IJRCS
International Journal of Robotics and Control Systems
Vol. 5, No. 6, 2025, pp. 2853-2872
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs
ASCEE

Advanced Fuzzy Logic for Enhanced Energy Management and MPPT in High-Performance Hybrid Renewable Microgrids

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ARTICLE INFO

Article history
Received October 28, 2025
Revised November 28, 2025
Accepted December 03, 2025

Keywords
Sustainable development;
Energy management system;
Fuzzy controller;
Optimization techniques;
MPPT

ABSTRACT

Renewable sources such as PV and WE are increasingly integrated into MGs, which rely on efficient EMSs and MPPT techniques for stable operation. This paper proposes an FLC-MPPT integrated within an EMS for a hybrid clean energy system comprising PV, WE, FC, battery, and EV units. The system architecture is modeled and simulated in MATLAB/Simulink, with the FLC regulating power flow and maintaining DC bus stability through coordinated converter control. The proposed approach is compared with the conventional P&O algorithm under varying irradiance, shading, and load conditions. Simulation results show that the FLC-MPPT consistently achieves higher efficiency (up to 99.99%), faster response times (as low as 0.003 s), and significantly lower power losses (reduced from 6.975 W to 1 W at 1000 W/m²). During dynamic scenarios, including partial shading and a 50% load increase, the FLC maintains a stable DC voltage (≈275 V) with rapid recovery times of 9–13 s. Furthermore, THD remains below 1.52% across all operating conditions, indicating high power quality. Overall, the proposed FLC-based EMS enhances hydrogen utilization, system efficiency, and stability, demonstrating superior adaptability and precision over conventional methods for clean and reliable energy management in hybrid MG applications.

1. Introduction

FF pollution, inflation, and adverse ecological effects from traditional PS generators have made the global transition to CE imperative. CESs like PV and WE are becoming more popular due to concerns about carbon emissions and climate change. The majority of conventional generators are predicted to be replaced via CESs by 2050, promoting the decentralization of PS and DESs [1]–[3]. PV systems' availability, sustainability, and cheap operating costs draw significant international investment. However, as T and G change, so does their output. PV systems can be IM or GC, with either option needing ESUs for consistent performance under low or no G [4], [5]. By stowing extra energy and releasing it during periods of high demand, ESUs provide high capacity, quick response, and effective ramp-rate management. Because of the nonlinear behavior of both PV arrays and ESUs, effective ESU charging is essential to system reliability and presents a technical challenge. Adaptive

https://dx.doi.org/10.31763/ijrcs.v5i6.2314

control techniques are necessary to preserve battery health because of this complexity. MPPT controllers are crucial for MP extraction under various circumstances in order to further increase efficacy [6]–[8].

MGs offer an efficient means of connecting DESs to PSs by integrating ESUs, PVs, WE, and DEs inside small-scale electrical circuits [9], [10]. They can function in either GC or IM modes; GC improves stability via the main grid, while IM guarantees local supply and demand balance. Converter advancements have enhanced the compatibility of MGs, which can function in AC/AC, AC/DC, DC/AC, or DC/DC modes. Interest in DC-MGs has increased due to the growing usage of DC energy sources and EVs. Renewable integration increases when DES prices decrease, although adoption is influenced by factors such as economics, legislation, and climate. EMS and effective control are essential. DA-EMS needs to maximize cost, security, and sustainability, but it's still challenging to estimate uncertainties in CES output, load, and cost. In order to handle such uncertainties, this work focuses on creating a forecasting-based controller [11]–[13].

Multiple MPPT methodologies, which may be broadly categorized into four groups: CG, IG, OG, and HAG, have been studied recently [14], [15]. In spite of their ease of use, affordability, and moderate complexity, P&O, INC, and FOCV are still widely used CG. Under quickly changing circumstances, OG, like GWO and PSO, provides accurate and adaptive MPP tracking. Tracking efficiency is further increased by hybrid approaches such as PSO-enhanced P&O. ANN and FLC are two examples of IG that employ AI concepts to manage ambiguity and structure discontinuity. While ANN adjusts to changes in T and G without the need for intricate PV models, FLC uses rule-driven thinking. Research demonstrates that, despite the price and difficulty compromises, these clever and HAG beat CG in tracking effectiveness, closure speed, and resilience [16]–[18].

These approaches are contrasted in terms of tracking speed, cost, mathematical complexity, and weather-dependent performance. Additionally taken into account are efficiency losses resulting from oscillations around the MPP. A hybrid GA–P&O technique decreased P&O oscillations in [19]. In [16], an MRAC attained 99.77% tracking efficacy in the presence of T and G changes. Although it was not tested under irregular G, the INC-PSO-MPC hybrid in [20] achieved MPP in 0.05 s with 99% efficacy. An FL estimator improved the flexibility of the INC approach in [21]. Despite its great complexity, an adaptive FLC improved by the MKH algorithm achieved 0.15 s convergence and 99.32% efficacy [22]. In a similar manner, [19] employed DSP hardware and adaptive FL for quick and precise MPP tracking.

Even though PV control and optimization have come a long way, it is still difficult to achieve accurate MPPT and reliable EMS in a variety of scenarios. The majority of research ignores the integration of several adaptive controllers into a single framework and the combined use of intelligent MPPT and ESU control. Because of its precision, ease of use, and adaptability in managing nonlinearities and operational restrictions, an FLC is used to close these gaps. Unlike ANN-based techniques, FLCs are excellent at handling nonlinear, uncertain, and dynamic inputs without the need for intricate system models or sizable training datasets, which makes them ideal for sophisticated PV system control despite tuning issues with membership functions, rule bases, and defuzzification [23], [24]. Several ambiguities in choosing EMS methods for MGs have been examined throughout recent publications. These ambiguities are addressed by six primary strategies: interval, FLC, robust, chance constraint, IGDT, and random tactics [25], [26]. Managing contemporary MGs, particularly those that depend on CESs, requires EMS. Both centralized and decentralized EMS arrangements exist [19]. Smart meters and quick communication networks are necessary for a CEMS, which gathers and processes data at a central location [27]. However, CEMS has to deal with issues including high security requirements, time delays, and intensive data processing. A DEMS operates locally for lonely MGs, controlling CESs with sophisticated power electronics [28]. DCEMS provides quicker response times, but in order to prevent grid failures, MGs with significant CES prevalence may need to coordinate [29]. There are other OG concepts for MGs, and FLC for FCs [30]. More research is still needed on DC/AC MGs. Various techniques for managing vagueness have been used in EMS optimization. To control load and CES vagueness, for example, GC-MGs employed random OG [31].

To improve MG dependability under PV, WT, and load vagueness, robust OG were subsequently devised [32]. IGDT, FLC, and interval methods address MG uncertainty differently, balancing robustness, precision, and complexity, with IGDT ensuring robustness, FLC modeling uncertainty, and the interval approach favoring simplicity [33]. A summary and conclusions of the reviewed EMSs& control papers are presented in Table 1.

Table 1. Summary and conclusions of reviewed EMSs & control papers

Ref.	Objective	Method / Technique	System Type	Main Contribution	Key Results / Findings
[34]	Improve EMS for residential grid-connected MG	FLC- EMS	Grid-connected MG	Real-time fuzzy EMS considering uncertainty	Enhances energy balance and reduces grid power exchange fluctuations
[35]	Predictive EMS for on/off-grid modes	Predictive FLC + MPC	Residential smart MG	New predictive fuzzy EMS capable of seamless mode switching	Reduces operating cost and improves reliability under uncertainty
[36]	Evaluate EMS using IoT data	FLC comprehensive evaluation	IoT-based EMS	Multi-criteria assessment of EMS performance	Improved decision-making accuracy and EMS reliability
[37]	Decentralized power mgmt. in hybrid AC/DC MG	SMC + decentralized architecture	Hybrid AC/DC MG	Robust decentralized control with RES	Improved voltage stability, power sharing, and disturbance rejection
[38]	Intelligent EMS for standalone systems	ANN controller	Standalone MG	ANN-based optimal energy flow	Better load–generation balance and reduced fuel consumption
[39]	Review of MG control for sustainable EMS	Survey paper	MGs	Comprehensive review of EMS methods	Identifies future trends in MG sustainability & control
[40]	Improve PV MPPT control	Type-2 FLC + multi-level DC–DC converter	PV systems	Advanced T2- FLC–MPPT	Faster tracking, improved efficiency under shading
[41]	MPPT for PMSG wind systems	Hybrid FLC–MPPT	Wind energy conversion	Reduced oscillations and improved stability	Increased tracking accuracy and power extraction
[42]	Optimize PV control	Hybrid FLC–PI + metaheuristic optimization	Grid-connected PV	Enhanced high-penetration PV performance	Reduced THD, faster dynamic response
[43]	EMS using mixed controllers	ANN, PID, fuzzy	Hybrid MG	Comparison of control strategies	ANN shows the best energy distribution performance
[44]	EMS for isolated MG with diesel, RES & storage	Coordinated multi-source EMS	Isolated MG	Improved diesel scheduling & RES integration	Lower fuel usage and improved system resiliency
[45]	Integrate Industry 4.0 & 5.0 for EMS	IoT, AI, digital twins	Industrial EMS	Framework for smart/efficient energy mgmt.	Higher automation and sustainability metrics
[46]	Improve energy efficiency in buildings	Optimization + BMS	Building EMS	CO_2 reduction via BMS-enhanced optimization	Significant reduction in energy waste
[47]	Intelligent EMS for AC MG	FLC-based intelligent control	RES-based AC MG	Adaptive EMS enhancing stability	Better voltage/frequency regulation
[48]	EMS with cyber-security & real-time load redistribution	SCED + threat analysis tool	Power system EMS	Incorporates cyber-physical security in EMS	Enhanced resilience to cyber-attacks

To maximize energy extraction and guarantee dependable operation under a variety of environmental conditions, this study suggests an EMS for the CE system. To improve power tracking under varying G and sustain effective ESU operation, the system combines an FL-based MPPT with an optimized PI regulator. A thorough parametric analysis demonstrates that the FL-MPPT works better than the P&O approach, increasing tracking accuracy and overall efficacy. MATLAB/Simulink simulations confirm the functionality of the integrated FL-MPPT controller in the studied system. Under dynamic circumstances, the EMS efficiently manages power flow among CE generation, load, and ESU while maintaining a steady DC-bus voltage.

The paper is organized as follows: Section 2 details the hybrid system components modeling. Section 3 outlines the EMS and applications of FLC. Section 4 presents implementation results and compares the FLC with the P&O method using MATLAB tests. Section 5 concludes the study and suggests future research directions.

2. Studied System Configuration

Fig. 1 depicts the architecture of the system proposed. The configuration comprises PV, wind, EV, electrolyzer, and electric loads. The generation units are connected to the DC bus through a boost converter equipped with an integrated FL-MPPT control algorithm. The energy storage subsystem employs batteries coupled through a bidirectional DC-DC converter. This converter maintains stable DC bus voltage regulation through controlled charging and discharging operations, automatically adjusting the power flow to preserve system stability and maintain consistent voltage levels across the DC Bus. The system includes a DC-AC inverter used to convert the DC voltage to AC. This ensures efficient power conversion and provides electricity to connected AC loads.

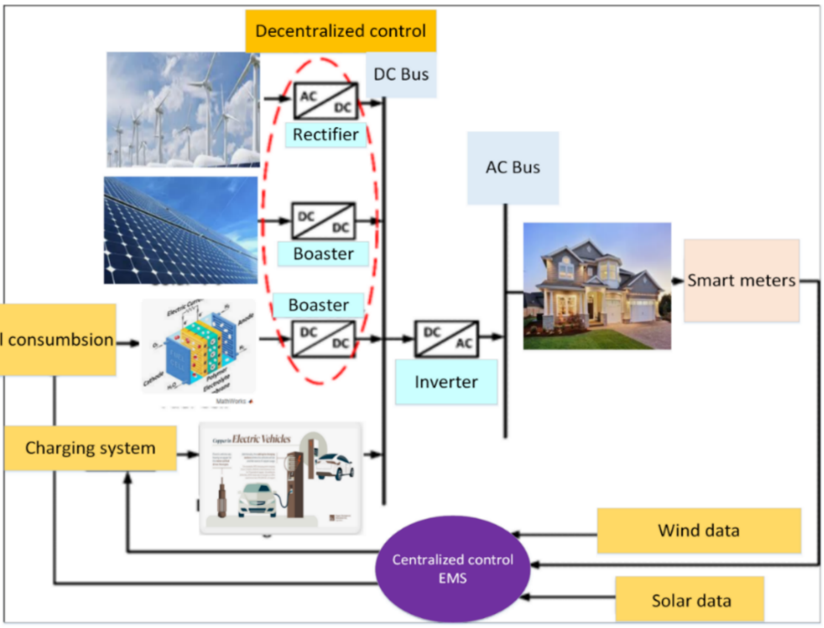


Fig. 1. Addressed system

2.1. PV Modeling

The I\V and P\V characteristics under changes in solar irradiance and temperature are depicted in Fig. 2 and Fig. 3. The PV model in MATLAB has been depicted in Fig. 4. The PV model has been fully discussed in [49], [50].

$$P_{pv}(t) = P_{r_{pv}} n_{pv} \eta_{pv} \eta_{wire} \frac{I(t)}{1000}\left(1-\lambda_T\left(T_{am}+\frac{(NOCT-20)}{800} I_{am}(t)-25\right)\right) \quad (1)$$

$$P_{tot\_pv}(t) = N_{pv} \times P_{pv}(t) \quad (2)$$

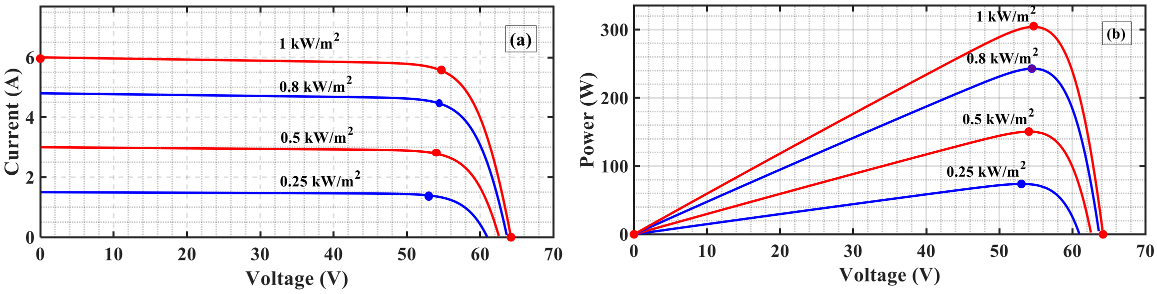
2.2. FC Modeling

The FC heap with H2 and air stream manager in MATLAB is depicted in Fig. 5. An FC model fully detailed and discussed in [51]–[53].

$$P_{fc-inv} = P_{H_2t-fc} \times \eta_{FC} \tag{3}$$

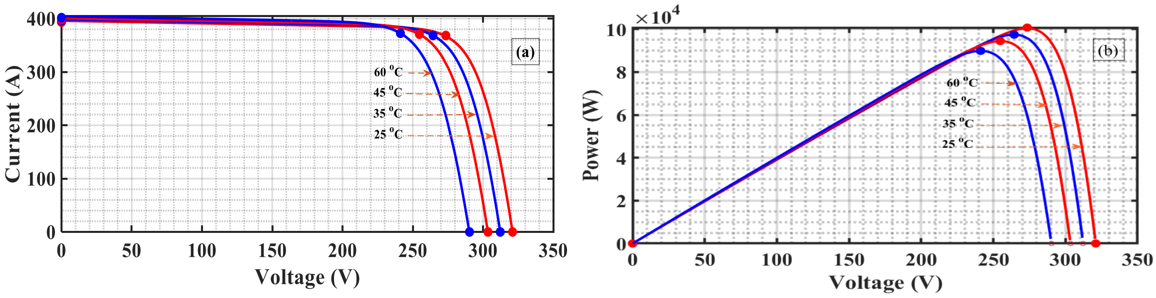
$$P_{fcs} = P_{\text{stack}} P_{fc,aux} \tag{4}$$

$$W_{H_2}(P_{fcs}) = \frac{P_{fcs}}{\eta_{fcs}(P_{fcs}) \cdot LHV_{H_2}} \tag{5}$$



(a) I-V characteristics (b) P-V characteristics

Fig. 2. Features of the PVS as I change



(a) I-V characteristics (b) P-V characteristics

Fig. 3. Features of the PVS as T changes

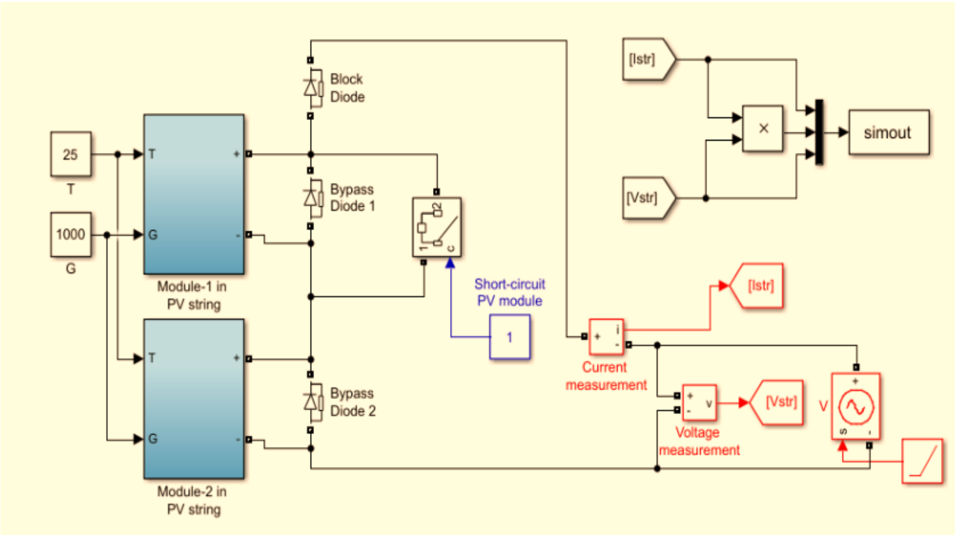


Fig. 4. PV model in MATLAB

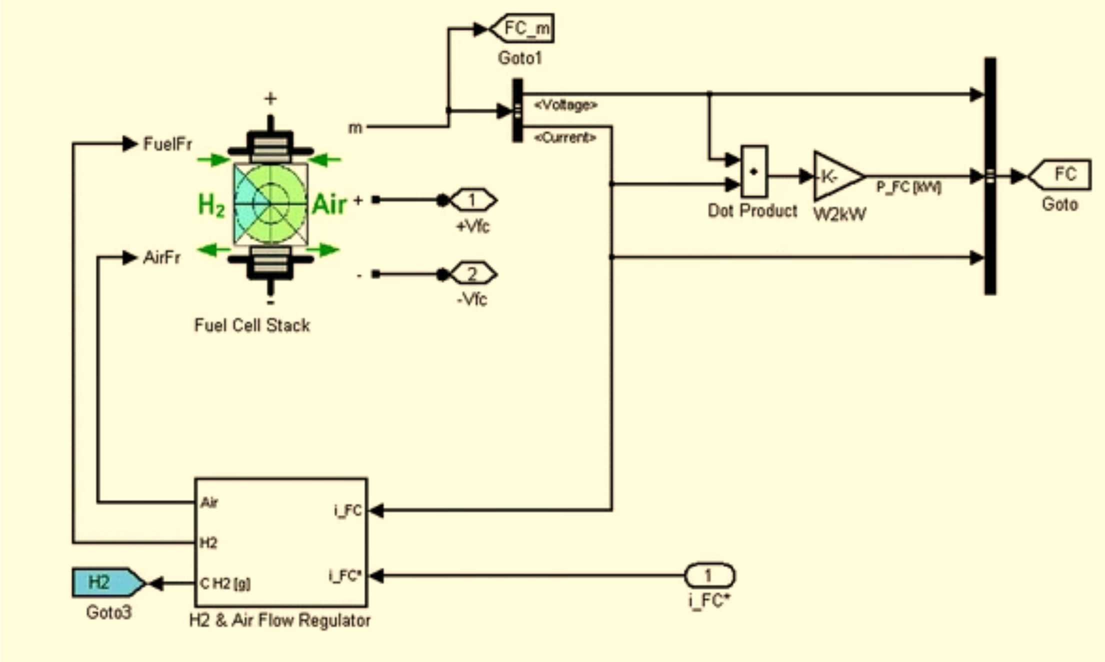


Fig. 5. FC heap with H_2 and air stream manager in MATLAB

2.3. EV Modeling

This model estimates the EV battery's energy content based on factors such as initial charge, energy exchanged with the MG considering charging/discharging efficiency, and self-discharge losses, while maintaining defined capacity limits. The EV model is depicted in Fig. 6. The model equations have been fully detailed in [54]–[56].

$$Eev_t = Eev_{t-1} + \sigma_{evr} * \Delta * P_t^{evr} - \frac{1}{\sigma_{evs} * \Delta * P_t^{evs}} - \beta ev * \Delta * Eev_t \tag{6}$$

$$Eev_{min} \leq Eev_t \leq Eev_{max} \tag{7}$$

$$Eev_{evf} \leq \rho \cdot Eev_{max} \tag{8}$$

$$P_{evs\,min} * evs_t \leq P_t^{evs} \tag{9}$$

$$P_t^{evs} \leq P_{evs\,max} * evs_t \tag{10}$$

$$P_{evr\,min} * (1 - evs_t) \leq P_t^{evr} \tag{11}$$

$$P_t^{evr} \leq P_{evr\,max} * (1 - evs_t) \tag{12}$$

2.4. Converter Modeling

The power generated by the inverter is computed using the following equations, in the ensuing manner. The applied converter modeling is fully described and discussed in [57]–[61].

$$P_{inv-AC} = \left(P_{fc-inv} \times P_{ren-inv}\right) \eta_{inv} \tag{13}$$

$$V_a(t) = \frac{V_{DC}}{2} S_1(t) - \frac{V_{DC}}{2} S_4(t) \tag{14}$$

$$V_b(t) = \frac{V_{DC}}{2}\ S_2(t) - \frac{V_{DC}}{2}\ S_5(t) \tag{15}$$

$$V_c(t) = \frac{V_{DC}}{2}\ S_3(t) - \frac{V_{DC}}{2}\ S_6(t) \tag{16}$$

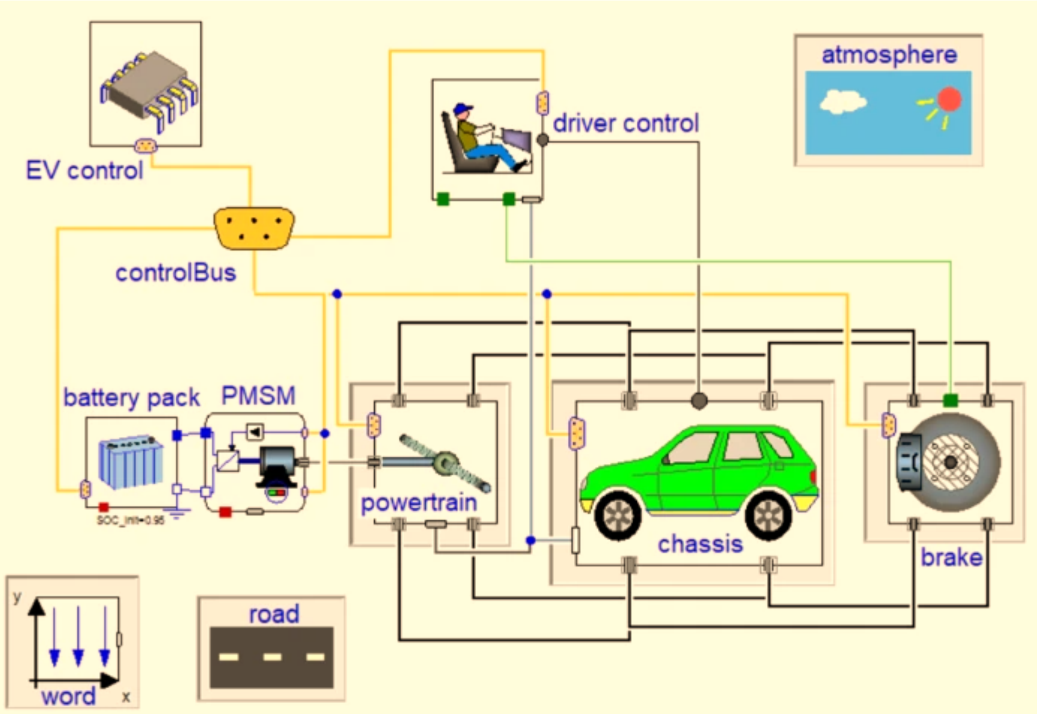


Fig. 6. EV model

2.5. WE Modeling

The WE hinge predominantly on the wind speed and the characteristics of the hub height. The used generator in this study is the DFIG, and its model consists of 4 differential equations (2 equations for both the stator and rotor voltage). The Eqs, expressed in the dq reference frame rotating at synchronous speed (ω_S), are given by Eqs., (20)-(28). The model of DFIG in MATLAB is depicted in Fig. 7. The model is fully detailed in [62]–[64].

$$V_2 = V_1 \left(\frac{H_2}{H_1}\right)^{\beta_{WT}} \tag{17}$$

$$P_w(t) = \begin{cases} n_w \eta_w P_{r_w} * \dfrac{\left(V^2(t) - V^2{}_{c_{in}}\right)}{\left(V^2{}_r - V^2{}_{c_{in}}\right)} & V_{c_{in}} < V(t) < V_r \\ n_w \eta_w P_{w_r} & V_r < V(t) < V_{c_{off}} \\ 0 & V(t) < V_{c_{in}}\ \ or\ \ V(t) < V_{c_{off}} \end{cases} \tag{18}$$

$$P_{tot\_w} = N_w \times P_w(t) \tag{19}$$

$$V_{ds} = R_S\, I_{ds} - \frac{d\psi_{ds}}{dt} - \omega_S\, \psi_{qs} \tag{20}$$

$$V_{qs} = R_S\, I_{qs} + \frac{d\psi_{qs}}{dt} + \omega_S\, \psi_{ds} \tag{21}$$

$$V_{dr} = R_r\, I_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_S - \omega_r)\psi_{qr} \tag{22}$$

$$V_{qr} = R_r\, I_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_S - \omega_r)\, \psi_{dr} \tag{23}$$

$$\psi_{ds} = L_s\, I_{ds} + L_m\, I_{dr} \tag{24}$$

$$\psi_{qs} = L_s\, I_{qs} + L_m\, I_{qs} \tag{25}$$

$$\psi_{dr} = L_r\, I_{dr} + L_m\, I_{dr} \tag{26}$$

$$\psi_{qr} = L_r\, I_{qr} + L_m\, I_{qs} \tag{27}$$

$$T_e = \frac{3}{2}\, P\, \left(\psi_{ds}\, I_{qs} - \psi_{qs}\, I_{ds}\right) \tag{28}$$

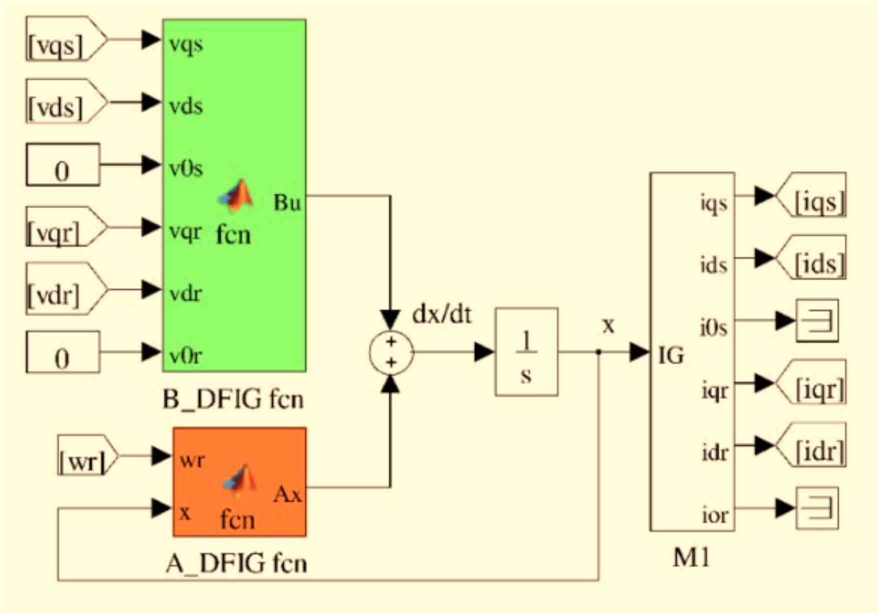


Fig. 7. Model of DFIG in MATLAB

3. The Investigated EMS Strategy-Based FLC

The EMS connects multiple elements and serves as the MGs' central interface and command unit. To control power flow and improve dynamic stability, it collects data from the MG components. The KPIs, including financial, eco-friendly, methodological, and program objectives, are optimized by EMS [65]–[67]. The technical features of EMS are the main emphasis here, which emphasize how it balances energy demand and enhances stability. The FC and battery charger system's EMS performance is evaluated using KPIs, primarily taking into account the power restrictions and SOC while charging and discharging. The following flow chart of Fig. 8 shows the system concepts and procedures used through the EMS in accordance with the earlier representations [68]–[70].

$$KPI_1 = \begin{cases} \sum_{t=1}^{t=e} P^{Ch}_{BESS,t} \leq \left(\partial_1 \times P^{Ch-max}_{Cap\text{ - }BESS,}\right) \\ \sum_{t=1}^{t=r} P^{Dish}_{BESS,t} \leq \left(\partial_2 \times P^{Disc-max}_{Cap\text{ -}BESS,t}\right) \end{cases} \tag{29}$$

$$KPI_2 = \begin{cases} SOC^{DC-min}_{BESS,t} \leq SOC^{DC}_{BESS,t} \leq SOC^{DC-max}_{BESS,t} \\ SOC_{BESS,t} = SOC_{BESS,(t-1)} \left(\dfrac{SOC^{Ch}_{BESS,(t-1)} - SOC^{Disch}_{BESS,(t-1)}}{P_{Cap-BESS}} \right) \end{cases} \tag{30}$$

$$KPI_3 = \begin{cases} P_{fcout} = NV_{cell} I \\ \dot{m}_{H2} = (NM_{H2})/nFI \\ \eta_{fc} = \dfrac{P_{fcout}}{LHV \dot{m}_{H2}} \end{cases} \tag{31}$$

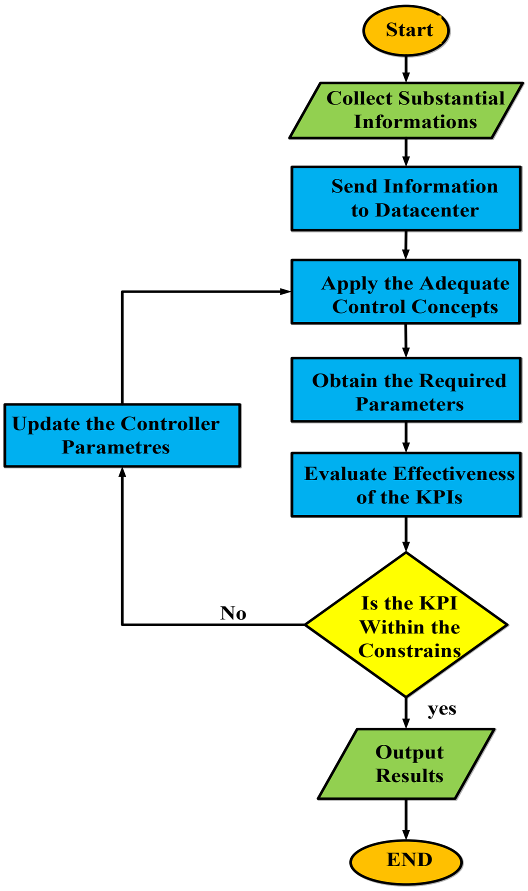


Fig. 8. Flow chart of the control process of EMS

Fuzzification, rule application, and defuzzification are all involved, as Fig. 9 illustrates. After being mapped to membership functions, inputs are processed using rule-based adaptation and transformed into clear control outputs. The process of fuzzification is described as follows. The FLC uses five membership functions (NB, NS, Z, PS, PB) with the Mamdani interface. Outputs are defuzzified using the center of gravity method [71], [72]. The applied FLC in the investigated EMS is seen in Fig. 10.

4. Simulated Results

MATLAB program validates the mathematical model through simulation. In this study, the proposed FLC-MPPT model is integrated into a complete CES (Fig. 1). The setup enables testing under various conditions. The FLC-MPPT performance is compared with the P&O to show the system efficiency, response time, and losses. A change has been made in the PV irradiance, and the rest of the system operated at normal rated values. To assess the FL-MPPT performance, a comparison with the P&O method was conducted under four irradiance levels (1000, 800, 600, and 400 W/m²) at 25 °C. The proposed FL-MPPT achieves exceptional tracking efficiency and speed across varying irradiance levels.

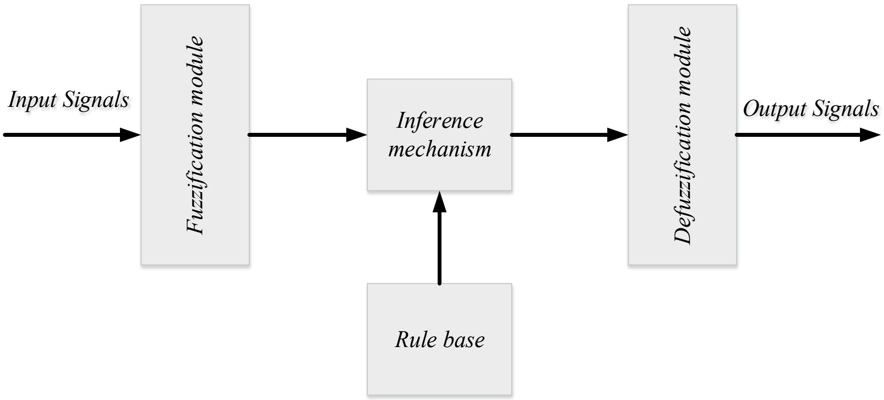
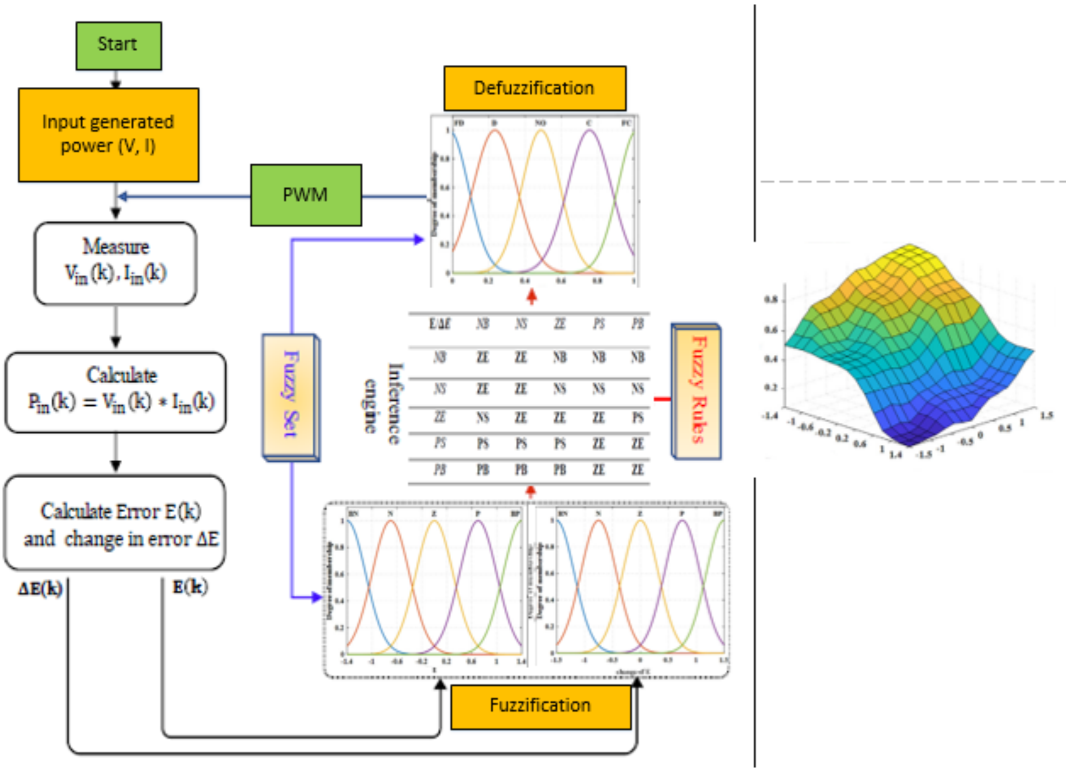


Fig. 9. Fuzzy logic control structure design



E/ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Fig. 10. Applied FLC in the investigated system

Fig. 11–Fig. 13 compare the performance of the proposed FLC and the P&O under varying solar irradiance levels. As shown in Fig. 11, the FLC consistently achieves slightly higher efficiency across all conditions, reaching 99.99% at 400 W/m² versus 99.97% with P&O, and maintaining superiority at 600 W/m² (99.9% vs. 99.9%), 800 W/m² (99.91% vs. 99.65%), and 1000 W/m² (99.76% vs.

99.71%). Fig. 12 demonstrates the FLC's faster dynamic response, attaining steady state in 0.009 s at 400 W/m² compared to 0.015 s for P&O, and further improving to 0.003 s, 0.0094 s, and 0.005 s at 600, 800, and 1000 W/m², respectively, outperforming P&O's 0.009 s, 0.021 s, and 0.0286 s. As shown in Fig. 13, the FLC also minimizes power losses, eliminating them at 400 W/m² (vs. 0.7 W for P&O) and significantly reducing them at higher irradiance levels—from 2.987 W to 0.989 W at 800 W/m² and from 6.975 W to 1 W at 1000 W/m². Overall, the proposed FLC demonstrates superior efficiency, faster response, and lower power losses, confirming its enhanced adaptability, precision, and tracking accuracy under changing solar conditions.

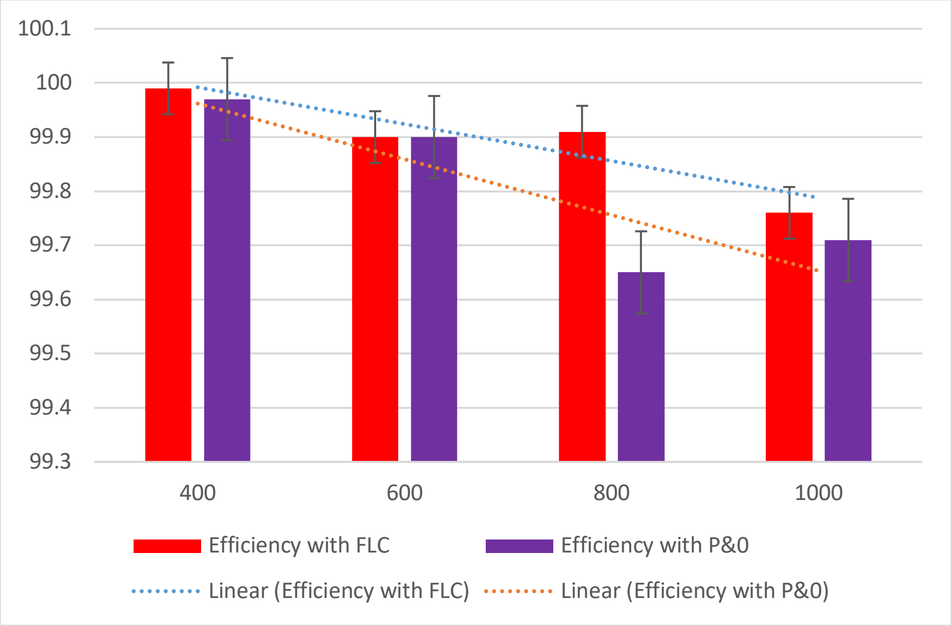


Fig. 11. System efficiency

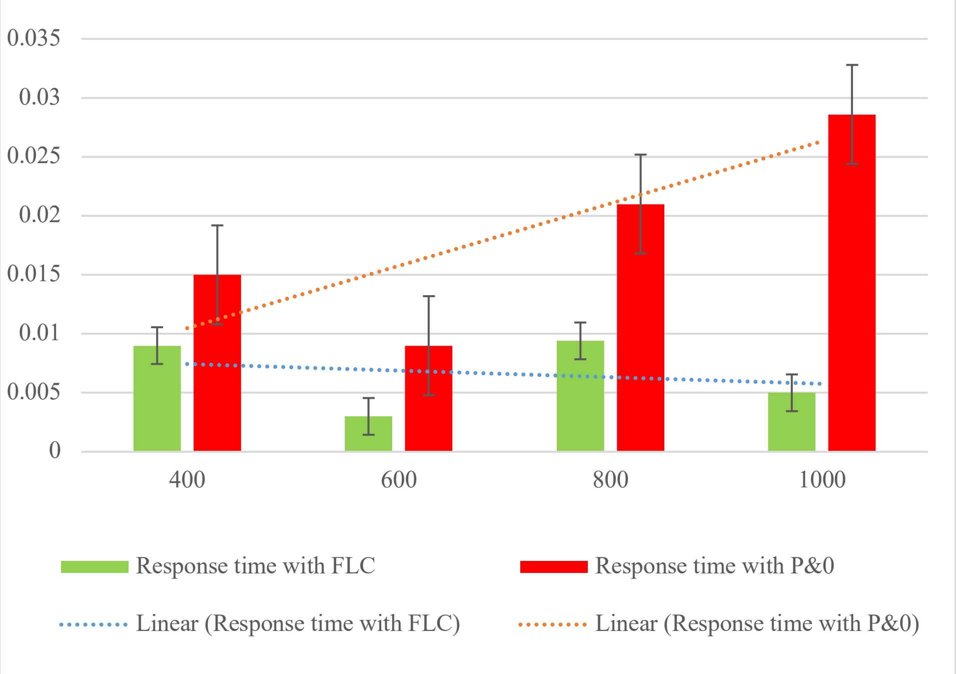


Fig. 12. Response time

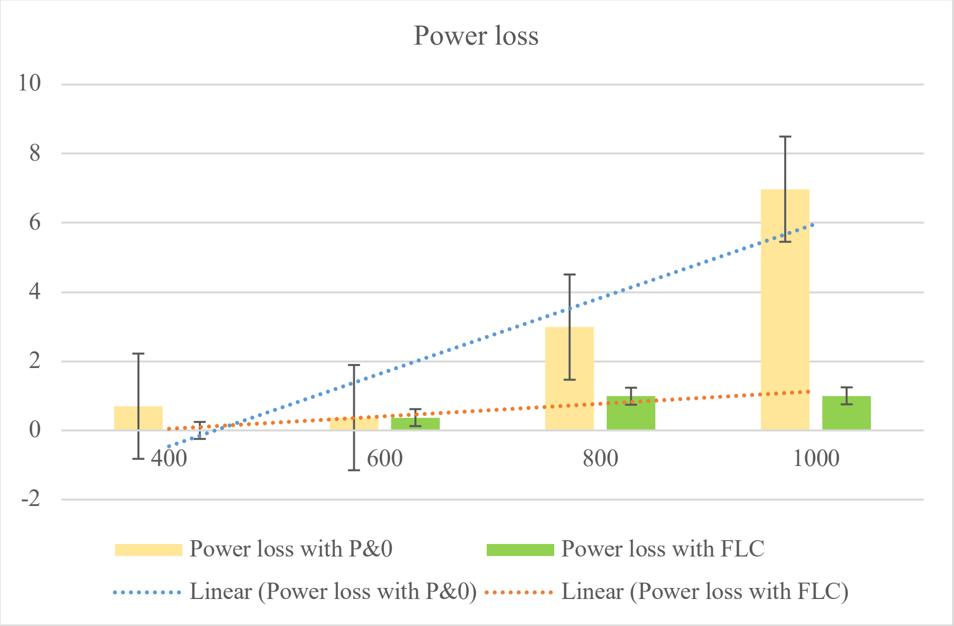


Fig. 13. Power loss

The EMS controlled by FLC was validated by analyzing the system's dynamic behavior under steady-state, partial shading, and load increase. As shown in Table 2, by preserving a more stable DC bus voltage, lowering FC consumption, and guaranteeing more seamless battery charging, the developed FLC enhances system stability. The FC and battery efficiently make up for the decreased solar output under partial shading, resulting in quicker voltage recovery. The DC voltage decrease approaches 275 V with recovery durations of 13 and 9 seconds, with an abrupt 50% load increase (130–150 s). In general, the FLC improves hydrogen usage, stability, and efficiency.

The THD of load voltage and current under various operating situations is compared in Fig. 14. Both voltage and current THD values are low in the steady-state (Case 1), at 1.492% and 1.497%, respectively, indicating clean power quality. Due to varying solar input, a little increase to 1.504% for voltage and 1.518% for current is seen under partial shadowing (Case 2). The THD values slightly increase to 1.513% and 1.521% after a load increase (Case 3), demonstrating that the system maintains good power quality and stability even under transient situations.

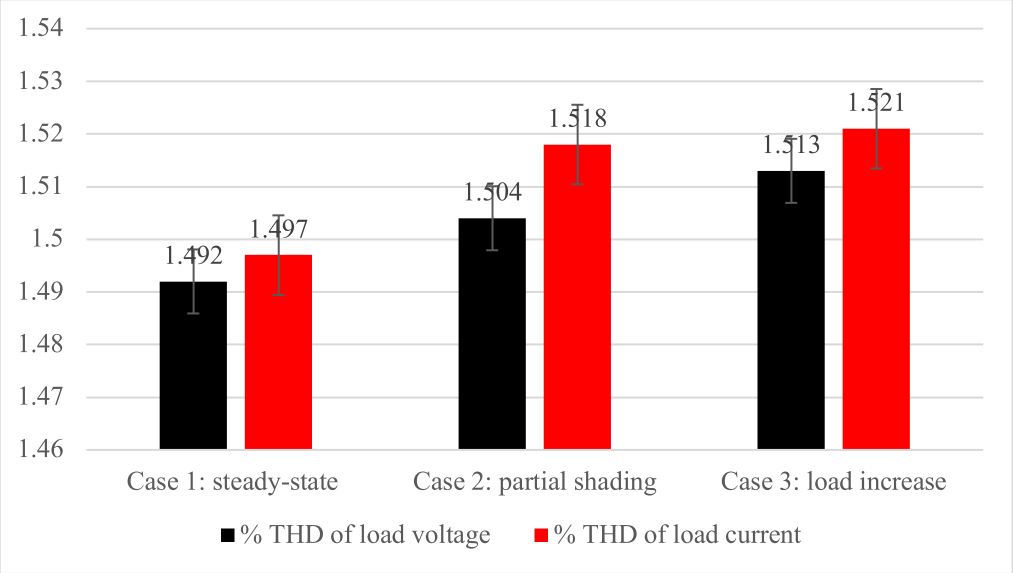
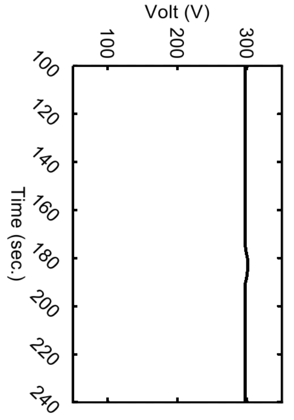
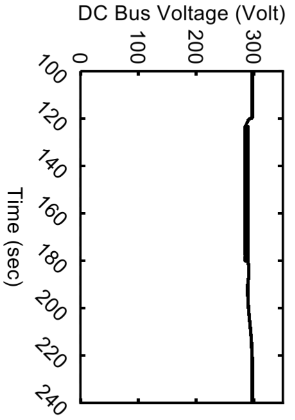
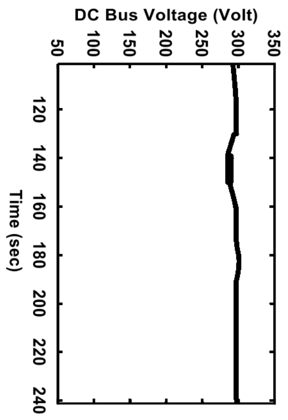
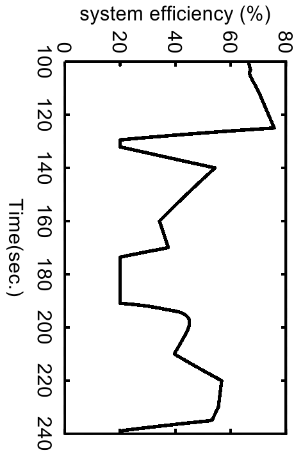
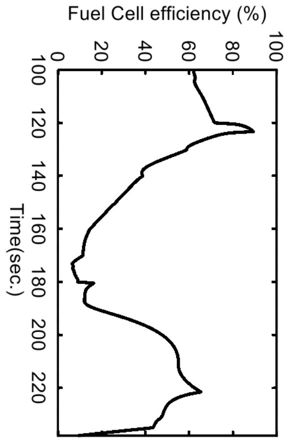
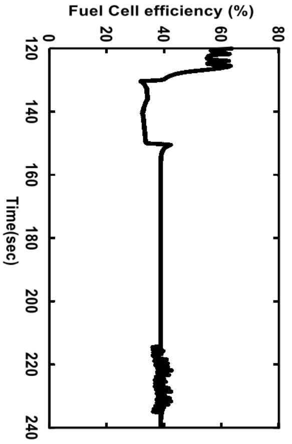


Fig. 14. %THD of load voltage and current under the 3 studied cases

Table 2. Some of the investigated model outputs under the 3 cases

Metrices	Case 1: steady-state	Case 2: partial shading	Case 3: load increase
VDC			
FC efficiency			

The performance comparison (Table 3) reveals clear trends across the reviewed EMS and control strategies for MGs and RESs. Overall, advanced artificial intelligence–based and FLC–enhanced controllers consistently achieve higher efficiencies, typically ranging between 94–99%, with ANN-based and FLC hybrid systems showing the strongest performance. Studies focusing on MPPT demonstrate exceptionally high tracking precision, reaching up to 99–99.1%, particularly in Type-2 FLC and hybrid MPPT algorithms, indicating their superiority under rapid environmental variations. Harmonic distortion performance also varies, with the best THD values falling between 1.8–2.5%, confirming the ability of optimized fuzzy controllers to significantly improve power quality. In terms of economic benefits, most approaches yield meaningful cost reductions, generally between 10–25%, with some systems achieving up to 22% savings through improved building energy optimization or fuel reduction in MGs. Collectively, Table 3 shows that intelligent and hybrid control techniques deliver the greatest improvements simultaneously in efficiency, MPPT accuracy, THD reduction, and overall operational cost savings.

5. Conclusions

This study presented an FLC-EMS integrated with an MPPT algorithm for a hybrid CESs comprising PV, WE, FC, battery, and EV units. The proposed control framework effectively manages power flow, maintains DC bus voltage stability, and optimizes energy utilization under varying environmental and load conditions. MATLAB/Simulink simulations confirmed that the FLC-MPPT significantly outperforms the P&O in terms of efficiency, response speed, and power loss reduction. Specifically, the FLC achieved up to 99.99% efficiency, faster dynamic response

(0.003 s), and minimized power losses (as low as 1 W at 1000 W/m²). Additionally, under partial shading and sudden load variations, the system exhibited rapid voltage recovery and stable operation, while maintaining low THD < 1.52%, ensuring high power quality. These results demonstrate the FLC's superior adaptability, robustness, and precision in handling nonlinearities and uncertainties inherent in renewable systems. Overall, the proposed FLC-based EMS provides an efficient, reliable, and sustainable control solution for hybrid MGs, promoting improved energy utilization and stability in clean energy integration. Future work will focus on hardware implementation, real-time testing using HIL platforms, and the extension of the controller to larger-scale smart grid applications.

Table 3. Numerical performance comparison of previously published works in this field in terms of (THD%, efficiency%, MPPT accuracy%, cost reduction%)

Paper	THD (%)	Efficiency (η %)	MPPT Accuracy (%)	Cost Reduction (%)
[34]	—	92–95%	—	10–18%
[35]	—	93–96%	—	15–22%
[38]	—	94–98% (ANN-based EMS)	—	10–20% (fuel savings)
[39]	2–5% (typical MG controllers)	90–98%	95–99%	5–25%
[40]	1.8–2.5%	97–99%	99.1%	6–10%
[41]	—	96–98%	98–99%	5–9%
[42]	2.0–3.0%	96–98%	99%	5–8%
[43]	—	95–98%	—	12–18%
[45]	—	93–97%	—	12–20%
[46]	—	90–95%	—	10–22% (building CO_2 optimization)
[47]	2–3%	95–98%	—	10–15%
[48]	—	90–94%	—	Avoided loss: 5–12%

List of Abbreviations

CESs: Clean energy sources
FFs: Fossil fuel
DESs: Distributed energy systems
G&T: Irradiance and temperature
IM: Isolated modes
MGs: Microgrids
MPPT: Maximum power point tracking
P&O: Perturb and observe
FOCV: Fractional open-circuit voltage
CG: classical group
HAG: Hybrid approaches group
GWO: Grey wolf optimizer
ANN: Artificial neural networks
FC: Fuel cell
KPIs: Key performance indicators
SOC: State of charge
P&O: Perturb and observe
EV: Electric vehicle
PV: photovoltaic source
WE: Wind source
PS: Power system
GC: Grid-connected
ESUs: Energy storage units
DEs: Diesel Engines
EMS: Energy management systems
DA: Day ahead
INC: Incremental conductance
IG: Intelligent group
OG: Optimization group
PSO: Particle swarm optimization
FLC: Fuzzy logic control
CEMS: Central EMS
DEMS: Decentralized EMS
IGDT: Information gap decision theory
THD: Total harmonic distortion
HIL: Hardware-in-the-loop

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Sustainable Development Goals: Sustainable Development Goals mapped to this document, Affordable and Clean Energy Goal 7.

Data Availability: The data used to support the findings of this study are available at reasonable request from the corresponding author.

Acknowledgment: The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/33392).

Funding: The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/33392).

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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