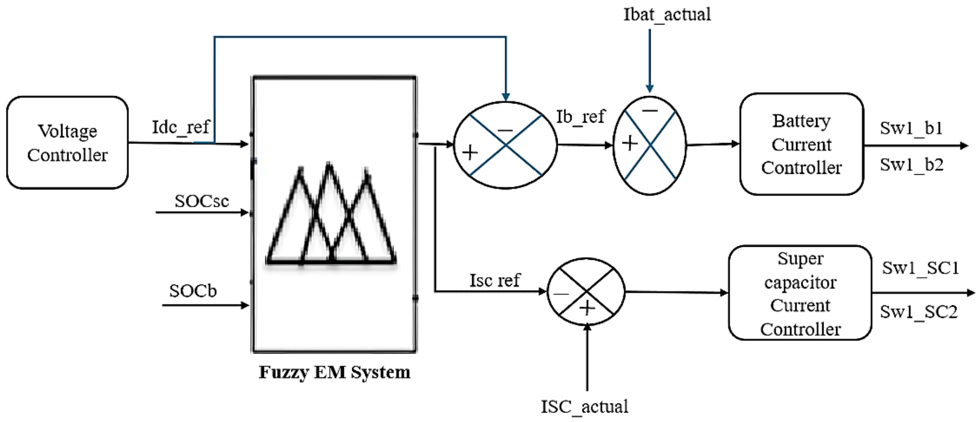

Figure 2. Fuzzy based energy management control strategy

Table 1. Membership function table

Membership function	SOCb-range (battery)	SOCsc-range (supercapacitor)
Low	0-15%	0-15%
Medium	15-85%	15-85%
High	85-95%	85-95%

3. FUZZY BASED ENERGY MANAGEMENT ALGORITHM

In the background of energy storage systems, efficient management of supercapacitor and battery charging/discharging is vital for optimizing performance and extending the lifespan of the components. The following fuzzy logic-based energy management algorithm outlines a control strategy based on the current reference (Idcref) and the state of charge (SOC) of both the battery (SOCb) and the supercapacitor (SOCsc).

3.1. Inputs and output

The inputs to the system include: Idcref (current reference), which indicates the system's operational mode—where a negative value signifies a generation condition (excess energy) and a positive value indicates a load demand condition (energy requirement); state of charge of battery (SOCb), which represents the battery’s current charge level categorized as low, medium, or high; and state of charge of supercapacitor (SOCsc), which reflects the current charge level of the supercapacitor, also categorized as low, medium, or high. The output of the fuzzy logic system is supercapacitor current reference (Iscref) and it determines the charging or discharging current for the supercapacitor, which can be zero, positive (charging), or negative (discharging).

3.2. Algorithm explanation

When the DC reference current (Idcref) is negative, the control of Iscref depends on the state of charge of the battery (SOCb) and super capacitor state of charge (SOCsc). If the state of charge of the battery is low and state of charge of super capacitor is medium or high, Iscref is set to zero, and in this scenario, the battery gets charged. If SOCb is medium and SOCsc is low, Iscref remains zero with only the battery charging. However, if SOCsc is medium or high, Iscref becomes positive, allowing both the battery and supercapacitor to charge. When SOCb is high, Iscref is set positive regardless of SOCsc, enabling supercapacitor charging to store the excess energy. Conversely, when Idcref is positive (load demand condition), and SOCb is low, Iscref is set to zero regardless of SOCsc, allowing only the battery to discharge while preserving supercapacitor charge. If SOCb is medium and SOCsc is low, Iscref remains zero, maintaining supercapacitor idleness. But if SOCsc is high, Iscref becomes negative, enabling the supercapacitor to discharge and reduce battery strain. When SOCb is high, and SOCsc is low, Iscref is again set to zero, with the battery discharging alone, while a medium SOCsc leads to a negative Iscref, allowing the supercapacitor to assist with load demand.

3.3. Control logic explanation

The control logic is broadly categorized into two conditions: the generation condition and load demand condition. Under the generation condition (Idcref = negative), when excess energy is available, the system prioritizes charging the battery, particularly if its state of charge (SOC) is low. The supercapacitor is charged only when the battery's SOC is medium or high, ensuring efficient energy utilization. Under the load demand condition (Idcref = positive), during energy demand, the battery discharges to supply the load, while the supercapacitor provides additional support by discharging when its SOC is medium or high. This helps reduce the load on the battery and enhances overall system responsiveness. The corresponding control logic flow chart is shown in Figure 3.

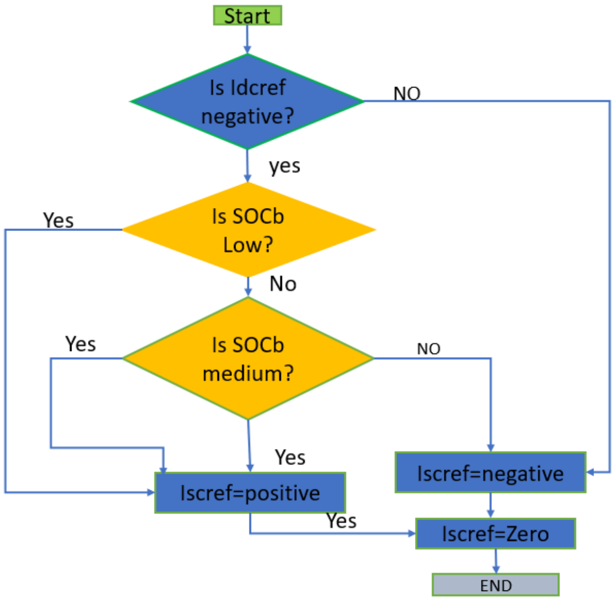

Figure 3. Flow chart of the proposed fuzzy-based energy system algorithm

4. RESULTS AND DISCUSSION

A fuzzy logic-based energy management system is designed for a photovoltaic (PV) system integrated with a hybrid energy storage system consisting of a supercapacitor and a battery. Both the battery and supercapacitor are linked in parallel to the DC bus. The implementation of the proposed system in MATLAB simulation is illustrated in Figure 4. The PV system is linked to the DC bus through a boost converter, which is implemented using the perturb and observe MPPT algorithm as given in Figure 5. The system is analyzed under three different operating scenarios: i) variation in power generation, ii) variation in load demand, and iii) simultaneous variation in both generation and load.

The PV system has a capacity of 2 kW, and detailed specifications of the storage components and converter parameters are provided in Table 2. Additionally, the performance of the fuzzy logic-based energy management system given in Figure 6 is compared with a dynamic cascaded dual-loop PI controller-based energy management system presented in [23], under identical operating conditions in standalone mode. In a dynamic cascaded dual-loop PI controller [23] output from the outer voltage controller will be given directly to the current controllers of the battery and super capacitor.

Table 2. Specifications of proposed microgrid

System component	Parameter	Quantity with units
PV module	Maximum power	250 W
	Open circuit voltage (Voc)	37.3 V
	Maximum power point voltage at V_{mp}	30.7 V
	Maximum power point current I_{mp}	8.15 A
	Short circuit current Isc	8.66 A
Battery nominal voltage	Voltage (V)	300 V
Battery rated capacity	Ah	48 Ah
Super capacitor capacitance	C	99.5
Super capacitor rated voltage	Voltage (V)	300 V

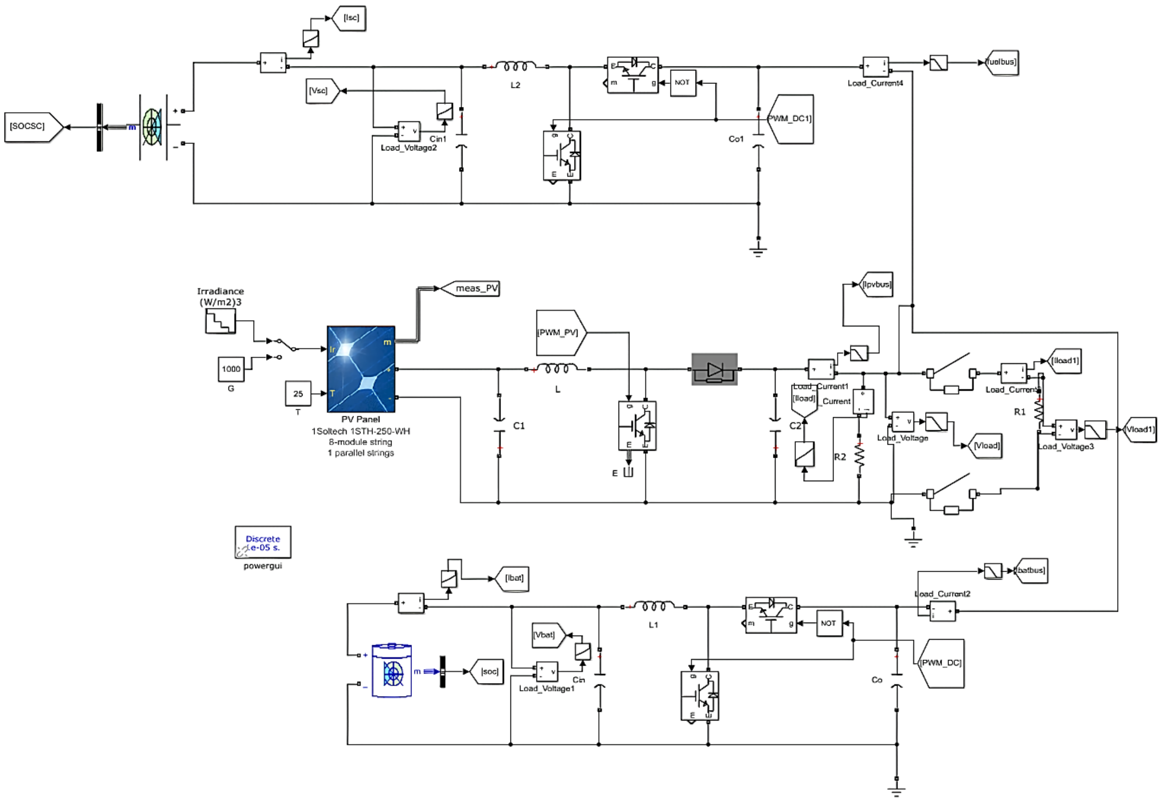

Figure 4. Simulation of the presented fuzzy-based microgrid

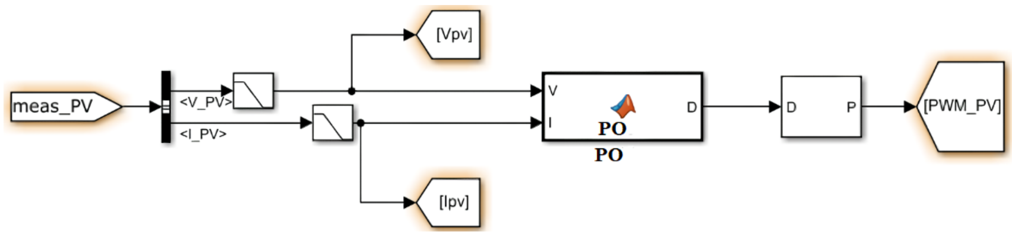

Figure 5. Boost converter control strategy

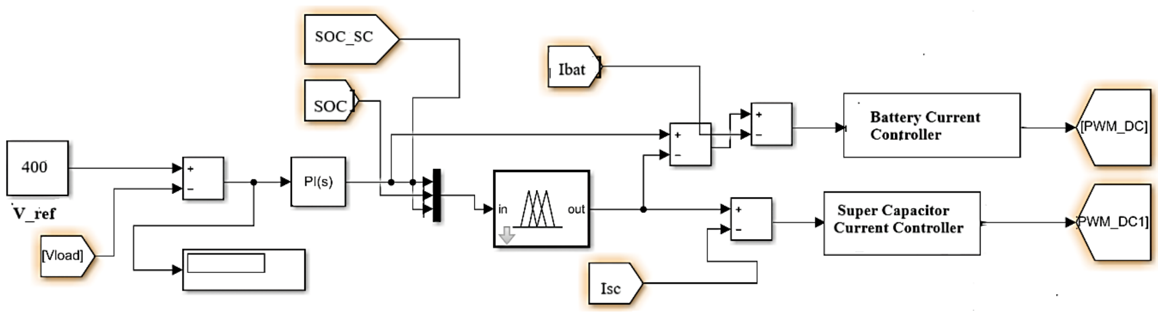

Figure 6. Simulation of the proposed system with fuzzy-based EM controller

4.1. Case 1: generation variation

4.1.1. Performance analysis of energy management system under generation variation

To assess the performance of the energy management system under generation variation, the load power is kept constant at 1,400 W, while the generation power is reduced from 2,000 W to 1,500 W at 1 second, as shown in Figure 7. This sudden decrease in power generation is effectively compensated by the hybrid energy storage system, consisting of a supercapacitor and a battery, ensuring a continuous power supply. The fuzzy logic-based energy management (EM) system successfully maintains the DC link voltage at 400 V, as illustrated in Figure 7. In contrast, when employing the dynamic dual-loop cascaded PI controller-based EM system, the abrupt reduction in generation results in a transient load fluctuation lasting 50 ms. During this period, the DC link voltage momentarily drops to 380 V before gradually recovering to 400 V within 50 ms, as shown in Figure 8. The comparative analysis demonstrates that the fuzzy logic-based EM system offers superior voltage regulation, ensuring enhanced load stability and overall system reliability.

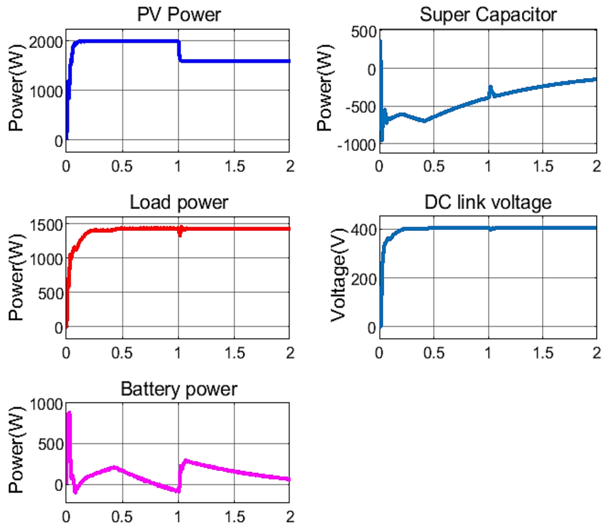

Figure 7. Simulation results for generation variation (fuzzy EM system)

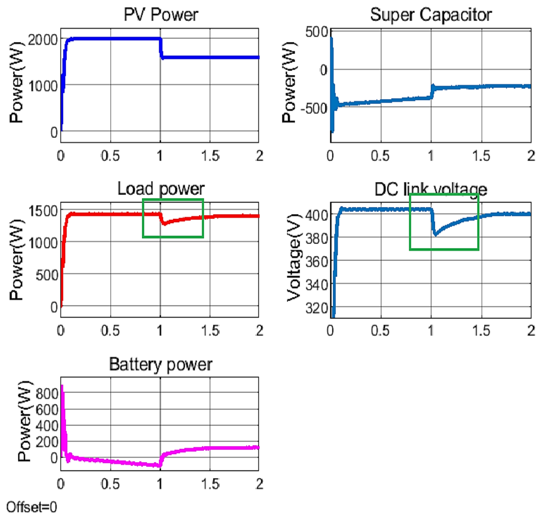

Figure 8. Simulation results for generation variation (cascaded dual loop PI controller)

4.2. Case 2: generation variation-generation is less than load

Impact of generation variation on energy management system performance for fuzzy-based system is given in Figure 9, which presents the system response to a generation variation, where the power generation is reduced from 2,000 W to 1,600 W at t = 1 second. The load power remains constant at 1,800 W, exceeding the available generation capacity after t = 1 s. To compensate for this shortfall, the hybrid energy storage system, comprising a battery and a supercapacitor, supplies the additional power. The supercapacitor plays a crucial role in handling transient power demands, ensuring that the DC link voltage remains stable throughout the transition.

To assess the system's performance under the same conditions, a dynamic dual-loop cascaded PI controller-based energy management system is also simulated. As illustrated in Figure 10, the introduction of generation variation leads to transient fluctuations in both load power and DC link voltage, lasting approximately 50 ms before stabilizing. This comparative analysis demonstrates that the fuzzy logic-based energy management system offers superior voltage regulation and enhanced system reliability under dynamic operational scenarios.

4.3. Case 3: load variation

4.3.1. Analysis of load variation on energy management system performance)

To evaluate the impact of load variation, the generated power is maintained at a constant 2,000 W, while the load is increased from 1,400 W to 1,800 W at t = 1 s, as depicted in Figure 11. Despite this sudden change in load demand, the DC link voltage remains stable at 400 V. The transient power demand resulting from the load variation is initially met by the supercapacitor, followed by the battery, as illustrated in Figure 11 for the fuzzy logic-based energy management (EM) system. In contrast, when the same scenario is simulated using a dynamic dual-loop cascaded PI controller-based EM system, the sudden load variation is also managed by the supercapacitor and battery. However, the DC bus voltage (drops to 380 V) experiences transient fluctuations lasting approximately 50 ms before stabilizing at 400 V, as shown in Figure 12. The comparative analysis of both systems indicates that while both approaches maintain a balance between generation and load and ensure DC link voltage stability, the fuzzy logic-based EM system demonstrates superior performance by offering faster voltage regulation and improved load reliability.

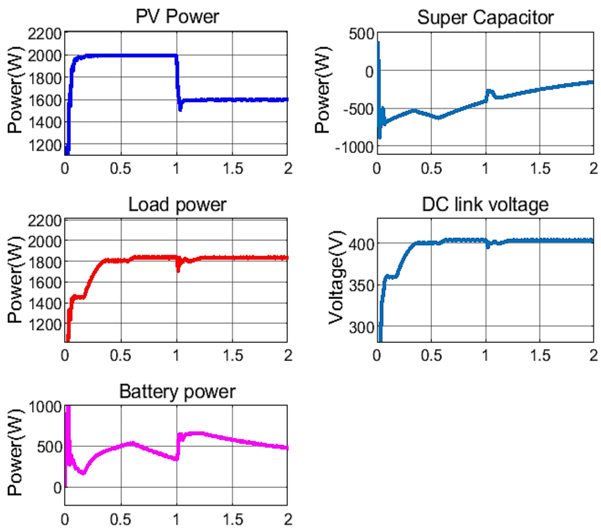

Figure 9. System response for generation variation (fuzzy EM system)

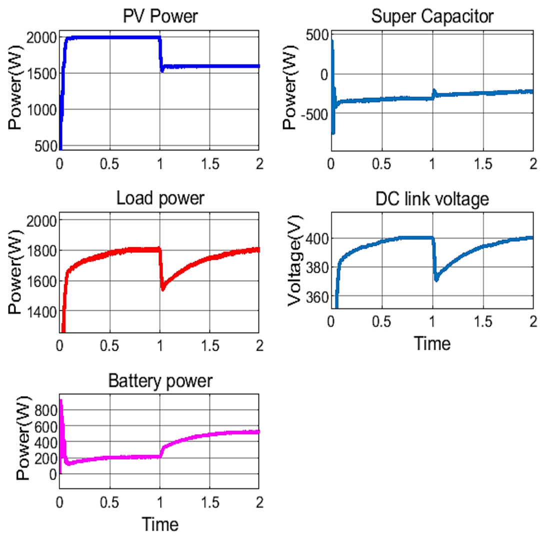

Figure 10. System response for generation variation (cascaded PI controller)

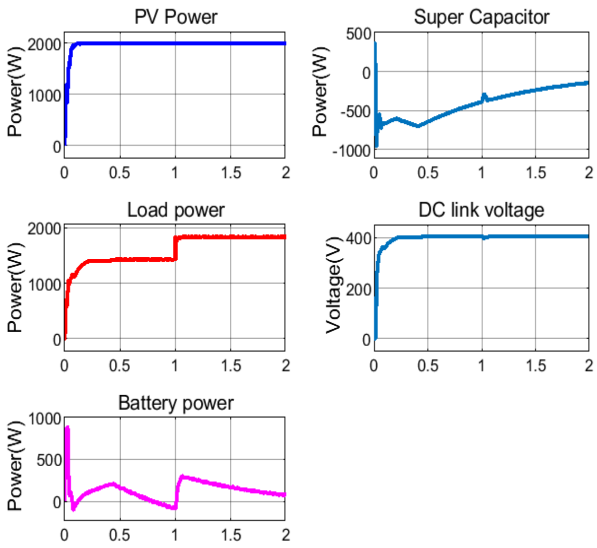

Figure 11 Simulation results for load variation (fuzzy EM system)

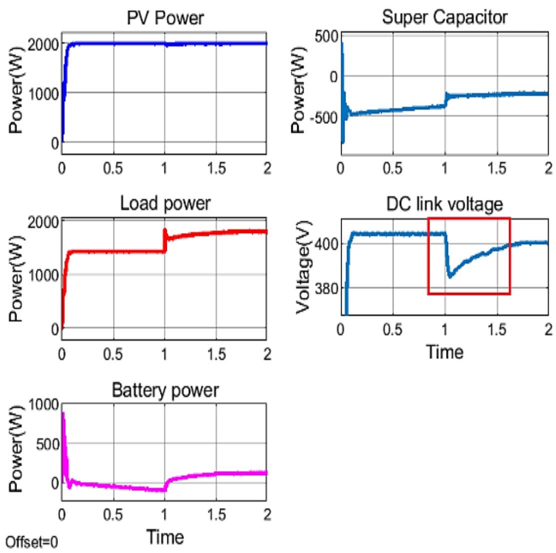

Figure 12 Simulation results for load variation (cascaded dual loop PI controller)

4.3.2. Evaluation of load variation in energy management systems

Another case of load variation is analyzed, with the results presented in Figure 13, for the fuzzy logic-based energy management (EM) system and Figure 14 for the dynamic dual-loop cascaded PI controller-based system. In this scenario, photovoltaic (PV) generation is maintained at 1,600 W, while the load power increases from 1,400 W to 2,000 W in 0.5 seconds. For the dynamic dual-loop cascaded PI controller-based EM system, it takes approximately 45 ms to reach the new load demand of 2,000 W after the load variation occurs. Similar to the previous case, the fuzzy logic-based system demonstrates superior performance in maintaining DC link voltage stability and ensuring load reliability. As illustrated in Figure 14, the PI controller-based system requires 25 ms to restore the DC link voltage following the load change, whereas the fuzzy logic-based approach provides a more stable and responsive regulation.

4.4. Case 4: generation and load variation

4.4.1. Analysis of generation and load variations in a DC microgrid

The performance of a DC microgrid is evaluated under simultaneous variations in generation and load power. Initially, photovoltaic (PV) generation is maintained at 2,000 W until 1 second, after which it decreases to 1,500 W. Similarly, the load power remains constant at 1,400 W until 0.5 seconds and then increases to 2,000 W. To analyze system behavior under these conditions, simulations are conducted for both the fuzzy logic-based energy management (EM) system and the dynamic dual-loop cascaded PI controller-based EM system.

Despite variations in both generation and load, the fuzzy logic-based EM system effectively maintains a stable DC link voltage, as illustrated in Figure 15. This stability is achieved as the battery compensates for the average power imbalance, while the supercapacitor handles transient fluctuations. Conversely, in the PI controller-based EM system, when generation decreases from 2,000 W to 1,500 W, transient fluctuations occur in both the load power and DC link voltage, lasting approximately 50 ms, as depicted in Figure 16. The comparative analysis indicates that the fuzzy logic-based EM system provides better load stability and faster DC link voltage regulation than the PI controller-based approach.

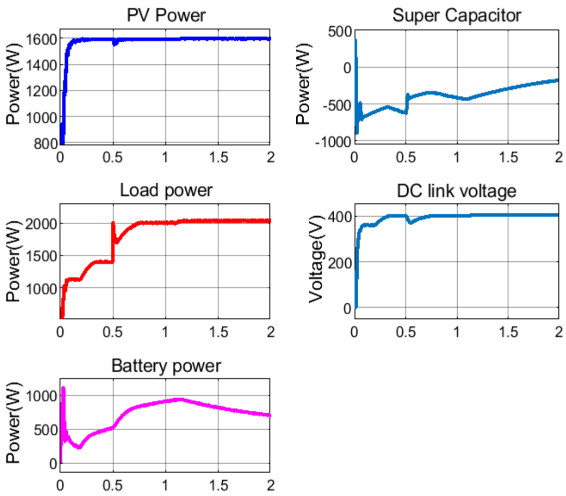

Figure 13. Load variation case 2 simulation (fuzzy EM system)

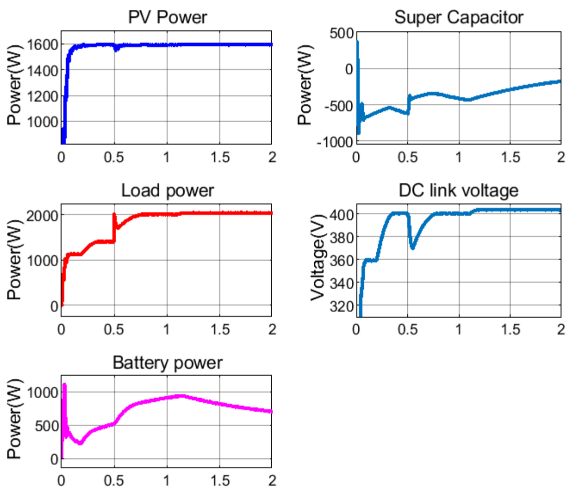

Figure 14. Load variation case 2 simulation (cascaded dual loop PI controller)

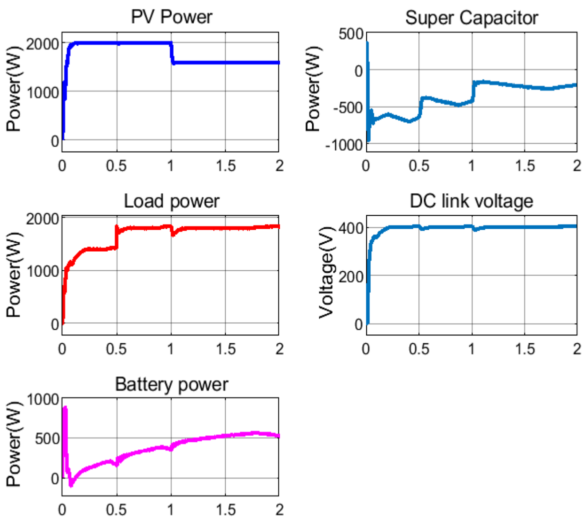

Figure 15. Simulation results for generation and load variation (fuzzy EM system)

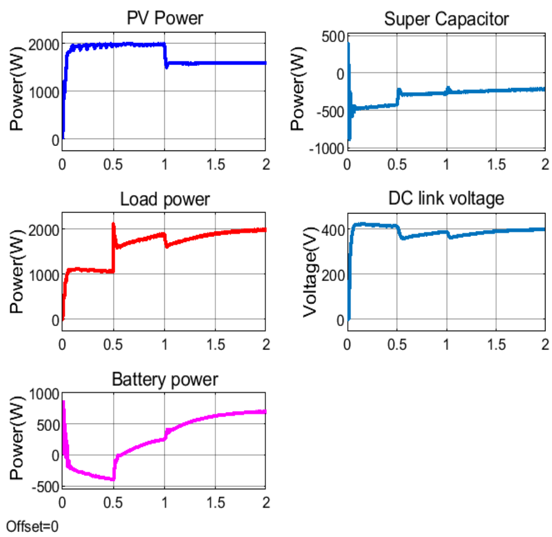

Figure 16. Simulation results for generation and load variation (cascaded dual loop PI controller)

Additionally, in a previously proposed fuzzy logic-based system, simultaneous variation in load and generation conditions is not analyzed. These results highlight the advantages of fuzzy logic in improving the reliability and efficiency of DC microgrid energy management. Based on the analysis of the three cases, it is evident that the DC bus voltage remains stable regardless of generation changes, load variations, or simultaneous fluctuations in both generation and load. The comparative results of fuzzy-based EMS and cascaded dual-loop PI-controller-based EMS are provided in Table 3 according to the settling time and DC link voltage after disturbances.

Table 3. Comparative analysis of proposed EMS performance and cascaded dual-loop PI-controller based EMS [23]

Cases Criteria	PI controller-based system DC voltage variation during disturbance	 Settling time	Fuzzy system DC voltage variation during disturbance	 Settling time
Generation variation (2,000 W→ 1,500 W, load = 1,400 W	0-15 V	20 ms	0	0.1 ms
Generation: 2,000 W→ 1,600 W, load = 1,800 W	0-15 V	20 ms	0	0.1 ms
Load variation Load: 1,400 W → 1,800 W, generation = 2,000 W	0-20 V	25 ms - 50 ms	2 V	0.1 ms
Load: 1,400 W→ 2,000 W, generation = 1,600 W	0-20 V	25 ms - 50 ms	2 V	0.1 ms
Gen and load variation Generation: 2,000 W→ 1,500 W, load: 1,000 W → 1,400 W	0-40 V	25 ms - 50 ms	0	0.2 ms

5. CONCLUSION

This study presents a detailed evaluation between a conventional PI controller-based energy management system and a fuzzy logic-based approach. Across various scenarios involving fluctuations in generation, load, generation and load, the fuzzy logic controller consistently outdone the PI controller. It preserved a stable DC link voltage with almost zero voltage deviation, while the PI controller exhibited variations of up to 40 V depending on the case. The response time of the fuzzy system was also significantly faster, achieving stabilization within 0.1–0.2 milliseconds, in contrast to the 20–50 milliseconds required by the PI controller, and comparatively fuzzy-based system operates 91% faster than the PI controller-based energy management system. The results of this study clearly demonstrate that fuzzy logic-based control offers a more dependable and efficient approach for managing hybrid energy storage systems. Additionally supercapacitor is utilized effectively not only for transient power requirements, but it also contributes load power requirement in this proposed fuzzy-based EMS.

Beyond the technical outcomes, the research emphasizes the critical role of intelligent control strategies in meeting the increasing demands on modern energy systems while addressing environmental sustainability. By integrating renewable energy sources with smart control techniques like fuzzy logic, microgrids can achieve greater operational efficiency and long-term resilience. The system developed in this work exhibited strong adaptability and responsiveness, highlighting its potential for practical, real-world deployment. Further enhancements could involve expanding the system to accommodate larger-scale microgrids with a wider variety of renewable sources—such as geothermal or biomass—which would also extend its applicability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Srinivas Babu					✓				✓	✓				
Siddalingappagouda Biradar					✓				✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] M. A. A. Rafi *et al.*, "Renewable energy-based hybrid microgrid for economically effective coastal electrification," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 8, pp. 1–5, Nov. 2021, doi: 10.1109/TASC.2021.3089118.

[2] S. Beheshtaein, R. Cuzner, M. Savaghebi, and J. M. Guerrero, "Review on microgrids protection," *IET Generation, Transmission & Distribution*, vol. 13, no. 6, pp. 743–759, Mar. 2019, doi: 10.1049/iet-gtd.2018.5212.

[3] H. Tiismus, V. Maask, V. Astapov, T. Korõtko, and A. Rosin, "State-of-the-art review of emerging trends in renewable energy generation technologies," *IEEE Access*, vol. 13, pp. 10820–10843, 2025, doi: 10.1109/ACCESS.2025.3528640.

[4] W. U. Rehman *et al.*, "The penetration of renewable and sustainable energy in Asia: a state-of-the-art review on net-metering," *IEEE Access*, vol. 8, pp. 170364–170388, 2020, doi: 10.1109/ACCESS.2020.3022738.

[5] J. De La Cruz, Y. Wu, J. E. Candelo-Becerra, J. C. Vásquez, and J. M. Guerrero, "Review of networked microgrid protection: architectures, challenges, solutions, and future trends," *CSEE Journal of Power and Energy Systems*, vol. 10, no. 2, pp. 448–467, 2023, doi: 10.17775/CSEEJPES.2022.07980.

[6] X. Liu, T. Zhao, H. Deng, P. Wang, J. Liu, and F. Blaabjerg, "Microgrid energy management with energy storage systems: a review," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 2, pp. 483–504, 2023, doi: 10.17775/CSEEJPES.2022.04290.

[7] S. Ahmad, M. Shafiullah, C. B. Ahmed, and M. Alowaifeer, "A review of microgrid energy management and control strategies," *IEEE Access*, vol. 11, pp. 21729–21757, 2023, doi: 10.1109/ACCESS.2023.3248511.

[8] F. Calero *et al.*, "A review of modeling and applications of energy storage systems in power grids," *Proceedings of the IEEE*, vol. 111, no. 7, pp. 806–831, Jul. 2023, doi: 10.1109/JPROC.2022.3158607.

[9] F. Garcia-Torres, C. Bordons, J. Tobajas, R. Real-Calvo, I. Santiago, and S. Grieu, "Stochastic optimization of microgrids with hybrid energy storage systems for grid flexibility services considering energy forecast uncertainties," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5537–5547, Nov. 2021, doi: 10.1109/TPWRS.2021.3071867.

[10] M. Billah, M. Yousif, M. Numan, I. U. Salam, S. A. A. Kazmi, and T. A. H. Alghamdi, "Decentralized smart energy management in hybrid microgrids: evaluating operational modes, resources optimization, and environmental impacts," *IEEE Access*, vol. 11, pp. 143530–143548, 2023, doi: 10.1109/ACCESS.2023.3343466.

[11] Z. Sarra, M. Bouziane, R. Bouddou, H. Benbouhenni, S. Mekhilef, and Z. M. S. Elbarbary, "Intelligent control of hybrid energy storage system using NARX-RBF neural network techniques for microgrid energy management," *Energy Reports*, vol. 12, pp. 5445–5461, Dec. 2024, doi: 10.1016/j.egyr.2024.11.023.

[12] F. Valencia, J. Collado, D. Saez, and L. G. Marin, "Robust energy management system for a microgrid based on a fuzzy prediction interval model," *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1486–1494, May 2016, doi: 10.1109/TSG.2015.2463079.

[13] P. Horrillo-Quintero *et al.*, "Dynamic fuzzy logic energy management system for a multi-energy microgrid," *IEEE Access*, vol. 12, pp. 93221–93234, 2024, doi: 10.1109/ACCESS.2024.3422009.

[14] M. Bilal, A. A. Algethami, Imdadullah, and S. Hameed, "Review of computational intelligence approaches for microgrid energy management," *IEEE Access*, vol. 12, pp. 123294–123321, 2024, doi: 10.1109/ACCESS.2024.3440885.

[15] P. Gupta, M. A. Ansari, and I. Ali, "Smart energy management techniques of microgrid: a review," in *2023 International Conference on Power, Instrumentation, Energy and Control (PIECON)*, Feb. 2023, pp. 1–6, doi: 10.1109/PIECON56912.2023.10085903.

[16] N. Guler, Z. M. Ismail, Z. Ben Hazem, and N. Naik, "Adaptive fuzzy logic controller-based intelligent energy management system scheme for hybrid electric vehicles," *IEEE Access*, vol. 12, pp. 173441–173454, 2024, doi: 10.1109/ACCESS.2024.3496897.

[17] V. Gopu and M. S. Nagaraj, "Adaptive fuzzy PID integrated renewable power management system for off grid and on grid conditions," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 4, pp. 2580–2590, Dec. 2024, doi: 10.11591/ijpeds.v15.i4.pp2580-2590.

[18] S. M. Belhadj, B. Meliani, H. Benbouhenni, S. Zaidi, Z. M. S. Elbarbary, and M. M. Alammar, "Control of multi-level quadratic DC-DC boost converter for photovoltaic systems using type-2 fuzzy logic technique-based MPPT approaches," *Heliyon*, vol. 11, no. 3, Feb. 2025, doi: 10.1016/j.heliyon.2025.e42181.

[19] N. Ouddah and L. Adouane, "Hybrid energy management strategy based on fuzzy logic and optimal control for tri-actuated powertrain system," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 6, pp. 5343–5355, Jun. 2019, doi: 10.1109/TVT.2019.2899880.

[20] M. A. E. Mohamed, S. M. R. Mohamed, E. M. M. Saied, M. Elsisi, C.-L. Su, and H. A. Hadi, "Optimal energy management solutions using artificial intelligence techniques for photovoltaic empowered water desalination plants under cost function uncertainties," *IEEE Access*, vol. 10, pp. 93646–93658, 2022, doi: 10.1109/ACCESS.2022.3203692.

[21] U. R. Nair and R. Costa-Castello, "A model predictive control-based energy management scheme for hybrid storage system in islanded microgrids," *IEEE Access*, vol. 8, pp. 97809–97822, 2020, doi: 10.1109/ACCESS.2020.2996434.

[22] A. A. Al Alahmadi *et al.*, "Hybrid wind/PV/battery energy management-based intelligent non-integer control for smart DC-microgrid of smart university," *IEEE Access*, vol. 9, pp. 98948–98961, 2021, doi: 10.1109/ACCESS.2021.3095973.

[23] S. Neelagiri and P. Usha, "Modelling and control of grid connected microgrid with hybrid energy storage system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 3, pp. 1791–1801, Sep. 2023, doi: 10.11591/ijpeds.v14.i3.pp1791-1801.

[24] M. Alsumiri, "Residual incremental conductance based nonparametric MPPT control for solar photovoltaic energy conversion system," *IEEE Access*, vol. 7, pp. 87901–87906, 2019, doi: 10.1109/ACCESS.2019.2925687.

[25] MathWorks, "Battery: Generic battery model," *The MathWorks Inc.*, 2024. [Online]. Available: https://www.mathworks.com/help/sps/powersys/ref/battery.html.

[26] MathWorks, "Supercapacitor: generic supercapacitor model," *The MathWorks Inc.*, 2024. [Online]. Available: https://www.mathworks.com/help/sps/powersys/ref/supercapacitor.html.

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