Fuzzy logic-based energy management system for a microgrid with hybrid energy storage: design, control, and comparative analysis

Suganthi Neelagiri[1], Pasumarthi Usha[1], Siddalingappagouda Biradar[2]
[1]Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering, Visveswaraya Technological University, Bangalore, India
[2]Department of Electronics and Communication Engineering, Dayananda Sagar Academy of Technology and Management, Bangalore, India

Article Info

Article history:

Received Mar 5, 2025
Revised Jun 2, 2025
Accepted Jul 23, 2025

Keywords:

Battery
Energy
Fuzzy
Microgrid
Supercapacitor

ABSTRACT

This paper presents a fuzzy logic-based energy management controller for a microgrid with a hybrid energy storage system. The microgrid integrates intermittent renewable energy sources. To provide high quality, reliable and sustainable power, the microgrid depends on energy storage devices. The proposed fuzzy logic-based energy management controller controls the energy storage system's power electronic converters by generating switching pulses based on the generation availability, load requirement, SOCs of battery, and supercapacitor. Additionally, a fuzzy logic-based energy management system is planned in such a way that high power needs are satisfied by supercapacitors and high energy needs are satisfied by batteries. To highlight the key benefits of utilizing a fuzzy logic-controlled hybrid energy storage system over PI -a controller-based cascaded dual loop energy management system, a comparative study is carried out. The results of the same is discussed elaborately in this paper. These studies were simulated using the MATLAB/Simulink software package.

Corresponding Author:

Suganthi Neelagiri
Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering
Visveswaraya Technological University
Shavige Malleswara Hills, Kumaraswamy Layout, Bangalore 560078, India
Email: suganthi_neelagiri@yahoo.com

1. INTRODUCTION

Globally, the requirement for electric power has been growing steadily over the past several decades with different growth rates across different regions. Since the early 1970's, the electric utility industry has consistently made efforts to integrate batteries into its operations [1] for large scale energy storage in a load leveling mode. Later batteries have been included at transmission and distribution level [2]. With mounting concerns regarding climate change and energy security led to increased adoption of distributed generation [3], this in turn created the concept of microgrids. The microgrids have emerged in remote or off-grid locations where access to national electricity grids was restricted or non-existent. Microgrids are integrated with various types of renewable energy sources (RES), mainly solar PV systems and Wind generators. The key challenges with solar and wind energy are their fluctuating and intermittent characteristics. To address these challenges and to maintain the quality power, stable voltage and frequency of microgrids in different operational modes, energy storage devices are integrated in microgrids [4]. Energy storage (ES) devices can be divided into two primary categories: high energy capacity ES for extended periods of discharge and high-power capacity ES for rapid discharge. Pumped hydro energy storage (PHES), compressed air energy storage (CAES), and electrochemical batteries fall under high capacity-energy storage capacity devices. These energy storage systems (ESS) have been widely deployed, from small-scale residential systems to different grid applications. Batteries are recognized as an important and efficient way of stabilizing microgrids. They are attractive because they are cost-effective, compact, and easy to deploy.

Li *et al.* [5] presents an overview of the research work carried out with various types of batteries like lead-carbon batteries [6], lithium iron phosphate batteries [7], all-vanadium redox flow batteries, used for mitigating the wind power fluctuations [8], [9] and to suppress the effect of intermittence nature of renewable energy sources. Most of these studies concentrated on utilizing a single ESS and it cannot meet the desired operational requirements of a micro grid due to its limitations in energy, power density, dynamic response, and life span. Microgrids are sensitive to load and generation changes, it requires an ESS capable of storing and delivering significant energy and power. Batteries high energy density makes them popular for energy storage, but they frequently are unable to keep up with microgrids' high-power requirements. These high-power requirements can occur during sudden changes in load, variations in generation, or when starting certain appliances such as refrigerators, air conditioners, and motors. When these demands are met by the battery, it experiences high current stress, which can shorten its lifespan [10]. Although batteries are commonly used for energy storage, an ideal standalone microgrid must be capable of meeting both the high-capacity power and energy demands of its loads. This work aims to harness the benefits of different energy storage solutions. Supercapacitors are emerging as effective temporary energy storage devices due to their high-power density; they can charge and discharge much quicker than batteries. Therefore, the main goal of this study is to propose a hybrid energy storage system that combines batteries and supercapacitors in order to maximize these devices advantages. A hybrid energy storage systems (HESS) generally consists of two complementary storage devices, one with high energy density and the other with high power density. This HESS combination is employed to meet long-duration energy needs, short duration power needs and to manage and stabilize the transients and rapid load fluctuations. The different topologies of HESS, comparison of topologies, and the control strategies of HESS are detailed in [11]. The energy management (EM) of microgrids with HESS and solar PV has been discussed in [12]-[16]. The microgrids integrated with wind turbines also need energy storage devices as the power output of wind turbines varies with changing wind speeds, which can be unpredictable and fluctuate from minute to minute or even second to second. Energy storage systems mitigate these fluctuations, providing a more stable and reliable power supply. The control and operation of microgrids integrated with wind turbines and HESS are explained in [17].

The energy management control of HESS involves a comprehensive approach to manage multiple storage technologies, optimizing performance, ensuring reliability, and integrating with non-conventional energy sources. In literature, many computational intelligence techniques have been proposed for various applications. Current research in this field is robust and ongoing. Numerous models have been suggested for optimizing microgrids and managing energy, including heuristic techniques such as game theory, evolutionary algorithms, and decision tree-based dynamic programming algorithms. Other methods include model predictive control and mixed-integer linear programming. However, these approaches can often be inefficient and time-consuming, and they do not guarantee a globally optimal solution. While linear and dynamic programming techniques may yield the best results, they frequently involve complex and resource-intensive processes. Further mathematical calculations are also required for techniques like model predictive control (MPC) and mixed-integer linear programming, as they rely on classical methods [18]-[26].

Fuzzy logic (FL) control methods are gaining popularity because they do not require mathematical modelling. Fuzzy controllers can effectively handle uncertainties, imprecision, and nonlinearities in the system, making them particularly suitable for the variable nature of renewable energy sources and load demand. Furthermore, fuzzy logic controllers ensure that energy storage devices are used efficiently, which helps prolong the lifespan of batteries and other storage elements while reducing operating costs [27]. The fuzzy controlled HESS can easily be scaled up to accommodate additional storage units or non-conventional energy sources as the microgrid grows. By managing the charge and discharge cycles effectively, the fuzzy controlled system helps in preventing issues like overcharging, deep discharging, and frequent cycling, thus maintaining grid stability and storage longevity [28]. This approach is robust, customizable, and provides reliable and efficient solutions. Fuzzy logic helps to quantify the system's fuzziness into a clear and measurable metric [29], [30]. According to the existing literature, most microgrids combine solar photovoltaic (PV) systems and batteries or wind generators with diesel generators and batteries. However, there has been limited research on the integration of solar PV and wind generators with HESS in a microgrid [31]. This study aims to address that gap by focusing on the integration of HESS within a microgrid that utilizes solar PV and wind generators. Additionally, this paper proposes a fuzzy logic-based energy management strategy for microgrids equipped with hybrid energy sources and ESS. Specifically, a FL based controller for HESS has been proposed to manage energy and maintain power balance in a microgrid under various scenarios. This control strategy provides improved DC link voltage regulation and enhances load reliability during sudden load and generation variations. The presented control strategy is compared with the classical PI controller-based approach. It also takes into account the state of charge (SOC) of energy storage devices and ensures it remains at a safe level. This paper is arranged with introduction as: i) section 1, ii) section 2 details system configuration and modelling, iii) section 3 explains control strategy, iv) section 4 is results and analysis, and v) section 5 is conclusion.

2. SYSTEM CONFIGURATION AND MODELING

The planned DC microgrid integrates both PV and wind energy sources, utilizing a hybrid energy storage system (HESS) that consists of batteries and supercapacitors. The PV system is connected to the microgrid through a boost converter, which is implemented with a perturb-and-observe maximum power point tracking (MPPT) algorithm. Additionally, a permanent magnet synchronous generator (PMSG) wind turbine is linked to the DC bus via an AC-to-DC converter and a DC-DC converter. The supercapacitor and battery are connected in parallel to the DC bus through bi-directional DC-DC converters. Control switching pulses for the DC-DC converters of the battery and supercapacitor are generated by a fuzzy-based energy management system (EMS). This system is demonstrated in Figure 1.

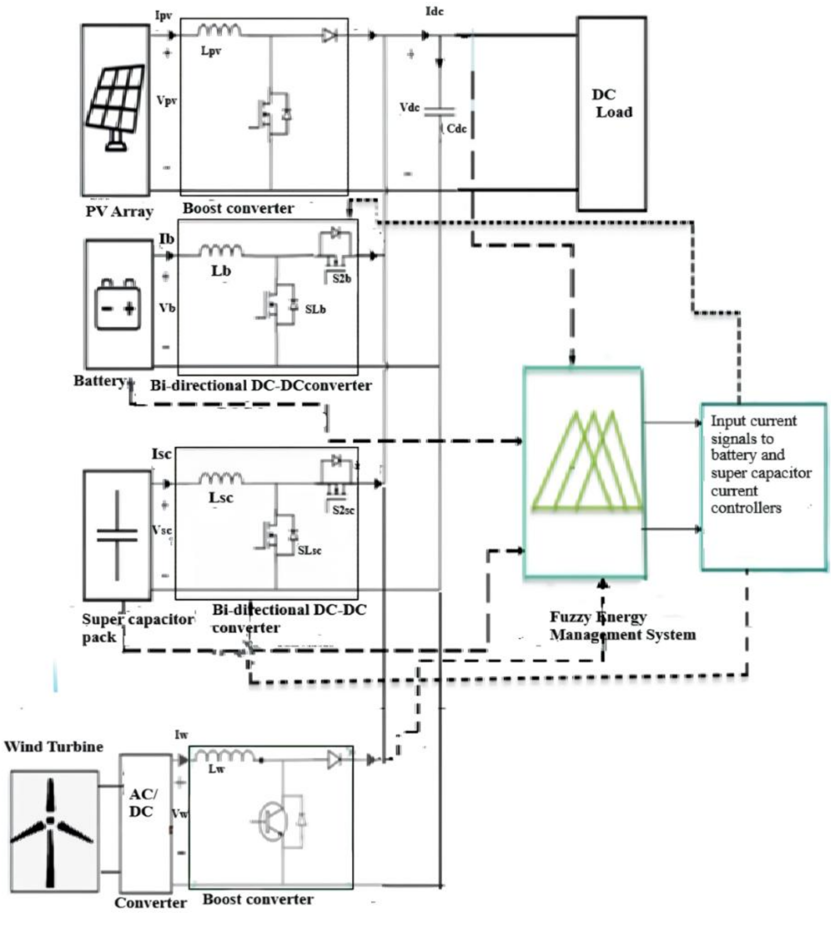


Figure 1. Proposed microgrid system with fuzzy based EMS

2.1. Photovoltaic system

A photovoltaic (PV) array with a capacity of 2 KW has been considered. In this proposed microgrid, the PV array consists of 8 modules connected in series. The equivalent model of the PV cell considered is shown in Figure 2. The PV array is connected to the DC bus through a boost converter (BC), whose duty cycle is adjusted to extract the maximum available power using the perturb and observe (P&O) algorithm. This algorithm illustrated in Figure 3 continuously modifies the converter's duty cycle to optimize the input resistance, aligning it with the internal resistance of the PV array at the maximum power point (MPP), thus ensuring that Rin equals Rmp. The converter's duty cycle '*Dmp'* at MPP can be computed using (1).

$$Dmp = 1 - \sqrt{(\frac{Rmp}{RL})} \quad (1)$$

Rmp = input resistance of PV array at MPP
R_L = output resistance of boost converter
And the inductor value of the BC is calculated using (2).

$$Lmin = (vm_P \times Dmp)/\ (\Delta\bar{I}out \text{ x } f) \quad (2)$$

Where,
Vmp = voltage at maximum power point
$\Delta\bar{I}out$ = permissible change in current (10%)
f = switching frequency
PV module parameters are given in Table 1.

2.2. Wind energy system

Permanent magnet synchronous generator (PMSG) based wind turbine is utilized in the proposed system. The MATLAB model of PMSG wind turbine is utilized for simulation of the proposed system. The PMSG wind turbine is popular because it has a greater efficiency and power factor, no gearbox system, not required continuous maintenance, flexible active and reactive power regulation, and dissipation, among other advantages. More than 65% of newly built wind turbines (in MW units) are based on this idea, with fixed-speed wind turbines accounting for 18% of the market.

The mechanical power (P_{mech}) generated in the wind turbine is given by (3).

$$P_{mech} = {}^1/_2 * \rho_{air} * \pi * R^2 * V^3{}_{wind} * C_p(\lambda, \beta) \quad (3)$$

Where,
ρ_{air} = air density (kg/m^3) = 1.225 kg/m^3
R = rotor radius (m)
V_{wind} = wind speed (m/s)

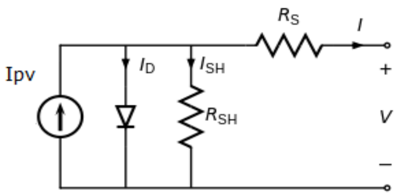


Figure 2. PV cell

Table 1. PV module details

S.NO	PV cell details	Magnitude
1	Short circuit current	8.66 A
2	Maximum voltage	30.7 V
3	Voltage at open circuit condition	37.3 V
4	Maximum current	8.15 A
5	Temperature coefficient of Voc	-0.36901
6	Maximum power	250.205 W
7	Temperature co-efficient of Isc	0.086998

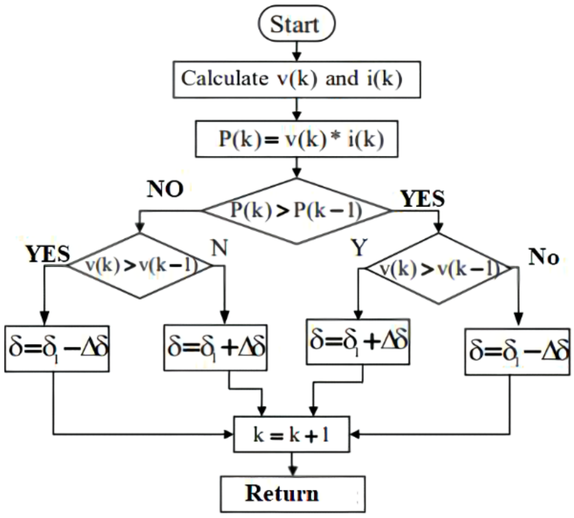


Figure 3. Flow chart of perturb and observe algorithm

The power efficiency factor, Cp, is influenced by the blade angle β and the tip speed ratio λ. Cp is a function of λ and β, and the optimal value of Cp falls between 0.52 and 0.55. The power output versus wind speed graph of the model used can be found in Figure 4. The specification of the chose wind turbine is given in Table 2.

2.3. Hybrid energy storage system (HESS)

Hybrid energy storage system considered in the presented work is Li-ion batteries and supercapacitors and the models available in MATLAB/Simulink have been utilized. Compared to prominently used lead-acid batteries, Li-ion batteries have a high energy density, battery capacity, long life, and 80-100% depth of charge. Additionally, they are not toxic to the environment since they use carbon as an anode and lithium salt as a cathode. The utilized MATLAB battery model takes into account seven variables, including temperature, state of charge (SOC), and current capacity. All these characteristics change as the battery is charged and discharged. Figure 5 shows the subsystems of the Simulink battery model created by MATLAB (2018). In this model, the battery is demonstrated as a current source control with internal resistance. The battery gets periodically charged or drained depending on its charge level and amount of electrical power generated. The voltage of the battery rises during charging, and the current rises during discharging. The discharge characteristics of the battery provide the model constraints. The accumulating and discharging characteristics are equal in measurement. The Simulink model of the battery is illustrated in Figure 5. In this work the supercapacitor model illustrated in Figure 6 is utilized, which is available in MATLAB. The supercapacitor is modelled as a regulated voltage source with internal resistance. Specifications of HESS are given in Table 3.

Table 2. PMSG wind system specification

Parameters	Value
Maxpower, wind speed	1 KW, 12 m/s
Rotor radius	1m
Tip speed	8.1
Air density	1.3 Kg/m^3

Table 3. HESS parameters

Parameters		Value
Battery nominal voltage	Voltage (V)	300 V
Battery rated capacity	Ah	48 Ah
Super capacitor capacitance	C	99.5 F
Super capacitor rated voltage	Voltage (V)	300 V
DC-DC converter parameters connected to battery	Inductance, capacitance, frequency, voltage	L = 0.02 mH, C = 300 μF, V_0 = 50 V

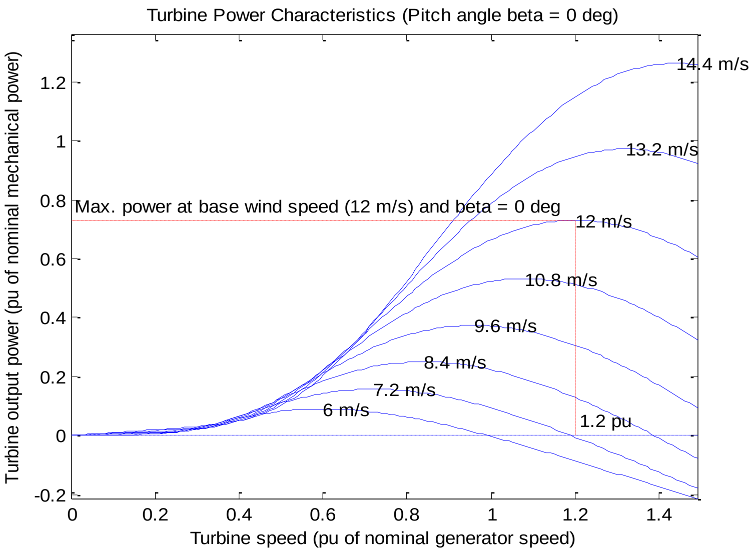


Figure 4. Wind turbine power output response for various wind speed

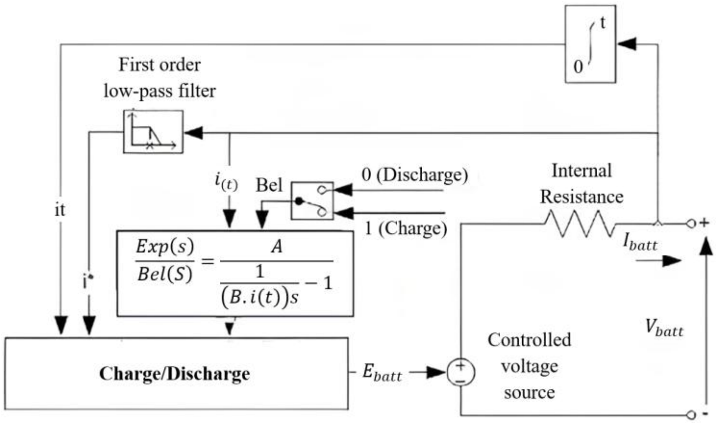


Figure 5. Simulink battery model (MATLAB)

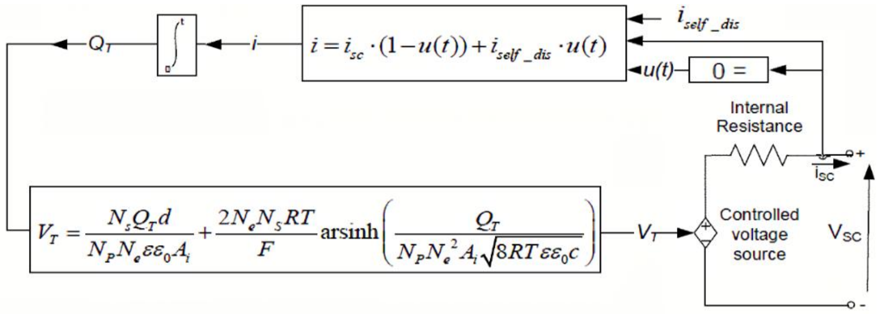


Figure 6. Super capacitor model MATLAB (2018)

3. CONTROL APPROACH

The energy management control strategy is designed to maintain a constant DC link voltage of 400 V. The diagram in Figure 7 illustrates the fuzzy-based energy management control system. The fuzzy controller takes the DC link current, battery state of charge (SOC), and supercapacitor SOC as inputs. Based on these inputs, the fuzzy system generates a current control signal, which is then used to create reference control signals for the battery and supercapacitor current controllers. The battery and supercapacitor current controllers produce switching pulses for their respective DC-DC bidirectional converters based on the FL algorithm. The fuzzy-based EMS utilizes the SOC of both the battery and supercapacitor, as well as the available DC link current, to generate the control output. The primary goal of this algorithm is to maintain a stable DC link voltage while avoiding a 100% depth of discharge of the energy storage devices and maintaining state of charge of battery at 50% and improve the battery life span. The control strategy involves obtaining the DC link reference current from a PI controller, which uses the deviation between the actual DC link voltage and the reference DC link voltage as its input. This DC link current signifies the total current requirement from the microgrid. The variable I_{dcref} is the sum of the supercapacitor reference current and the battery reference current, as expressed in (4).

$$I_{dcref} = I_{batref} + I_{scref} \quad (4)$$

Where,
I_{dcref} = total DC link current reference
I_{batref} = reference current for battery controller
I_{scref} = reference current for super capacitor
The DC bus voltage is regulated to a constant value by representing the DC bus using (5).

$$C\frac{dv_{dc}}{dt} = i_{scref} + i_{batref} + i_{pv} + i_{wind} - i_{load} \quad (5)$$

The DC link current input of the fuzzy system, specifically the Mamdani model, is defined by two membership functions: positive and negative, as illustrated in Figure 8(a). The allowable range for variations in the DC link current is from -5 to 5, also shown in Figure 8(a). Additionally, the state of charge (SOC) of the battery (denoted as SOCbat) is another input for the fuzzy energy management (EM) system, characterized by three membership functions: low, medium, and high. The SOC of the battery ranges from 0% to 100%. Similarly, the SOC of the supercapacitor is represented by the same three membership functions: low, medium, and high. The SOC range considered for both the battery and the supercapacitor is 0% to 100%, as depicted in Figures 8(b) and 8(c).

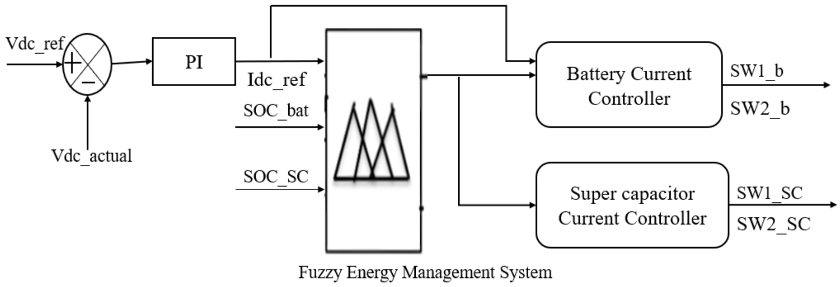


Figure 7. Fuzzy based EMS control strategy

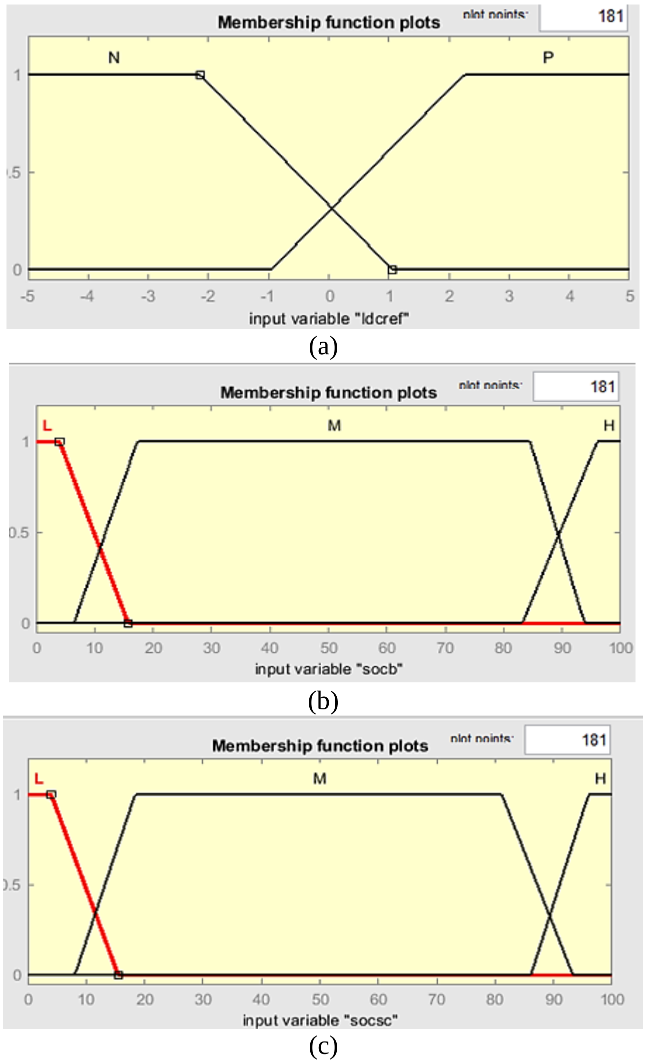


Figure 8. Input membership functions: (a) Idcref, (b) SOC battery, and (C) SOCsc

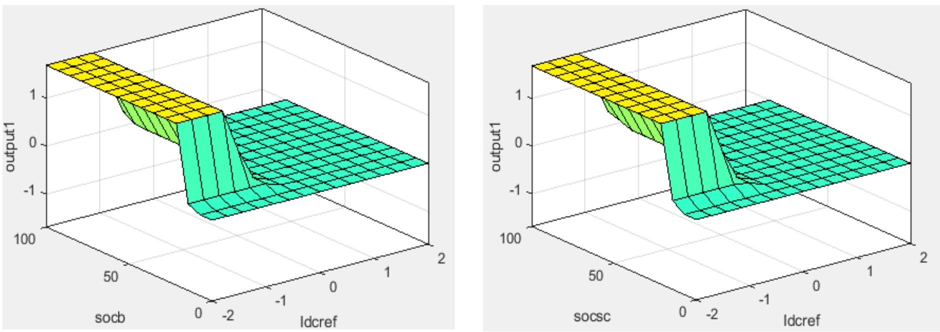
The details are given in Table 4. I_{dcref} is the total current requirement of the microgrid. I_{dcref} will be negative if generated power is greater than the load. It will be positive, when load demand is more than the generated power. The fuzzy controller rules are designed based on the SOCs of ESS and I_{dcref} to achieve the load requirement. Any excess energy will be stored in the battery and supercapacitor based on their SOC levels as per the fuzzy rules provided in Table 5, and the corresponding fuzzy surface is illustrated in Figure 9. The fuzzy energy management control algorithm is detailed in Table 5.

Table 4. Membership function table

Membership function	SOCb-range battery	SOCsc- range supercapacitor
Low	0-20%	0-20%
Medium	20-85%	20-85%
High	85-95%	85-95%

Table 5. Fuzzy control algorithm rules

I_{dcref} (N-generation more, P-load demand more)	SOCb	SOCsc	I_{scref}
N -generation more than load	0-20%	20-85%	Zero (battery gets charged)
	0-20%	85-95%	Zero (battery gets charged)
	20-85%	0-20%	P (SC gets charged)
	20-85%	20-85%	Zero (battery and SC gets charged)
	20-85%	85-95%	Zero (battery gets charged)
	85-95%	0-20%	P (SC gets charged)
	85-95%	20-85%	P (SC gets charged)
	85-95%	85-95%	P (battery and SC gets charged)
P -load demand more than generation	0-20%	0-20%	N (battery and SC discharges)
	0-20%	20-85%	N (SC discharges)
	0-20%	85-95%	N (SC discharges)
	20-85%	0-20%	Zero (battery discharges)
	20-85%	85-95%	N (battery and SC discharges)
	85-95%	0-20%	Zero (battery discharges)
	85-95%	20-85%	N (battery and SC discharges)



(a) (b)

Figure 9. Fuzzy surface: (a) SOCb and (b) SOCsc

4. RESULTS AND ANALYSIS

The proposed microgrid with PV and PMSG-wind energy systems is simulated in MATLAB. The simulation of the proposed microgrid system is depicted in Figure 10 and simulation of fuzzy logic-based energy management system is given in Figure 11. From Figure 11, it can be observed that DC link current, SOCs of battery and SC is given as input to fuzzy logic controller.

The fuzzy logic controller generates current references based on the inputs and the fuzzy logic-based energy management algorithm. These current references are provided to the current controllers of both the battery and the supercapacitor. The reference currents are then compared to their actual currents, and the difference is sent to the current controllers to produce the necessary switching pulses. The proposed FL based EM controller is analyzed for four different scenarios as follows: i) generation variation, ii) real time generation variation of PV and wind, iii) load variation, additionally iv) comparative analysis is carried out between the proposed fuzzy based energy management system and PI -controller based cascaded dual loop energy management system proposed in [31] for standalone mode and the detailed analysis of PI controller-based EM s is given in [31].

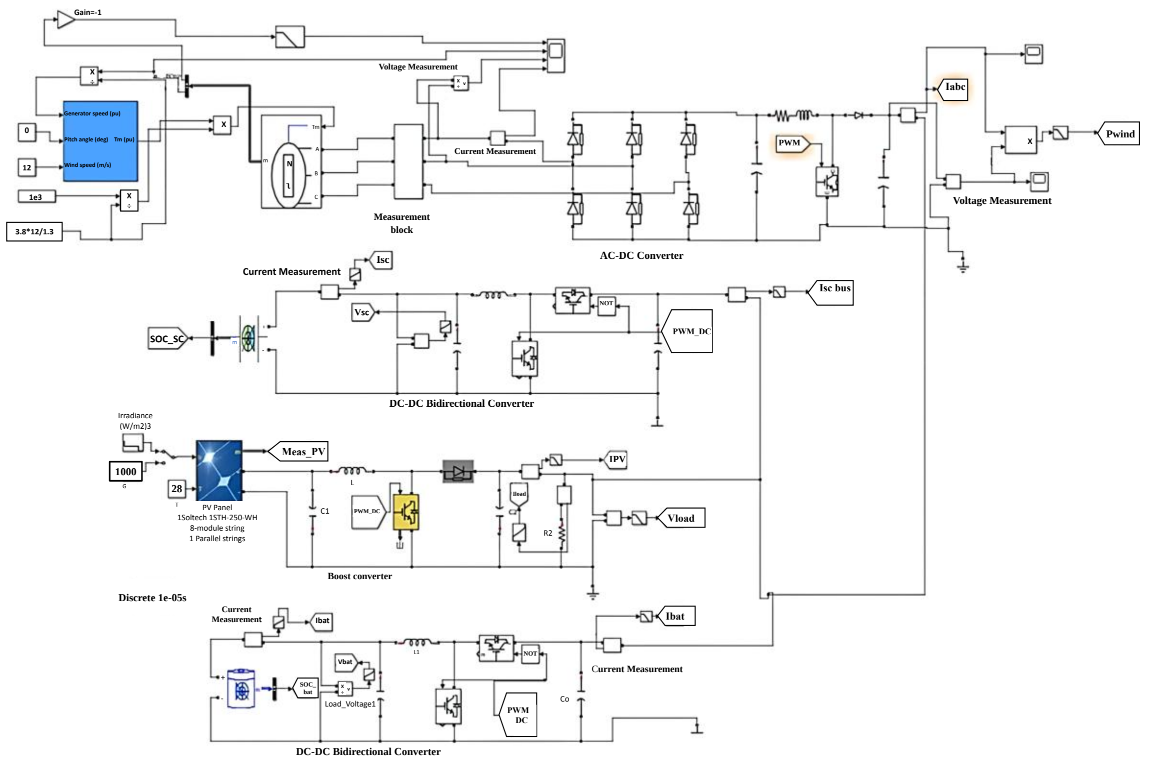


Figure 10. Simulation of the presented microgrid

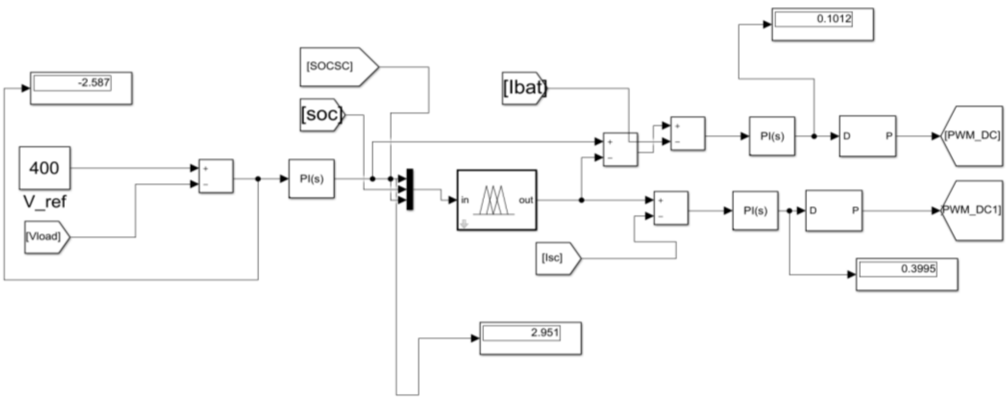


Figure 11. Fuzzy-based EM controller (simulation)

4.1. Generation variation

4.1.1. Case 1: Load power less than generating power

To verify the system performance for generation variation, the load power of the proposed microgrid is kept constant at 1,600 W. Wind power remains at 800 W while the PV generation power is varied between 1,000 W and 500 W at t = 1 second, as shown in Figure 12. During the first one second, the power generated from wind and PV is excess than the load power of 1,600 W. The extra power is stored in the supercapacitor as per the fuzzy algorithm given in Table 5 as both battery and supercapacitor are in the medium charge level. At t = 1 second, when the PV generation power is reduced to 500 W, the supercapacitor delivers the transient power requirement of the load, followed by the battery as per the fuzzy energy management system, as depicted in Figure 12. Throughout this process, the DC link voltage is sustained at a fixed value of 400 V, as demonstrated in Figure 12 for the fuzzy logic-based EM control system. The same scenario is simulated with dual-loop cascaded PI controller-based EM presented in [31].

However, in the case of the cascaded dual-loop PI controller-based EM system, this sudden change in generation variation leads to load fluctuation for 50 ms, and the DC link voltage reduces to 385 V. It gradually restores to 400 V in the next 50 ms as shown in Figure 13. Therefore, from the analysis, it is evident that fuzzy-based EM system offers fast DC link voltage regulation and load stability and reliability.

4.1.2. Case 2: Real time PV and wind generation variation

To investigate the generation variation condition of the presented microgrid with HESS devices, real solar irradiation and wind speed data were collected from the websites of the Global Wind Atlas and the National Renewable Energy Laboratory and used as inputs to the modelled PV and wind energy systems of the suggested microgrid. One whole day data is taken and converted into 24 sec data to do simulation study. And the simulation of the same is given in Figure 14. From the Figure 14, it can be observed that PV generation is varying throughout the day, and wind power generation fluctuates between 700 to 750 W.

For this generation variation proposed microgrid is simulated for load power of 2,000 W. Additionally it can be noted from Figure 14 that, irrespective of the fluctuations in the PV and wind generation, proposed MG with HESS maintains energy balance by preserving the DC link voltage at 400 V. Extra energy required is delivered by SC and battery. This same scenario is simulated with dual-loop cascaded PI controller-based EM and is illustrated in Figure 15. And in this case, when the generation variation is introduced, the load and DC-bus voltage fluctuates for 30 ms, and then restores to the steady condition, as depicted in Figure 15.

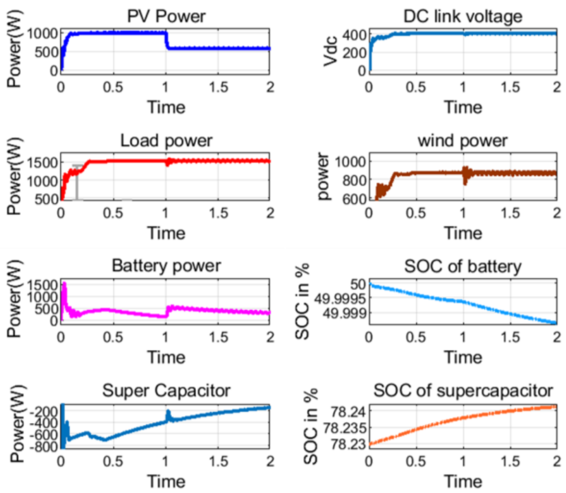


Figure 12. Generation variation (fuzzy)

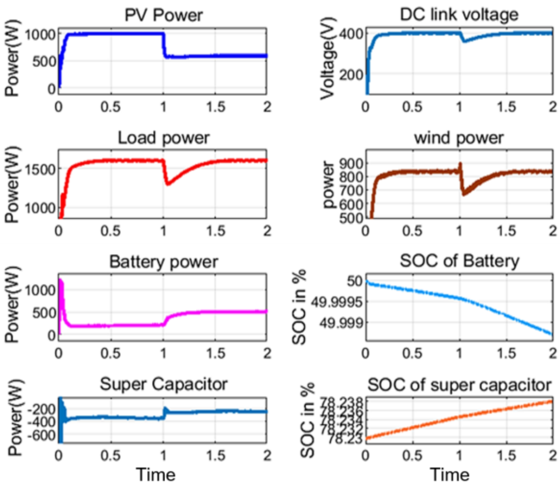


Figure 13. Simulation results for generation variation (PI controller)

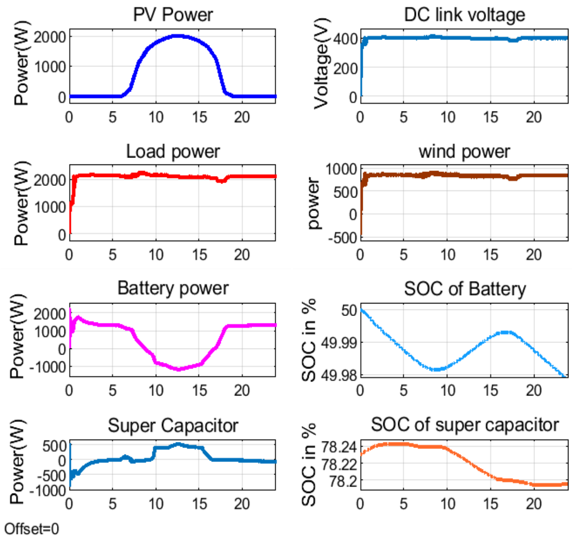


Figure 14. Real time generation variation (fuzzy)

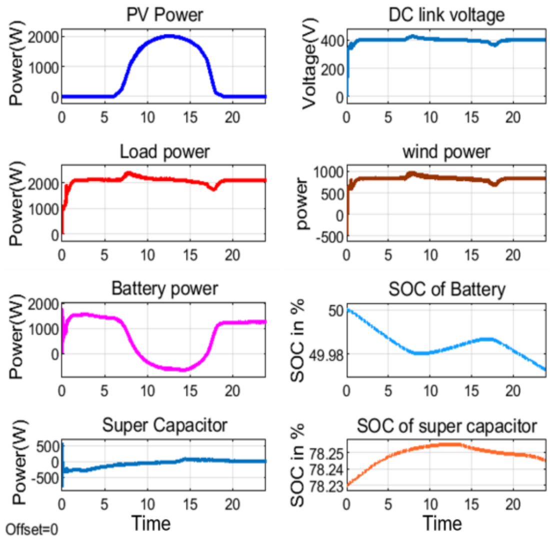


Figure 15. Real time generation variation (PI-controller)

4.2. Load variation

4.2.1. Case 1: with generating power more than load power

To study the load variation, the PV generation is kept constant at 1,600 W and wind power at 800 W. The load is changed from 1,400 W to 2,000 W at t = 0.5 s, as shown in Figure 16. Initially, from 0 to 0.5 sec, the generation power combining wind and PV is 2,300, and the load power is 1,400. In this case, the generation power is more than the load power, so the extra available power is utilized to charge the HESS. At 0.5 second, when the load power is increased from 1,400 W to 2,000 W, the sudden transient is supplied by the supercapacitor, and then it is supplied from generating sources, as shown in Figure 16. In the case of FL-based EM controller, the DC link voltage is also sustained at 400 V. The same scenario is simulated with PI controller-based dual-loop cascaded EM, when an unexpected load change happens, the DC link voltage fluctuation occurs for 50 ms. This happens even though it is managed by the supercapacitor and battery, and then it restores to 400 V, as shown in Figure 17.

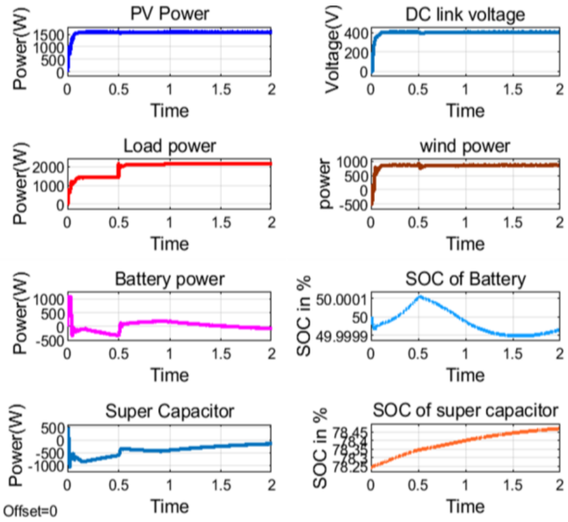


Figure 16. Load variation1 (fuzzy)

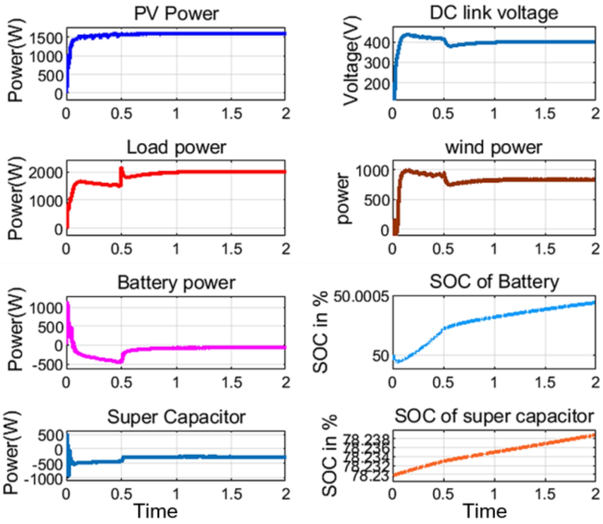


Figure 17. Load variation1 (PI controller)

4.2.2. Case 2: Load variation-load power is more than the generation

Another load change scenario is analyzed, and the results are presented in Figure 18 for the EM based on FL and in Figure 19 for the PI controller based dual-loop cascaded energy management systems. The PV generation is maintained at 1,600 W, and the load power is increased from 1,500 W to 2,500 W at 0.5 seconds. In the case of the cascaded dual-loop PI controller-based EM system, it took approximately 45 milliseconds to achieve 2,500 W load power after the load change is introduced. Fuzzy-based systems once again demonstrated good results in terms of DC link voltage and load reliability. It took 50 milliseconds to restore the DC link voltage after the load change, as depicted in Figure 19.

To analyses the pattern of the system performance, further system is simulated for different cases. The results are tabulated in the Table 6. From the analysis table it is observed that fuzzy based system performs better compared to the PI controller, it quickly restores the DC link voltage with load reliability.

Table 6. Consolidation of results: comparison between HESS

Scenario	PV power change	Wind power	Load power change	PI controller EMS (voltage deviation/restoration time)	Fuzzy EMS (voltage deviation restoration time)
Generation variation	1,000 W to 500 W	800 W	1,600 W	15 V / 50 ms	2 V / 2 ms
	100 W to 500 W	800 W	1,800 W	15 V / 30 ms	2 V / 2 ms
Load variation	1,600 W	800 W	1,400 W to 2,000 W	15 V / 50 ms	2 V / 2 ms
	1,600 W	800 W	1,500 W to 2,500 W	15 V / 50 ms	2 V / 2 ms
Generation & load variation	1,000 W to 500 W	800 W	1,500 W to 2,000 W	15 V / 50 ms	2 V / 2 ms
	1,500 W to 1000 W	800 W	1,500 W to 2,000 W	15 V / 50 ms	2 V / 2 ms

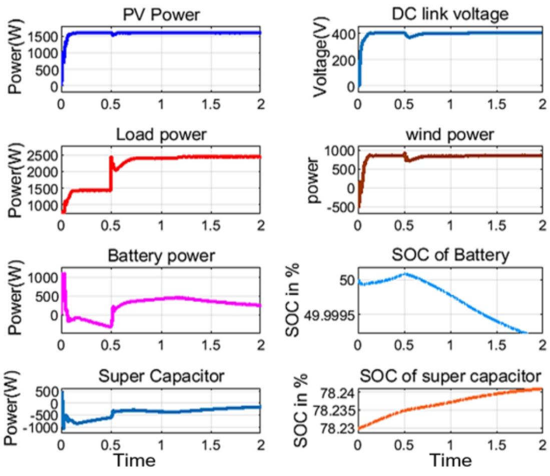


Figure 18. Load variation (fuzzy)

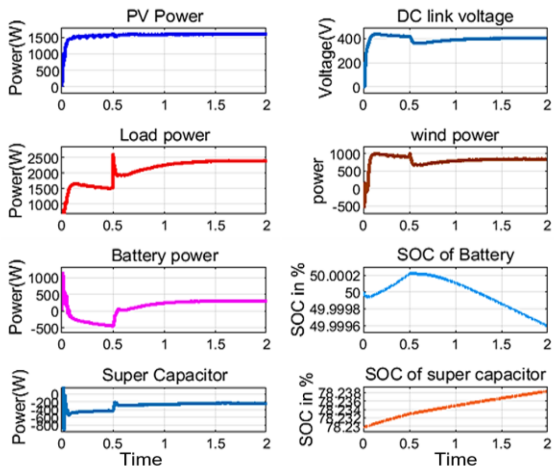


Figure 19. Load variation (PI-controller)

5. CONCLUSION

Energy management system for a presented microgrid with a HESS designed using fuzzy logic. The analysis focused on the system's performance under various load and generation circumstances. The investigation shows that even in the occurrence of power and load mismatches, the DC link voltage maintained constant. The comparative evaluation highlights the superior performance of the fuzzy logic-based energy management system (EMS) over the conventional PI controller-based EMS in ensuring DC link voltage stability under dynamic operating conditions. The fuzzy logic approach effectively minimizes voltage deviations to 2 V, whereas the PI controller exhibits significantly higher fluctuations of 15 V, potentially affecting system reliability. Additionally, the fuzzy-based EMS achieves rapid voltage restoration within 2 ms, demonstrating a 25-fold improvement over the PI controller's 50 ms recovery time. These results indicate that the fuzzy logic-based EMS is a more effective and adaptive control approach for HESS in microgrids. By offering enhanced voltage stability, quicker response to disturbances, and improved power quality, the fuzzy logic approach emerges as a more robust alternative to traditional PI-based controllers, making it well-suited for modern energy management applications. While the proposed fuzzy logic-based EMS has demonstrated significant improvements in voltage stability and dynamic response, there is potential for further enhancement. Future research can focus on integrating artificial intelligence (AI) and machine learning (ML) techniques to develop an adaptive and self-learning EMS capable of real-time optimization based on historical and predictive data. Additionally, the implementation of hybrid control strategies combining fuzzy logic with reinforcement learning or MPC can further improve system efficiency and resilience. Experimental authentication using hardware-in-the-loop (HIL) simulations and real-time microgrid implementations will also be essential to validate the effectiveness of the planned system in practical applications.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Suganthi Neelagiri	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Pasumarthi Usha		✓			✓				✓	✓				
Siddalingappagouda Biradar					✓				✓	✓				

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

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] R. M. Elavarasan *et al.*, "A comprehensive review on renewable energy development, challenges, and policies of leading indian states with an international perspective," *IEEE Access*, vol. 8, pp. 74432–74457, 2020, doi: 10.1109/ACCESS.2020.2988011.

[2] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, A. Yudhana, and M. Facta, "A review of recent advances on hybrid energy storage system for solar photovoltaics power generation," *IEEE Access*, vol. 10, pp. 42346–42364, 2022, doi: 10.1109/ACCESS.2022.3165798.

[3] S. Rehman, H. U. R. Habib, S. Wang, M. S. Buker, L. M. Alhems, and H. Z. Al Garni, "Optimal design and model predictive control of standalone HRES: A real case study for residential demand side management," *IEEE Access*, vol. 8, pp. 29767–29814, 2020, doi: 10.1109/ACCESS.2020.2972302.

[4] A. A. Khodadoost Arani, G. B. Gharehpetian, and M. Abedi, "A novel control method based on droop for cooperation of flywheel and battery energy storage systems in islanded microgrids," *IEEE Systems Journal*, vol. 14, no. 1, pp. 1080–1087, Mar. 2020, doi: 10.1109/JSYST.2019.2911160.

[5] X. Li *et al.*, "A unified control of super-capacitor system based on bi-directional DC-DC converter for power smoothing in DC microgrid," *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 3, pp. 938–949, 2023, doi: 10.35833/MPCE.2021.000549.

[6] V. F. Pires, A. Cordeiro, D. Foito, and J. F. A. Silva, "Dual output and high voltage gain DC-DC converter for PV and fuel cell generators connected to DC bipolar microgrids," *IEEE Access*, vol. 9, pp. 157124–157133, 2021, doi: 10.1109/ACCESS.2021.3122877.

[7] D. Hofer, J. Schmitt, A. McClung, N. Smith, and F. K. Bulnes, "Economic modeling of the application of battery and pumped thermal energy storage to self-contained microgrid on the southwest research institute campus," in *2024 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT)*, IEEE, Jan. 2024, doi: 10.1109/EESAT59125.2024.10471197.

[8] Y. Basheer, S. M. Qaisar, A. Waqar, F. Lateef, and A. Alzahrani, "Investigating the optimal DOD and battery technology for hybrid energy generation models in cement industry using HOMER pro," *IEEE Access*, vol. 11, pp. 81331–81347, 2023, doi: 10.1109/ACCESS.2023.3300228.

[9] I. N. Jiya, A. Salem, H. Van Khang, and R. Pomarnacki, "Integrated multiport DC-DC and multilevel converters for multiple renewable energy source integration," *IEEE Access*, vol. 11, pp. 132483–132495, 2023, doi: 10.1109/ACCESS.2023.3336567.

[10] M. I. Hossain, W. M. Hamanah, M. S. Alam, M. Shafiullah, and M. A. Abido, "Fault ride through and intermittency improvement of renewable energy integrated MMC-HVDC system employing flywheel energy storage," *IEEE Access*, vol. 11, pp. 50528–50546, 2023, doi: 10.1109/ACCESS.2023.3277968.

[11] M. Biglarahmadi, A. Ketabi, H. Reza Baghaee, and J. M. Guerrero, "Integrated nonlinear hierarchical control and management of hybrid AC/DC microgrids," *IEEE Systems Journal*, vol. 16, no. 1, pp. 902–913, Mar. 2022, doi: 10.1109/JSYST.2021.3050334.

[12] S. Augustine, M. K. Mishra, and N. Lakshminarasamma, "A unified control scheme for a standalone solar-PV low voltage DC microgrid system with HESS," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 2, pp. 1351–1360, Jun. 2020, doi: 10.1109/JESTPE.2019.2916421.

[13] A. Chirayarukil Raveendran and U. B. Manthati, "Dynamic power sharing assisted hybrid controller for PV fed isolated DC microgrid," *IEEE Systems Journal*, vol. 17, no. 1, pp. 1087–1097, Mar. 2023, doi: 10.1109/JSYST.2022.3195812.

[14] J. Alshehri, A. Alzahrani, and M. Khalid, "Voltage and frequency control of microgrids with distributed generations and battery energy storage," in *2019 8th International Conference on Renewable Energy Research and Applications (ICRERA)*, IEEE, Nov. 2019, pp. 381–385. doi: 10.1109/ICRERA47325.2019.8996929.

[15] A. F. Bastos, T. A. Nguyen, R. H. Byrne, and R. Weed, "Replacing transmission infrastructure with solar and energy storage systems: An islanded microgrid case study," in *2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, IEEE, Apr. 2022, pp. 1–5. doi: 10.1109/ISGT50606.2022.9817557.

[16] M. U. Mutarraf, Y. Terriche, K. A. Khan Niazi, C.-L. Su, J. C. Vasquez, and J. M. Guerrero, "Battery energy storage systems for mitigating fluctuations caused by pulse loads and propulsion motors in shipboard microgrids," in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*, IEEE, Jun. 2019, pp. 1047–1052. doi: 10.1109/ISIE.2019.8781182.

[17] P. J. Chauhan, B. D. Reddy, S. Bhandari, and S. K. Panda, "Battery energy storage for seamless transitions of wind generator in standalone microgrid," *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 69–77, Jan. 2019, doi: 10.1109/TIA.2018.2863662.

[18] S. Pradhan, B. Singh, and B. K. Panigrahi, "Adaptive position observer for multimode wind-BES based microgrid interfaced to distribution network," *IEEE Transactions on Industry Applications*, vol. 58, no. 4, pp. 5081–5092, 2022, doi: 10.1109/TIA.2022.3170003.

[19] V. Narayanan and B. Singh, "Seamless operation of an SRG based WEGS and a bidirectional converter interfaced BES microgrid under polluted grid conditions," *IEEE Transactions on Industry Applications*, vol. 59, no. 6, pp. 7744–56, 2023, doi: 10.1109/TIA.2023.3306741.

[20] X. Li and S. Wang, "A review on energy management, operation control and application methods for grid battery energy storage systems," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 1026–1040, Jun. 2019, doi: 10.17775/CSEEJPES.2019.00160.

[21] R. R. Deshmukh, M. S. Ballal, and H. M. Suryawanshi, "A fuzzy logic based supervisory control for power management in multibus DC microgrid," *IEEE Transactions on Industry Applications*, vol. 56, no. 6, pp. 6174–6185, Nov. 2020, doi: 10.1109/TIA.2020.3012415.

[22] X. Liu, Y. Suo, Z. Zhang, X. Song, and J. Zhou, "A new model predictive current control strategy for hybrid energy storage system considering the SOC of the supercapacitor," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 325–338, Feb. 2023, doi: 10.1109/JESTPE.2022.3159665.

[23] S. T. P. Srinivas and K. Shanti Swarup, "A new mixed integer linear programming formulation for protection relay coordination using disjunctive inequalities," *IEEE Power and Energy Technology Systems Journal*, vol. 6, no. 2, pp. 104–112, Jun. 2019, doi: 10.1109/JPETS.2019.2907320.

[24] L. Hammer and E. M. Veith, "Towards designing robust and resilient hybrid renewable energy systems," in *2022 IEEE International Conference on Power Systems and Electrical Technology (PSET)*, IEEE, 2022, pp. 376–382. doi: 10.1109/PSET56192.2022.10100405.

[25] V. Gopu and M. S. Nagaraj, “Islanded microgrid: hybrid energy resilience optimization,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 35, no. 2, p. 693, Aug. 2024, doi: 10.11591/ijeecs.v35.i2.pp693-703.
[26] T. Sutikno, A. C. Subrata, and A. Elkhateb, “Evaluation of fuzzy membership function effects for maximum power point tracking technique of photovoltaic system,” *IEEE Access*, vol. 9, pp. 109157–109165, 2021, doi: 10.1109/ACCESS.2021.3102050.
[27] J. Khodabakhsh and G. Moschopoulos, “Simplified hybrid AC–DC microgrid with a novel interlinking converter,” *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5023–5034, Sep. 2020, doi: 10.1109/TIA.2020.2996537.
[28] 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.
[29] C. Ali *et al.*, “An enhanced active disturbance rejection control scheme for DC voltage regulation in photovoltaic grid-connected four-leg inverter using a sliding mode observer,” *IEEE Access*, vol. 13, pp. 18623–18643, 2025, doi: 10.1109/ACCESS.2025.3533015.
[30] B. C, S. CK, S. NS, J. Sharma, and J. M. Guerrero, “Interval type2 fuzzy logic-based power sharing strategy for hybrid energy storage system in solar powered charging station,” *IEEE Transactions on Vehicular Technology*, vol. 70, no. 12, pp. 12450–12461, Dec. 2021, doi: 10.1109/TVT.2021.3122251.
[31] S. Neelagiri and P. Usha, “Energy management of PV wind based microgrid with hybrid energy storage systems,” *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 4, pp. 2128–2138, 2022, doi: 10.11591/ijpeds.v13.i4.pp2128-2138.

BIOGRAPHIES OF AUTHORS

Suganthi Neelagiri received the bachelor's degree in Electrical and Electronics Engineering from Bharathiyar University in 2001, the master's degree in Electrical Power and Energy System from Uttara Pradesh Technical University in 2013, and completed philosophy of doctorate degree in Electrical Engineering from Visvesvaraya University in October 2024, She is currently working as an Assistant Professor at the Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering. Her research areas include microgrid, renewable energy systems, energy storage systems. She can be contacted at email: suganthi_neelagiri@yahoo.com.

Pasumarthi Usha received the bachelor's degree in Electrical and Electronics from J.N.T.U, College of Engineering Kakinada in 1990, the master's degree in Power System with emphasis in High Voltage from J.N.T.U, College of Engineering Kakinada in 1992, and the Ph.D. in HVDC Power Transmission from Visvesvaraya Technical University in 2013, respectively. She is currently working as a Professor at the Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering. Her research areas HVDC power systems, microgrid, and power electronics. She can be contacted at email: pu1968@yahoo.co.in.

Dr. Siddalingappagouda Biradar is currently working as an associate professor in the Department of Electronics and Communication Engineering, Dayananda Sagar Academy of Technology and Management, Bangalore. He has completed 12 years of Teaching Experience, previously, he was working at Don Bosco Institute of Technology, Bangalore, 2011-2019. He earned his BE [Electronics & Communication Engg.] from B.L.D.E. A’s Dr. P. G Halakatti College of Engineering & Technology, Vijaypura in 2007, M.Tech. [DC&N] from KLS Gogte Institute of Technology, Belagavi in 2011, and Ph.D. from Visvesvaraya Technological University (VTU), Belagavi in 2019, pursuing post-doctoral fellowship in 5G and 6G Technologies from Srinivas University, 2022 respectively. He has published more than 30 research articles in international conference proceedings and journals, and was awarded with best paper. He can be contacted at email: s.biradar-ece@dsatm.edu.in.