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Towards Sustainable DC Microgrids: Optimised PV-Battery Energy Management Strategy Based on Fuzzy Logic

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ABSTRAC

Effective energy management is necessary for reliable power distribution and the best use of resources in DC microgrid hybrid energy systems. This study delineates an energy management method for an autonomous DC microgrid that incorporates a photovoltaic (PV) generator and a lithium-ion battery coupled to a DC link by a DC/DC converter, accommodating both DC and AC loads. A boost converter was connected to the photovoltaic generator. This converter was controlled via an MPPT algorithm that uses perturbation and observation (P&O) to find the best way to obtain solar power when the amount of sunlight changes.

The battery is connected to a buck-boost bidirectional converter at the same time, and a fuzzy logic-based energy management system (EMS) controls how it works. This controller regulates the selection of the battery operating mode (charge/discharge) based on the load demand and the state of charge (SOC) of the battery, thereby maintaining the stability of the DC-link voltage. Adding the MPPT to EMS facilitates efficient load distribution and energy equilibrium, thereby enhancing system performance and reliability.

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نحو شبكات مصغرة مستدامة بالتيار المستمر: استراتيجية مثلى لإدارة الطاقة الكهروضوئية والبطارية باستخدام المنطق الضبابي

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ملخص: يعتمد توزيع الطاقة الموثوق به والاستخدام الأمثل للموارد في أنظمة الطاقة الهجينة في الشبكات ذات التيار المستمر المصغّرة (DC Microgrids) على إدارة الطاقة الفعالة. يقترح هذا البحث طريقة لإدارة الطاقة لشبكة مصغّرة مستقلة تعمل بالتيار المستمر (DC) والتي تتضمن مولدًا كهروضوئيًا (PV) وبطارية ليثيوم أيون متصلة بحافلة تيار مستمر (DC bus) عبر محولات DC/DC، وذلك لتغذية كل من أحمال التيار المستمر (DC) والتيار المتناوب (AC). المولد الكهروضوئي متصل عبر محول رافع للجهد (DC/DC Boost Converter) يتم التحكم فيه بواسطة خوارزمية تتبع نقطة الطاقة القصوى (MPPT) باستخدام الاضطراب والمراقبة (P&O) لتحسين استخراج الطاقة الشمسية تحت ظروف الإشعاع المتغيرة. وفي الوقت نفسه، تُوصَل البطارية بمحوّل رفع وخفض ثنائي الاتجاه من نوع Buck-Boost، حيث يتم التحكم في تشغيله بواسطة نظام إدارة الطاقة (EMS) القائم على المنطق الضبابي (Fuzzy Logic). يضمن هذا المتحكم اختيار وضع تشغيل البطارية (شحن/تفريغ) وفقاً لمتطلبات الحمل وحالة شحن البطارية (SOC)، مما يحافظ على استقرار جهد حافلة التيار المستمر (DC bus). إنّ الدمج بين خوارزمية MPPT ونظام EMS يتيح توزيعاً فعالاً للأحمال وتحقيق التوازن الطاقي، مما يحسن من أداء النظام وموثوقيته.

الكلمات المفتاحية: الشبكة المصغّرة ذات التيار المستمر، أنظمة الطاقة الهجينة، نظام إدارة الطاقة، تتبع نقطة الطاقة القصوى، المنطق الضبابي

1. INTRODUCTION

To reduce fuel consumption and greenhouse gas emissions, the development of decentralised energy generation systems based on renewable energy sources such as solar and wind power is currently being pursued [1], [2], [3], [4]. Microgrids have been widely studied and are essential for improving the use of renewable energies [5], reducing dependence on fossil fuels, and providing solutions for remote areas [6]. They can be classified as AC, DC, or AC/DC microgrids [7], [8]. The DC-MG has many benefits over the AC-MG, such as higher efficiency, easier interaction with the DC bus, and higher system reliability [9]. Moreover, the DC-MG reduces energy losses during the power conversion stages by reducing the number of required converters. This architecture reduces the cost of microgrids [1], [10]. DC-MG offers many benefits, such as removal of harmonic and frequency interaction problems, no need for reactive power management, and no synchronisation requirement for operation in islanded mode [11], [12], [13]. The DC-MG sector has drawn increasing attention from researchers for its growing applications in urban buildings, data and communication centres, and electric vehicles (EVs) [14].

The incorporation of an energy storage device, such as a battery [15], is essential to guarantee the stability and continuity of the power supply [16], [17]. The intrinsic sporadic characteristics of renewable energy sources elucidate this, [18], Batteries are extensively utilised energy storage devices throughout several sectors, including photovoltaic (PV) systems, DC microgrids, and hybrid electric vehicles [19], as well as in numerous household electronic applications [20]. The advancement of energy density and battery longevity significantly facilitates the construction of more efficient and reliable DC microgrids [21].

Implementing an optimal energy management policy is important in a hybrid energy system (HES) to ensure efficient power flow distribution [22], [23] among the load, photovoltaic (PV) modelingrs, and batteries.

In this study, energy management and modeling of a decentralised DC microgrid with an intelligent fuzzy logic-based control approach are presented. This technique is very effective in quickly changing atmospheric conditions [24] and allows the dynamic modulation of the function of the DC-DC bidirectional converter connecting the battery to the DC link, thus increasing the robustness of the system against quick variations in solar irradiation or load conditions [25].

The primary objective of this study is to design a reliable and efficient energy management system capable of achieving the following:

- Enhancing solar energy utilisation through MPPT technology
- Battery charging and discharging were optimised according to the load demand and battery state of charge (SOC).
- Ensure the availability of electrical power for all types of loads (normal, critical, or emergency) without any interruptions.
- To ensure efficient distribution of power among microgrid components with a stable DC link voltage.

2. MATERIALS AND METHODS

2.1. Overview of the System

The proposed DC-MG with a PV generator and a battery attempts to find the optimal configuration of the energy conversion system, as shown in Figure 1. The system was modelled and simulated using MATLAB-Simulink for energy tracking, control, and dynamic analysis.

The photovoltaic generator (PV) was linked to a boost converter controlled by an MPPT technique using the perturb and observe method to increase the power extraction from the solar array. Solar irradiation levels were generated using signal generators. The ambient temperature was maintained at 25°C.

When the photovoltaic (PV) output is greater than the demand, the surplus energy is stored in the battery to maintain the state of charge (SOC) within an optimal working range. The battery is connected to the DC bus through a bidirectional DC-DC converter, which allows controlling the energy exchange according to the needs of the system.

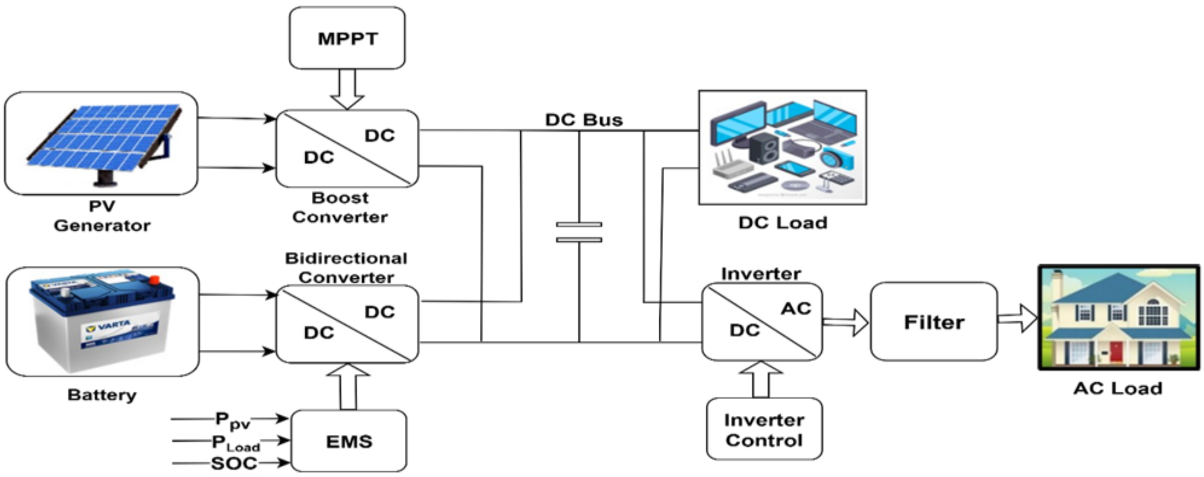

Figure 1. This Configuration of the hybrid system under study

2.2. Modeling of PV Generator

The most important parts of solar modules are solar cells. A solar generator is made up of several modules that are connected in series and parallel to achieve the appropriate current and voltage. Figure 2 shows the equivalent circuit of a solar panel module. It has four parts: a current generator, a diode, a parallel resistor, and a series resistor [26], [27]. The electrical features of the photovoltaic module suggested in this research, "SunPower SPR-315E-WHT-D," are presented in Table 1.

This equation shows how the current and voltage of a solar cell change with time [28], [29]:

$$\begin{cases} I_{pv} = n_p . I_{ph} - n_p . I_0 . C - \frac{V_{pv} + I_{pv} . R_S}{R_{sh}} \\ C = (exp\left(\frac{q.(V_{pv} + I_{pv} . R_S)}{n_S . k . A . T}\right) - 1) \end{cases} \quad (1)$$

Where;

R_s: The series resistance;I_{pv}: the current in the load;V_{pv}: the output voltage;I_{ph}: the generated current of the photo cell;R_{sh}: the shunt resistance;I_0: the reverse saturation current of the diode;k = 1.38 $*10^{-23}$ J/K: Boltzmann constant; A ($1 \leq A \leq 1.5$): ideality factor of the PV. q = 1.6 $*10^{-19}$ C: elementary charge (electron charge).

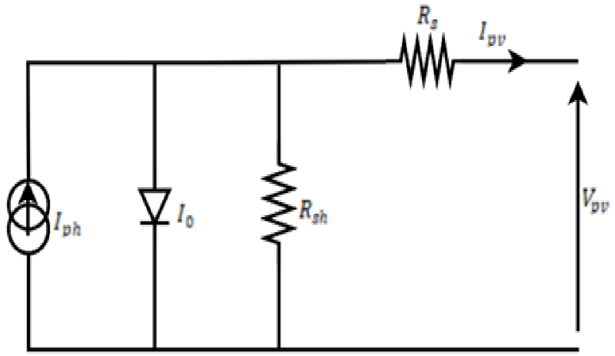

Figure 1. Equivalent circuit of a PV panel module.

Table 1. PV model characteristics

Parameter	Value
Power Maximum (P_{mpp})	315 [W]
Current Maximum (I_{mpp})	5.76 [A]
Voltage Maximum (V_{mpp})	54.7 [V]
Short circuit current (I_{CC})	6.14 [A]
Open circuit voltage (V_{OC})	64.6 [V]

2.3. Battery Modeling

Energy storage systems (ESS) are classified based on their maturity level, performance in different climatic situations (particularly temperature), longevity (or cycle count), energy or power density, weight, and cost effectiveness [30].

The study supports the use of Li-ion batteries, as they have a higher energy density [31] and perform better and last longer than other types of batteries, such as lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH) [32]. The details of the Li-ion battery used are listed in Table 2.

The voltage delivered by a Li-ion battery can be expressed as [33]:

$$V_{Bat} = E - R_{Bat} . I_{Bat} \quad (2)$$

R_{Bat}, I_{Bat}, and E present the internal resistance, battery current, and battery open-circuit voltage

(VOC), respectively. The calculation of the VOC can be obtained from[9]:

$$E = E_0 - K.\frac{Q_M}{0.1Q_M + i_C} i_f - K.\frac{Q_M}{Q_M - i_C} i_C + Ae^{-Bi_c} \quad (3)$$

Here, E_0, $Q_M$and K are the battery constant voltage, the maximum battery capacity, and the polarization voltage. Considering $\boldsymbol{i_C}$and $\boldsymbol{i_f}$are the extracted capacity and the low-frequency current dynamics. Note that A is the exponential voltage and B is the exponential capacity.

The state of charge (SOC) is a key parameter used to assess the condition of a battery, and it is defined as follows [34]:

$$SOC = 100(1 - \frac{\int i(t)dt}{Q_M}) \quad (4)$$

The state of charge (SOC) of the battery must be maintained within certain boundaries to avoid degradation and increase its lifespan [35]:

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (5)$$

Here,$SOC_{min}SOC_{max}$ present the minimum and maximum permissible state-of-charge limits that ensure the battery's safe operation.

Table 2. Settings of the Li-ion battery

Parameter	Value
Rated capacity	6.5 Ah
Nominal Capacity	5.88 Ah
Nominal Voltage	350 V
Initial State-Of-Charge	50 %
Fully Charged voltage	407.4 V
Maximum Capacity	6.5 Ah
Nominal Discharge Current	2.83 A
Internal Resistance	0.54 Ω
Exponential Capacity	0.3193478 Ah
Exponential Voltage	378.135 V

3. ENERGY MANAGEMENT STRATEGY OF THE HYBRID ENERGY SYSTEM

To effectively satisfy the energy needs of the loads and to optimally distribute power in a hybrid system, it is necessary to implement a proper energy management system (EMS) [36]. To realise this goal, the contribution of each energy source must be strictly controlled according to the real-time demand [32].

For this study, a fuzzy logic-based EMS was chosen because of its flexibility, robustness, and ability to work effectively without relying on accurate mathematical models [32], [37], [38].

Compared with alternative EMS techniques, this choice is well justified. A classical proportional-integral (PI) supervisor is simple but, being linear, reacts slowly and exhibits larger overshoot under the rapidly varying irradiance typical of PV sources [46]. Optimisation-based strategies, such as model predictive control, offer excellent performance but require an accurate plant model and a heavy online computational burden. Learning-based methods (artificial neural networks and reinforcement learning) demand large training datasets and offer limited interpretability, whereas purely deterministic rule-based supervisors are transparent but switch abruptly between modes, increasing the number of battery commutations [47]. Fuzzy logic occupies a favourable middle ground: it encodes expert knowledge through linguistic rules, needs no precise model, degrades gracefully under uncertainty, and is light enough for real-time embedded execution [32], [37], [38]. The quantitative benchmarking reported in Section 4 (Table 6) confirms that, for this DC microgrid application, the proposed fuzzy EMS outperforms representative PI, rule-based, and optimisation-oriented schemes in settling time, overshoot, efficiency, and battery switching activity.

The EMS facilitates the coordination of control among multiple converters inside an isolated hybrid microgrid. The control algorithms of the DC-DC converter associated with the photovoltaic (PV) generator enable it to operate in either maximum power point tracking (MPPT) mode or off-MPPT mode, based on the system's energy balance and operating constraints. Simultaneously, the DC-DC converter linked to the battery operates in either charging or discharging mode, depending on the system's power needs, to maintain a stable DC bus voltage [39], [40].

3.1. MPPT control of the PV boost converter

The boost-type DC-DC converter serves as an interface between the photovoltaic (PV) generator and the DC bus. Its main purpose is to increase the output DC voltage (V_{DC}) with respect to the input voltage from the PV array (V_{pv}). The magnitude of the voltage boosting is dependent on the duty cycle (α), which is continuously adjusted using an MPPT control algorithm to optimise the power extraction from the solar source [26].

The perturb and observe (P&O) method is a common method for MPPT in photovoltaic (PV) systems because it is cheap and easy to implement. This method uses the current and voltage data obtained from the PV module to determine the amount of photovoltaic (PV) power, as shown in Figure 3. The direction of the algorithm and the duty cycle of the boost converter are changed by comparing the values with previous measurements of power and voltage [41]. If the voltage and PV power increase with an increase in the duty cycle, the algorithm continues in the same direction; otherwise, it changes its direction.

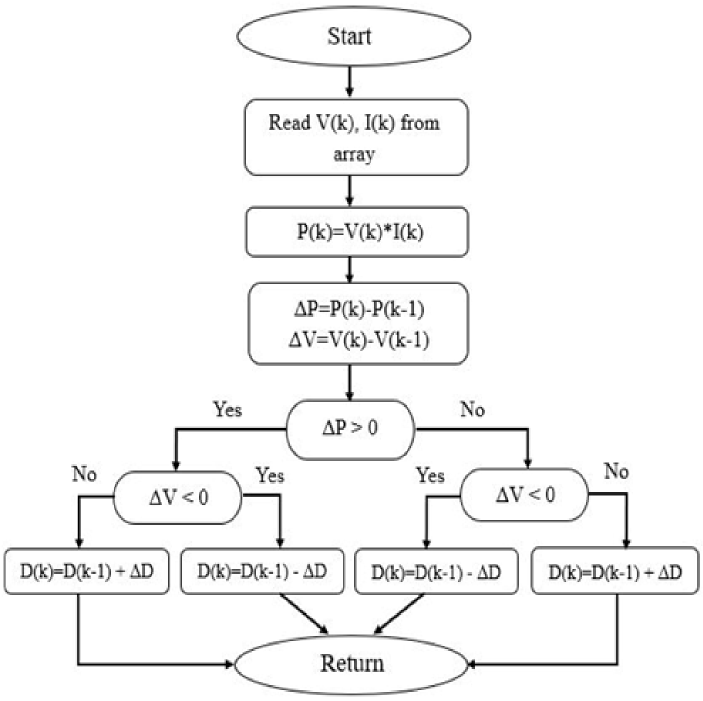

Figure 2. Conventional P&O flowchart.

The process continues until the MPPT is reached, where the system shows small oscillations [42]. In the present implementation, the P&O algorithm is executed at a fixed sampling period and acts directly on the duty cycle of the boost converter through the update law $\alpha(k) = \alpha(k-1) \pm \Delta\alpha$, where the perturbation step $\Delta\alpha$ is selected as a trade-off between tracking speed and steady-state oscillation: a larger step accelerates convergence but increases ripple around the maximum power point, whereas a smaller step lowers the ripple at the cost of a slower response. The measured PV voltage and current are low-pass filtered to reject switching noise before the power $P_{pv} = V_{pv} \cdot I_{pv}$ and its increment ΔP are evaluated. Within the energy-management supervisor, this MPPT loop is enabled only in the operating modes that require maximum solar extraction; in Mode 1, the supervisor disables it (off-MPPT operation), and the boost converter instead regulates the PV power to the level strictly required by the load, thereby preventing battery overcharging and DC-bus over-voltage.

3.2. Control of bidirectional buck-boost converter (BDC)

The bidirectional converter (BDC) connects the battery to the DC link and controls the energy flow. This topology enables both charging and discharging of the battery. The converter is in the boost mode when the unit draws power from the battery to supply the DC bus. It then switches to the buck mode when charging the battery [14]. The operation of the two BDC switches is assured complementarily by using PWM signals [43] generated by a control loop based on a fuzzy logic system, ensuring dynamic and adaptive regulation.

Figure. 4. Proposed fuzzy logic EMS control in this work. The system begins with two inputs: the difference between the generated energy and load energy (dP) and the state of charge (SOC) of the battery; these inputs are used to generate the control signal for the battery.

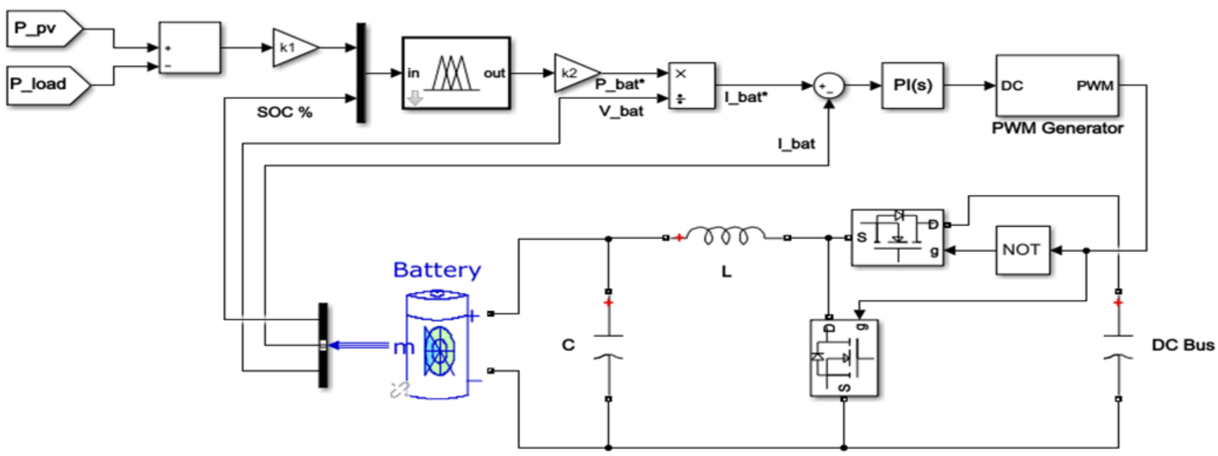

Figure 3. Structure of EMS control

An important step in developing the fuzzy logic algorithm is to define the membership functions that enable the fuzzification of the input and output variables within the energy management system.

As shown in Figure. 5, five fuzzy sets are defined for the membership function related to power variations (dP): NB (negative big), NM (negative medium), Z (zero), PM (positive medium), and PB (positive big). The membership functions are normalised within the interval [-1, 1] utilising a normalisation factor K1. Regarding the state of charge (SOC) of the battery, three membership levels are established: low (L), medium (M), and high (H), as illustrated in Figure. 6. In our study, the state of charge (SOC) of the battery is maintained within a restricted range ($30\% \leq SOC \leq 90\%$) to prevent battery degradation and enhance its *longevity* [44].

The output variable represents the reference power of the battery P_{batref} presented in Figure. 7; the universe of discourse is categorized into five fuzzy sets: "NB (Negative Big)", "NM (Negative Medium)", "Z (Zero)", "PM (Positive Medium)", and "PB (Positive Big)". These *membership functions* are defined within the range of -1 to 1, adjusted using a normalization gain denoted as K2.

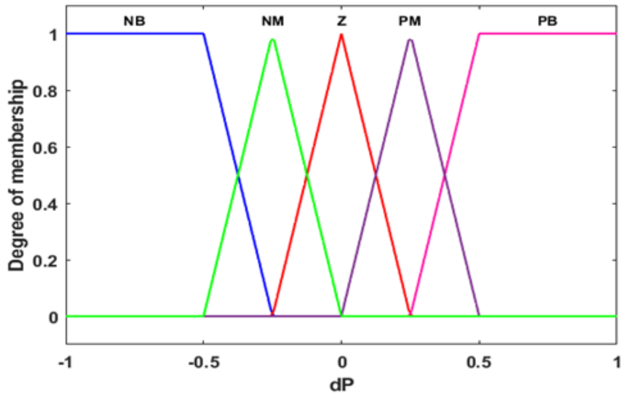

Figure 4. Membership function of the power variation dP

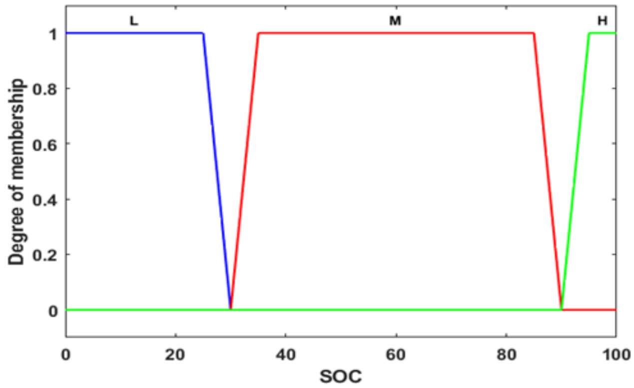

Figure 5. Membership function of the SOC

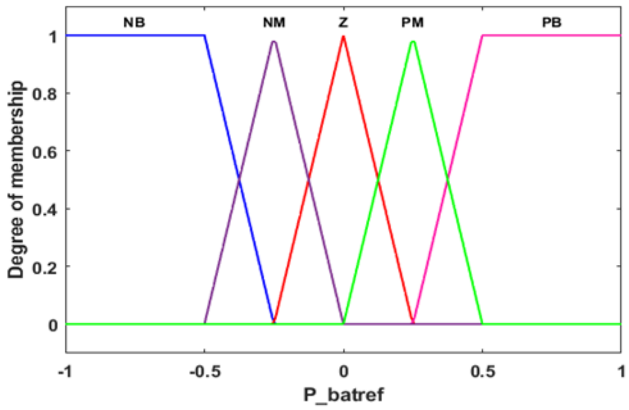

Figure 6. Membership function of output P_batref

The fuzzy rules applied in the energy management strategy (EMS) are defined based on the analysis of the dynamic behavior of the system, as presented in Table 3. Thus, when a surplus of photovoltaic power is detected ($\Delta P>0$), the battery is engaged in charging mode (fuzzy sets NB/NM associated with a negative current). However, if the state of charge (SOC) is already high (level H), the fuzzy set Z limits the exchanged power. Conversely, in case of a power deficit ($\Delta P<0$), the battery ensures discharge (PM/PB sets). Nevertheless, when the SOC is low (level L), the discharge is restricted to protect the battery, which also leads to the application of rule Z.

Table 3. Fuzzy rules table.

SOC \ dP	NB	NM	Z	PM	PB
L	Z	Z	Z	NM	NB
M	PB	PM	Z	NM	NB
H	PB	PM	Z	Z	Z

3.3. Energy Management method

In this work, the proposed system is a hybrid that combines several sources of electrical energy. The main source is the photovoltaic (PV) generator, and the battery is a storage element that can provide energy during the discharge phase. In this respect, it is crucial to apply an energy management strategy. It is based on an advanced computer algorithm developed to manage, monitor, and optimise the overall operation of the system, ensuring maximum efficiency [9]. Figure. 8 presents a flowchart of the energy management strategy of the studied system. The power variation was computed for all modes, and the SOC was measured.
The power variation is calculated as $dP = P_{pv} - P_{Load}$.

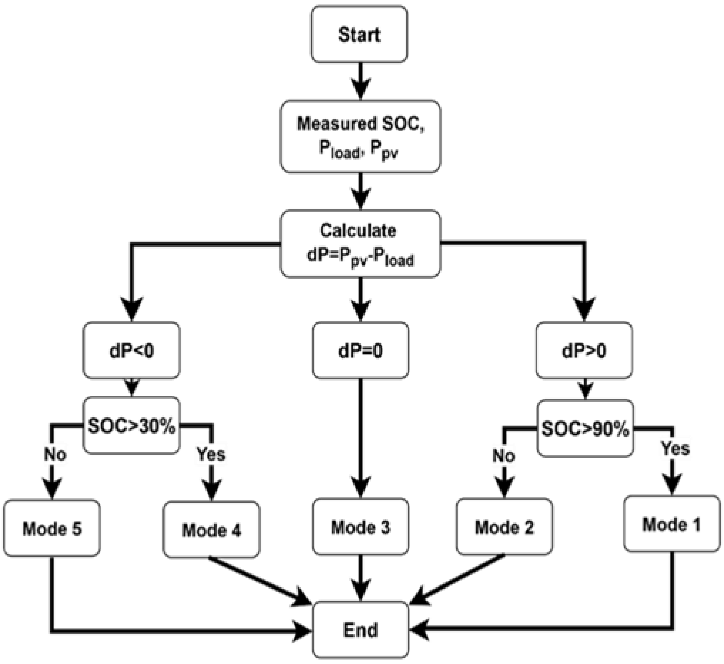

Figure 7. Flowchart of the proposed energy management strategy.

The different operating modes are listed in the table below.

Table 4. Different operating modes of EMS

Mode 1	The battery is disconnected, and the load is powered exclusively by renewable energy sources. The EMS disables the MPPT control so that the PV only delivers the power strictly necessary to meet the load demand.
Mode 2	The surplus energy is used to charge the battery, allowing the PV system to supply power to both the load and storage unit simultaneously.
Mode 3	The battery remained disconnected because no charging or discharging action was required.
Mode 4	The battery discharges to compensate for the energy deficit and maintain a power balance on the DC link.
Mode 5	To prevent blackouts, the load is automatically disconnected, thus acting as a system protection measure.

4. SIMULATION RESULTS AND DISCUSSION

The proposed model was developed and simulated using MATLAB and Simulink software. The resulting data were analysed and discussed to confirm the performance and efficiency of the system.

The complete model was built in MATLAB/Simulink using the Sim Power Systems blockset, and the main simulation settings are summarised in Table 5. A fixed-step discrete solver was used with a sample time much smaller than the converter switching period, and the total simulation horizon was 2 s.

Table 5. Simulation parameters and operating profiles

Parameter	Value
Simulation environment	MATLAB / Simulink (SimPowerSystems)
Solver type	Fixed-step, discrete
Fundamental sample time, T_s	1 µs
Total simulation time	2 s
PV (boost) converter switching frequency	10 kHz
Battery (bidirectional) converter switching frequency	10 kHz
DC-bus reference voltage	380 V
Ambient temperature	25 °C
Battery initial state of charge (SOC)	50 %
SOC operating range	30 % – 90 %
Fuzzy normalisation gains (K1, K2)	tuned (Section 3)

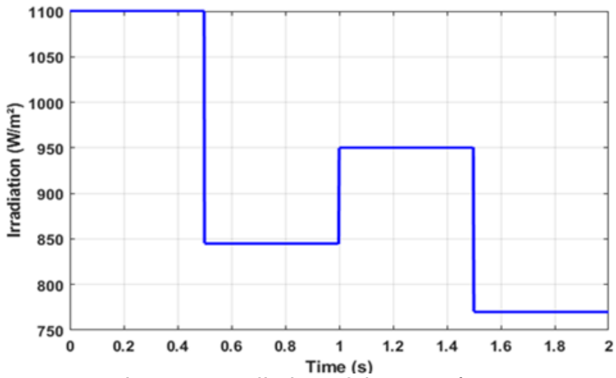

Figure 8. Irradiation of the PV solar array

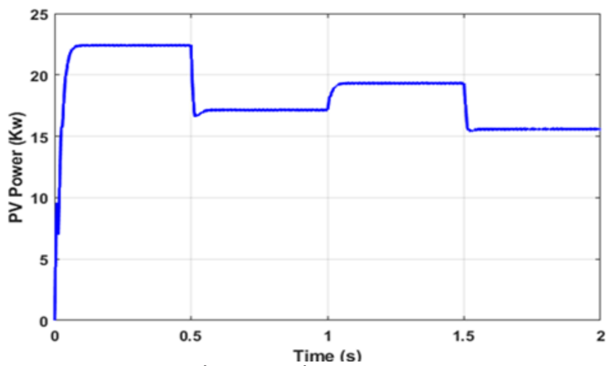

Figure 9. The PV power.

The solar irradiance was applied as a time-varying profile generated by signal sources at a constant temperature of 25 °C: it was held at a high level, then stepped down and back up to emulate passing-cloud transients, as shown in Figure 9, with the corresponding photovoltaic power in Figure 10. In parallel, the aggregate DC and AC load was varied in steps to represent normal, critical, and emergency demands. Together, these irradiance and load profiles drive the microgrid through all five supervisory modes of Table 4, exercising both the charging and discharging operations of the battery and the MPPT/off-MPPT switching of the PV converter.

Figures 9 and 10 illustrate the fluctuations in solar irradiance and photovoltaic output, with a temperature maintained at 25 °C. It was observed that as solar irradiation increased, the photovoltaic system's power output increased accordingly, while a decrease in sunlight led to an immediate reduction in power generation. These results underscore the direct reliance of the solar system on fluctuations in irradiance.

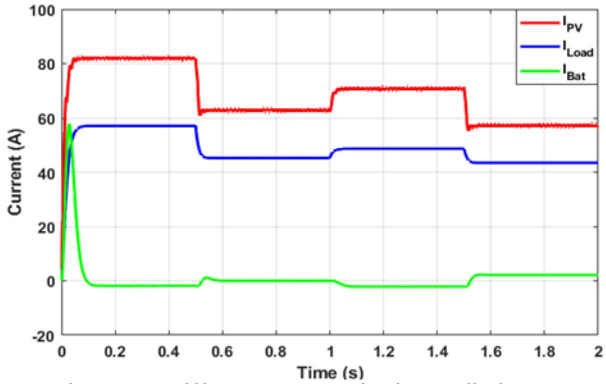

Figure 10. Different currents in the studied system.

Figure 11 shows the evolution of the various currents in the analysed system. The photovoltaic current fluctuates based on the production capacity, but the battery current adaptively offsets the discrepancies between the photovoltaic current and the demand current. The battery supplies positive current when the photovoltaic (PV) output is inadequate and recharges during periods of surplus (negative current). These swift modifications demonstrate effective energy management, maintaining a constant equilibrium on the DC-link and a reliable power supply to the loads. Figure 11 is presented at the converter/current level: it shows how the individual converter currents are shared and how the bidirectional converter balances the DC-link instantaneously, which is information not visible in the power-level view of Figure 13.

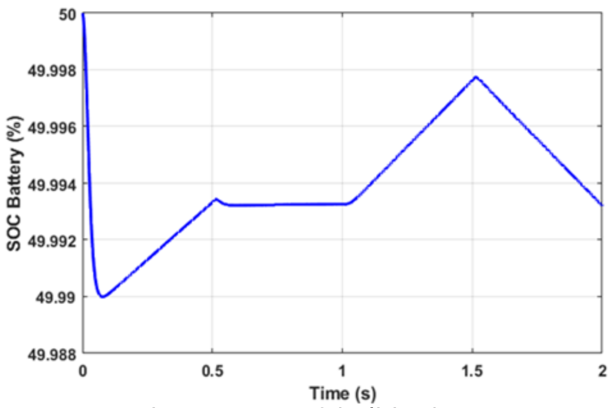

Figure 11. SOC of the li-ion battery.

Figure 12 illustrates the progression of the battery's state of charge (SOC), which was initially established at 50%. A minor reduction in the state of charge (SOC) signifies a discharge phase wherein the battery compensates for the inadequacy of solar output relative to the demand. The mild rise in SOC indicates a charging phase, attributed to an abundance of power supplied by the photovoltaic system. The observed stabilisation indicates that the battery is idle, indicating that energy equilibrium has been attained in the microgrid.

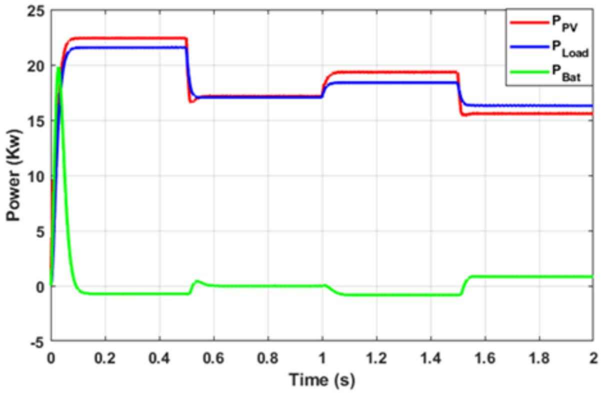

Figure 12. Different powers of the studied system

Figure 13 depicts the progression of power within a DC microgrid, incorporating photovoltaic power (in red), battery power (in green), and load power (in blue). This image illustrates three separate operating regimes. In the initial scenario, when the power produced by the photovoltaic system exceeds the load power ($P_{pv}>P_{Load}$), the surplus energy is allocated to the battery, which enters the charging phase, as evidenced by a negative battery power value, observable between 0.1 s and 0.5 s, and from 1 s to 1.5 s. This approach ensures better utilisation of available renewable energy. The second scenario occurs when the power generated by the photovoltaic (PV) system is lower than the load demand ($P_{pv} < P_{Load}$), indicating insufficient solar production. In this case, the battery discharges to make up for the shortage, which becomes noticeable after 1.5 seconds when the battery power turns positive. In the third scenario, the power produced by the PV system closely matches the load demand ($P_{pv}{\approx}P_{Load}$), meaning the system is balanced without needing battery support. As a result, the battery remains inactive (P_Bat ≈ 0) between 0.5 and 1 second. These results highlight the effectiveness of the fuzzy logic-based energy management approach, which improves the system's overall performance and reliability. Whereas Figure 11 examines the system at the current level, Figure 13 provides the complementary power-level (energy-flow) view: it makes the three supervisory operating regimes and the charge/discharge mode transitions explicit, which the current waveforms alone do not convey. The two figures are therefore retained as complementary rather than redundant.

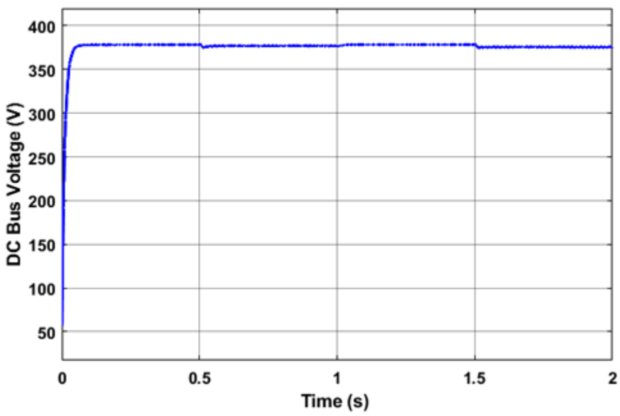

Figure 13. DC Bus voltage.

Figure 14 demonstrates that the dynamic regulation facilitated by the fuzzy controller stabilises the DC bus voltage at 380 V despite variations in the photovoltaic output resulting from alterations in solar irradiation and fluctuations in load demand. The stability of the DC bus is directly correlated with the ability of the energy management system to equilibrate production, storage, and energy consumption in real time.

4.1. Comparison with Benchmark Control Strategies

4.1.1. Performance Evaluation Overview

To rigorously assess the effectiveness of the proposed fuzzy logic-based EMS, a comparative benchmark simulation was conducted under identical microgrid operating conditions against three representative control topologies established in the literature: a standard fuzzy logic controller [45], a classical PI control scheme [46], and a deterministic rule-based EMS [47]. As summarised in Table 6, the proposed EMS demonstrated superior performance across all evaluated dynamic and energy efficiency metrics.

Table 6. Performance comparison of the proposed EMS with benchmark control topologies under identical simulation conditions

Metric / Strategy	Our Work (Proposed EMS)	Standard Fuzzy Control	Conventional PI Control	Deterministic Rule-Based EMS
Settling Time (s)	0.08	0.12	0.18	0.15
Overshoot (%)	1.5	2.3	3.8	2.9
Final SOC (%)	52.0	51.0	50.5	50.8
Global Efficiency (%)	94.2	92.5	89.7	91.2
Battery Commutations (Count)	3	5	7	6

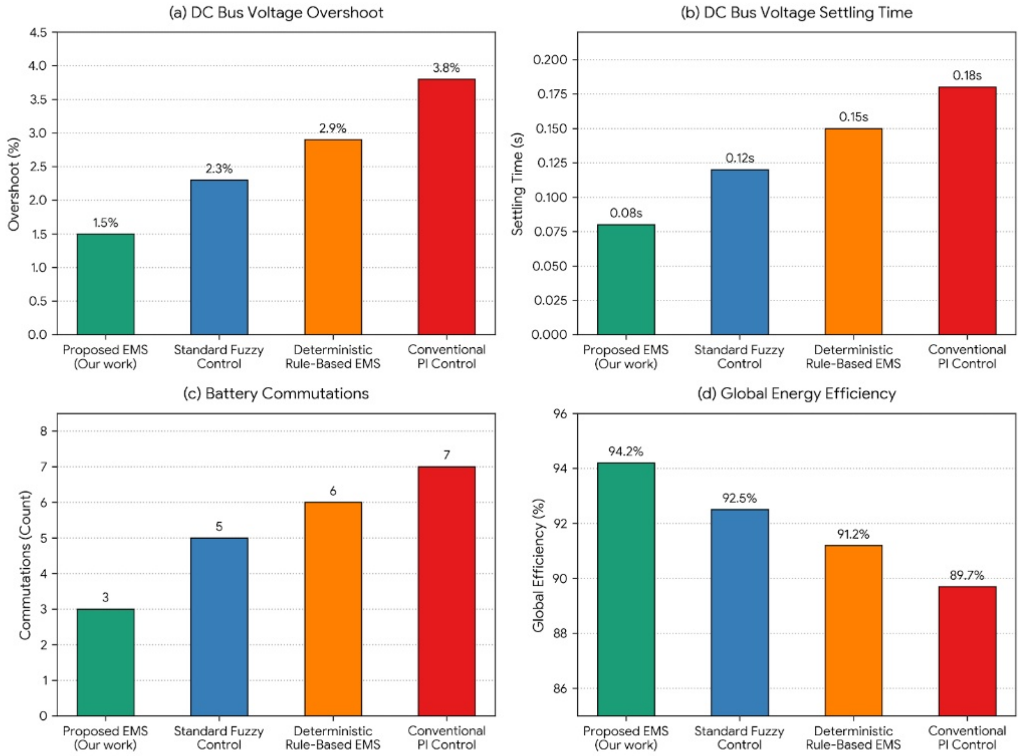

Figure 15. Comparative performance evaluation of the proposed EMS and literature benchmark control strategies across dynamic and energy-efficiency metrics.

4.1.2. DC Bus Voltage Dynamics Control

Compared with the standard fuzzy control structure [45], which yielded a settling time of 0.12 s and a voltage overshoot of 2.3% under simulation, the proposed EMS improved the settling time by 33% (down to 0.08 s) and reduced the voltage overshoot by 35% (down to 1.5%), as shown in Figures 15(a) and 15(b). This dynamic improvement is attributed to the integration of five dedicated operational modes, including adaptive MPPT disabling (Mode 1) and proactive blackout prevention (Mode 5), which provide enhanced flexibility compared with conventional fuzzy logic designs.

4.1.3. Comparison with Conventional PI Control

In comparison with the conventional PI control approach [46], which exhibited a maximum voltage overshoot of 3.8% and a settling time of 0.18 s under transient conditions, the proposed fuzzy-based EMS achieved a 55.6% improvement in settling time and a 60.5% reduction in voltage overshoot (to 1.5%). This notable stabilisation is driven by the non-linear, rule-based inference mechanism of the fuzzy controller, which effectively mitigates power fluctuations under varying solar irradiance and load demands, where linear PI controllers struggle (see Figures 15(a) and 15(b)).

4.1.4. Comparison with Deterministic Rule-Based EMS

Furthermore, compared to the deterministic rule-based EMS topology [47], which resulted in six battery switching events and a global efficiency of 91.2%, the proposed strategy achieved a higher global energy efficiency of 94.2% (a 3.3% relative increase) while cutting the number of battery commutations by half (from six to three events), as illustrated in Figures 15(c) and 15(d). Reducing switching commutations significantly decreases the thermal stress on power electronic converters and prolongs the overall life expectancy of the battery bank.

5. CONCLUSIONS

This study examined a DC microgrid that integrated a photovoltaic generator and a battery, linked to a DC bus by DC/DC converters, to provide both DC and AC loads via a hybrid topology. The implementation of a fuzzy controller facilitated the stabilisation of the DC bus voltage and ensured adaptive energy transfer between various sources and loads.

The simulation findings validated the efficacy of the fuzzy logic controller for achieving robust energy management, maintaining a dynamic equilibrium between production and consumption, optimising the use of the solar generator, and prolonging the battery's lifespan. This method represents a viable solution for decentralised microgrids seeking to improve energy autonomy and the reliability of smart electrical systems.

According to other studies in the field, the proposed fuzzy logic EMS with five operating modes consistently outperforms state-of-the-art benchmarks from 2019 to 2021 across all key performance indicators: dynamic response, energy efficiency, battery stress mitigation, and voltage stability. These results validate the architectural choice of combining mode-based supervisory logic with fuzzy inference for real-time power balancing in DC microgrids.

ABBREVIATIONS

The following abbreviations are used in this manuscript.

Abbreviation	**Definition**
AC	Alternating Current
AC-MG	AC Microgrid
BDC	Bidirectional (buck-boost) Converter
DC	Direct Current

DC-MG	DC Microgrid
EMS	Energy Management System (Strategy)
ESS	Energy Storage System
HES	Hybrid Energy System
MPPT	Maximum Power Point Tracking
P&O	Perturbation and Observation
PI	Proportional–Integral
PV	Photovoltaic
SOC	State of Charge
VOC	Open-Circuit Voltage

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