A Comparative Analysis of Recent MPPT Algorithms (P&O\INC\FLC) for PV Systems

Yahiaoui Maamar [1], I. M. Elzein [2], Afif Benameur [3], Horch Mohamed [4], Mohamed Metwally Mahmoud [5*], Mohamed I. Mosaad [6], Salma Abdelaal Shaaban [7]
[1] University of Mascara, Road of Mamounia, Mascara (29000), Algeria
[2] Department of Electrical Engineering, College of Engineering and Technology, University of Doha for Science and Technology, Doha P.O. Box 24449, Qatar
[3, 4] Automatic Laboratory, Higher National School of Electrical and Energetic Engineering of Oran, University of Tlemcen, 13000, Algeria
[5, 7] Electrical Engineering Department, Faculty of Energy Engineering, Aswan University, Aswan 81528, Egypt
[6] Electrical & Electronics Engineering Technology Department, Yanbu Industrial College (YIC), Royal Commission Yanbu Colleges & Institutes, Yanbu 46452, Saudi Arabia
Email: [1] maamar2904@gmail.com, [2] 60101973@udst.edu.qa, [3] afifafif22@yahoo.fr, [4] mohamed.horch@mail.univ-tlemcen.dz, [5] metwally_m@aswu.edu.eg, [6] m_i_mosaad@hotmail.com, [7] salma@energy.aswu.edu.eg
*Corresponding Author

***Abstract*—Although solar (PV) power generators have been widely deployed, one important barrier to their effective energy capture is weather variability. It is a very challenging effort for these systems to operate at MPPT. Conventional MPPT methods still had an excessively long convergence period to the MPP. Because of their superior data processing, intelligent approaches are nevertheless given a reasonable length of time to reach the maximum point, beginning with the objective of keeping the PV generator in the MPP with outstanding performance. To accomplish MPPT, a comparison between intelligent (fuzzy control (FLC)) and conventional algorithms (perturb-and-observe (P&O) and the incremental conductance (INC)) is investigated. To do this, a mathematical model of PV cells based on two diodes with shunt and series resistors is created with MATLAB/Simulink. The model characteristics curves with the parameters listed in the MSR SOLAR datasheet are compared. Finally, we compared the results of the FLC with those of the P&O and the INC. The results obtained demonstrated the superiority of the FLC-MPPT controller.**

Keywords*—*Solar Energy; MPPT Methods; Fuzzy Control; Perturb-and-Observe Control; Incremental Conductance Control.

I. INTRODUCTION

One of the necessities for humankind is electricity, and power system operators have long struggled to supply it with an increasing need via both traditional and unconventional methods. Around the world, utilities are concentrating on renewable energy sources (RESs) like solar (PV), hydro, biomass, and wind energy systems to meet the constantly rising need for power [1]-[8]. In 2021, RESs accounted for 33% of the world's electrical capacity, with PV, wind, and hydropower leading the way. In 2020, it created around 11.5 million employment and avoided more than 2 billion metric tons of CO_2 emissions in 2019. By 2024, RESs capacity addition is expected to have increased by 50%, with PV and wind systems playing a major role in this expansion [9]-[14].

By 2030, it is anticipated that the total investment in the RESs industries will amount to $2.6 trillion. Current governments are pledging to meet ambitious RESs targets, like the EU's 32% RESs goal for 2030, highlighting the sector's importance in an RESs future. The surge in the adoption of electric cars is closely linked to the growth of RESs [15]-[18]. A more sustainable way to lessen our reliance on fossil fuels is through RESs. It is also a clean source of energy and requires little upkeep [19]-[21]. Through declining costs, technological advancements that have reduced costs and increased efficiency, and some new government incentives, PV systems are becoming cheaper [22]-[25].

A unidirectional DC-DC boost converter (BC) is utilized to maximize power extraction from the PV since it generates DC power, and an inverter effectively transforms power into AC to satisfy load demands [26]-[29]. The two primary types of PV systems are grid-tied type (GTT) and isolated type (IT). The cost of the IT is considerable because storage tools (STs) are required to sustain the variance in DC power. Installation and maintenance expenses are extremely minimal for GTT categories since they do not need an ST [30]-[32].

The MPPT control is a significant issue in the field of PV systems, we have a problem with the efficiency of energy conversion, and to solve this problem, it's necessary to use the MPPT controller to extract the maximal power (MP) in the PV modules in different climatic conditions [33]-[36]. This leads the scientific research to the development of new electronic components to implement modern controls capable of processing data in a short time to achieve an excellent temporal response in the MPPT control and to apply a sophistic controller on the PV energy conversion system, among the researches carried out in the field of PV system control we have: Ref. [37] realized the incremental conductance control (INC) with a variable increment step-size (ISS) to improve the performance of the INC with a fixed ISS in terms of response time and accuracy. Refs. [38], [39] proposed the comparative study between the fuzzy logic (FLC) and ANFIS you are using the current and power as input of the FLC and the ANFIS controller to reduce the calculation.

Ref. [40] proposed the modified P&O for extracting MP from the PV. This algorithm is used to eliminate the MPPT deviation to around the MPP. Ref. [41] proposed the FLC-MPPT to solve the problem of the oscillation around the MPP in the P&O. Ref. [42] realized the INC-MPPT by an FLC to reach MP. Ref. [43] uses the neuro FLC to give the standard voltage of the MPP, to ensure the system's overall stability, use the integral backstepping controller. Ref. [44] proposes a modified P&O to extract the MP available, this method is based on power disturbance instead of voltage or current (V\I) disturbance, for the synchronization of powers to inject a sliding mode controller to the networks has been used. Ref. [45] uses an MPPT command based on the knowledge of the load current to extract the MP, unlike the other methods, which are based on the V\I knowledge. Ref. [46] proposes a P&O control with a variable step size to improve the convergence time towards the MPP of the classic P&O control. Ref. [47] proposes a comparative study between the performances of the P&O control and the FLC under partial shading conditions. Ref. [48] realized adaptive FLC based on comparing an FLC's output with a triangular signal to generate the duty cycle that maintains the GPV system in the MPP.

Ref. [49] proposed a comparative study between three MPPT methods: Traditional P&O, drift-free P&O, and amended technique for quickly shifting environmental circumstances. Ref. [50] proposes improving the INC-MPPT to achieve a good follow-up of the MPP. Ref. [51] implemented a PI controller with variable gain. The variation of the PI parameters is carried out with the help of an FLC supervisor; the validation of the performance is achieved with the experimental implementation and a comparison with a classical PI and P&O in MPPT control. Ref. [52] proposed a contrast study of the PV system controlled by the Takagi-Sugeno, FLC Mamdani, and P&O sorts. Refs. [53], [54] proposed an MPPT procedure with optimized PID to increase the performance of the P&O. Ref. [55] proposed a new variable step size INC-MPPT.

To accomplish our goal, which is to extract the MP that is available in a PV system at any given moment, we have suggested in this work a comparison analysis of the control: P&O, INC, and FLC. The remainder of this research is structured as follows: The modeling and simulation of the system components, PV, and boost converter (BC) are covered in Section 2. The MPPT techniques, P&O, INC, and FLC, are presented in Section 3. The properties of the MPPT control are compared and analyzed in part 4, with the main conclusion presented in the last part.

II. PV System

Fig. 1 displays a diagram of a PV power generation from a PV source which consists of the following elements: PV panel, BC, load charge, and MPPT controller to ensure the operation of the PV at the MPP.

A. Mathematical Model of PV

Several mathematical models of the PV panel are presented in the literature to simulate all the phenomena existing in an actual panel [56]-[60]. Fig. 2 displays a similar drawing of a PV cell which is made up of an I source modeling the luminous flux, 2 resistors modeling the losses, a shunt resistor (R_p), a series resistor (R_s), and 2 diodes for the polarization of the solar cell (SC) and the phenomenon of recombination of the minority carriers. This additional diode is equivalent to the chemical effects of electron recombination. The following equation gives the produced I by the model [61]-[64].

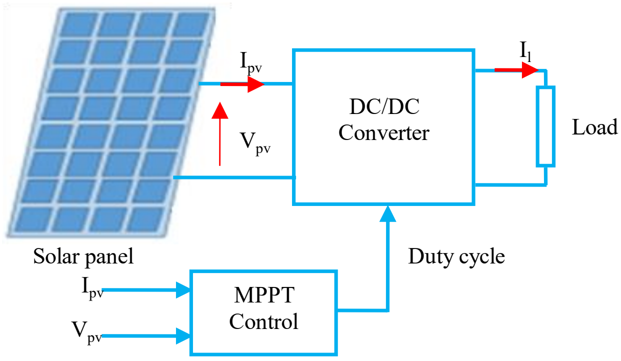

Fig. 1. Principle schema of PV system

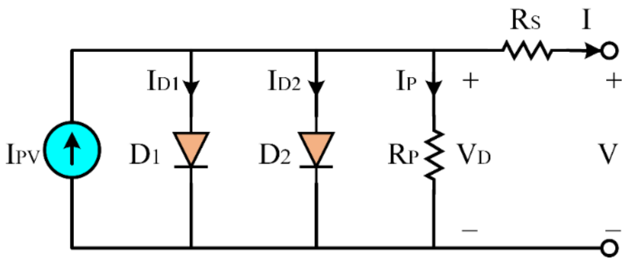

Fig. 2. Diagram of the SC

$$I = I_{PV} - I_{d1} - I_{d2} - \frac{V + IR_s}{R_p} \quad (1)$$

The photo-current (I_{PV}) is defined as:

$$I_{PV} = \frac{E}{E_{ref}}\left[I_{cc} + K_i\,(T_C - T_{ref})\right] \quad (2)$$

where E is the solar radiation (SR) (W/m^2), E_{ref} is the SR of reference 1000 W/m^2, T_c is the ambient temperature of SC, and T_{ref} is the reference temperature (T_{ref} = 25°C).

The diode current (I_d) which the Shocly equation can be expressed as:

$$I_d = I_s\left(e^{\frac{q\,Vd}{Ak\,Tc}} - 1\right) \quad (3)$$

where A is the ideality factor of the diode, k is the Boltzmann constant, q is the electron charge, and T_C is the SC temperature.

The diode current loss (I_s) is expressed as:

$$I_s = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 e^{\left[\frac{-qE_g}{KA}\left(\frac{1}{K}-\frac{1}{T_{ref}}\right)\right]} \quad (4)$$

The inverted saturation current (I_{rs}) of the SC is expressed as:

$$I_{rs} = \frac{I_{cc}}{e^{\left(\frac{q\,Voc}{N_s\,K A\,Tc}\right)} - 1} \quad (5)$$

where E_g is the energy for the passage of a free electron between the valence and conduction bands of the semiconductor, (N_s and N_p) are the number of SCs in series and parallel, respectively. So, we will have the current equation of the SC as follows:

$$I = N_p I_{PH} - N_p I_{d1}\left(\frac{q(V-Irs)}{e^{A1kTc}} - 1\right) - NpI_{d2}\left(\frac{q(V-Irs)}{e^{A2kTc}} - 1\right) - \frac{\frac{Np}{Ns}V + Irs}{Rp} \tag{6}$$

Fig. 3 displays the features of curves V-I and V-P.

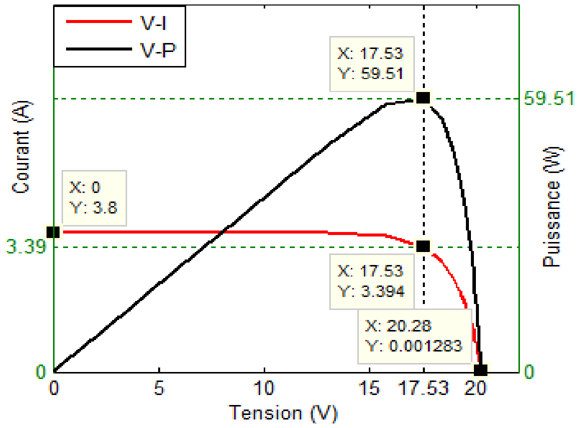

Fig. 3. V-I and V-P panel characteristics curve

To validate our proposed panel model, a comparison was made between the data of the V-I and V-P characteristics curve shown in Fig. 3 with the data of the MSX60 panel model datasheet, as shown in Table I. In addition, the electrical characteristic of the MSX60 module is seen in Table II.

TABLE I. CHARACTERISTICS OF MSX60 MODULE AND PROPOSED PANEL MODULE

	I_{sc} (A)	V_{oc} (V)	P_{max} (W)	V_{opt} (V)	I_{opt} (A)
MSX60 module	3.8	21.1	60	17	3.46
Proposed module	3.8	20.28	59.51	17.53	3.39

TABLE II. ELECTRICAL CHARACTERISTIC OF MSX60 MODULE

MP (Pmax)	60W
V (Vmp)	17.1V
I (Imp)	3.5A
I_{SC}	3.8A
V_{oc}	21.1V

B. BC Structure and Model

To extract the MP available at a given time, the PV system's BC acts as an adaption element amid the load and the SC. Furthermore, Fig. 4 shows the BC's model brick.

The BC's mathematical model is provided by the next formulas [65]-[68]:

$$\frac{di_L}{dt} = \frac{E}{L} - \frac{V_{dc}\,(1-u)}{L} \tag{7}$$

$$\frac{dV_{dc}}{dt} = \frac{i_L\,(1-u)}{C} - \frac{V_{dc}}{RC} \tag{8}$$

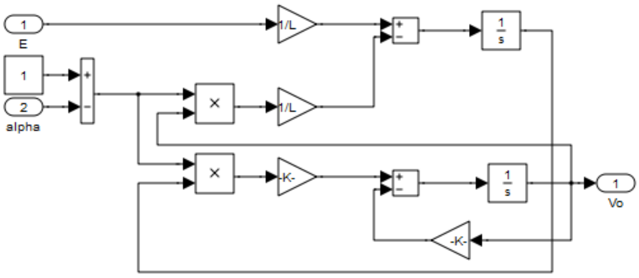

Fig. 4. Simulation block of a BC

III. INVESTIGATED MPPT CONTROL METHOS

In PV systems, there is only one MPP at each instant of time. Therefore, this system is constantly moving, and the MP is difficult to reach. Researchers propose using control methods to maintain the PV function at the MPP or around it to remedy this problem.

A. P&O Method

The P&O technique hinges on the V_{PV} and the monitoring of the impact of this fluctuation on the PV harvest power [69]-[71]. The P&O method's workflow is shown in Fig. 5. To determine P_{PV} (k-1), V_{PV} and I_{PV} are calculated at each cycle (C). The value of P_{PV} (k-1) determined in the preceding C is contrasted with this P_{PV} (k). The V_{PV} is further regulated identically as the previous C if the level of power produced has risen. The V_{PV} is modified in the reverse manner as in the previous cycle if the electricity output has dropped. Consequently, V_{PV} is disrupted during every MPPT-C. The V_{PV} fluctuates about the ideal value V_{PV} until the MPP is obtained.

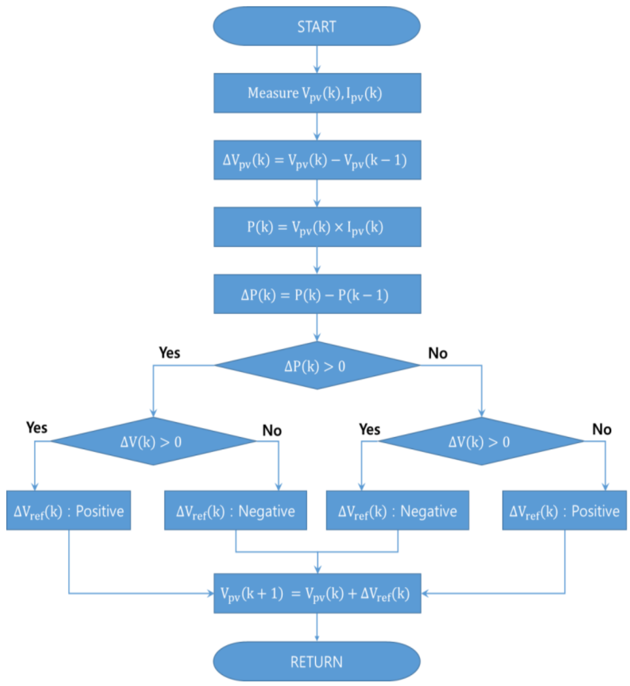

Fig. 5. The P&O workflow

B. INC Method

The P-V shape of the SC serves as the basis for the INC operation [72]-[74]. The MPP (point B) in Fig. 6, and the slope (S) is zero. We can observe from the MPP that the right side has a –S while the left side has a +S. Formulas (10) through (12) display what's happening at every point. In Equations (10) – (12), $I_{PV}./V_{PV}$ is the conductance, and dI_{PV}/dV_{PV} is the IN of the alteration in conductance [51], [75]. INC flowchart shown in Fig. 7.

In general, the voltage from the source is positive to conclude the critical results of the INC method.

In point "A," The MP is on the left, so we must increment.

In point "B," We are on the MP.

In point "C," The MP is on the right, so we have to decrement.

$$\frac{dP}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} \tag{9}$$

$$A: \frac{dP}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} < 0 \rightarrow \frac{dI_{pv}}{dV_{pv}} < -\frac{I_{pv}}{V_{pv}} \tag{10}$$

$$B: \frac{dP}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} = 0 \rightarrow \frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \tag{11}$$

$$C: \frac{dP}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} > 0 \rightarrow \frac{dI_{pv}}{dV_{pv}} > -\frac{I_{pv}}{V_{pv}} \tag{12}$$

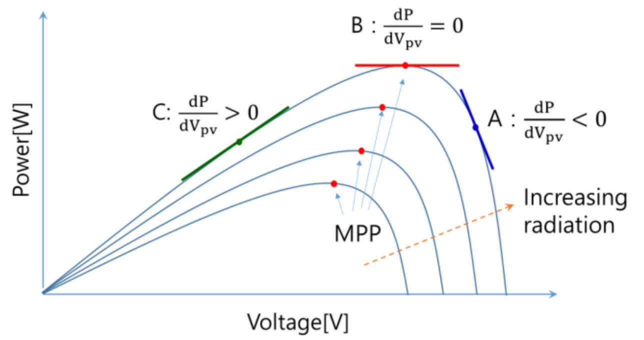

Fig. 6. P-V characteristic of PV cells

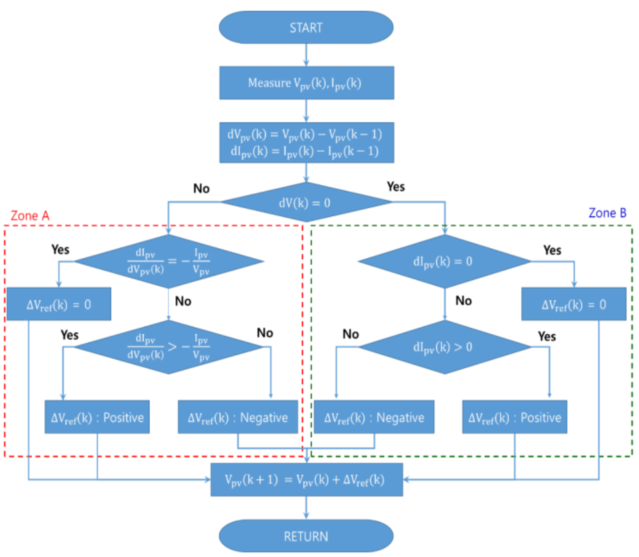

Fig. 7. INC flowchart

C. FLC Method

The proposed FLC entails two inputs, which are: error (E), and dynamic error (ΔE). The input $E(k)$ displays whether the scheme's working point is to the left or right of the MPP, while the input $\Delta E(k)$ displays the mark of the variation as illustrated in Table III. The output of the FLC-MPPT is the duty C of the BC ΔD, so the control law is embodied as tails [76]-[80].

$$E = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{13}$$

$$\Delta E = E(k) - E(k-1) \tag{14}$$

The investigated scheme is presented in Fig. 8, Membership function plots for E, ΔE, and ΔD shown in Fig. 9, Characteristic surface of the FLC shown in Fig. 10.

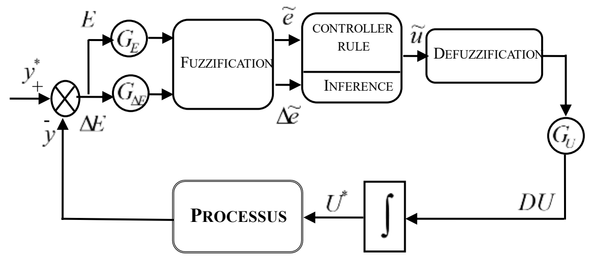

Fig. 8. Proposed control scheme

TABLE III. FLC RULE TABLE

E(k)\ ΔE(k)	ΔD				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PB	NS	NS	NS	ZE	ZE
PS	NB	NB	NB	ZE	ZE

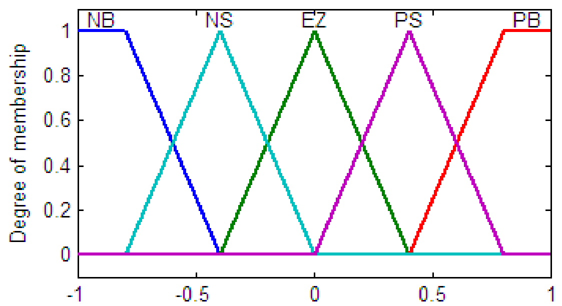

Fig. 9. Membership function plots for E, ΔE, and ΔD

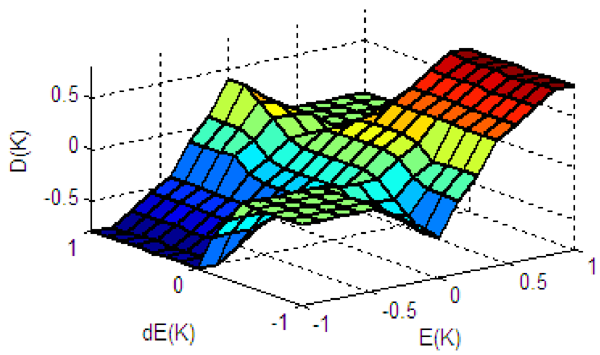

Fig. 10. Characteristic surface of the FLC

IV. RESULTS AND DISCUSSIONS

Many simulations are run in MATLAB/Simulink to assess the suggested MPPT techniques' efficiency. The response and precision data of the investigated methods are presented in Table IV. Furthermore, the performance evaluation of these methods is listed in Table V in terms of response time (RS), tracking accuracy (TA), and stability.

A. *Case I*

In conditions 25C° and 1000 W\m^2, the results are represented in Fig. 11. From Fig. 11, we can see that the P&O reaches the MPP after a time of 0.33s and stays close to the MP. In the INC, we can see that the time to reach the MP is 0.79, but for the FLC, we can see that the FLC has a good time response equal to 0.11s. It is evident from this image, which compares the three methods, that the FLC produces results with high TA and acceptable RS.

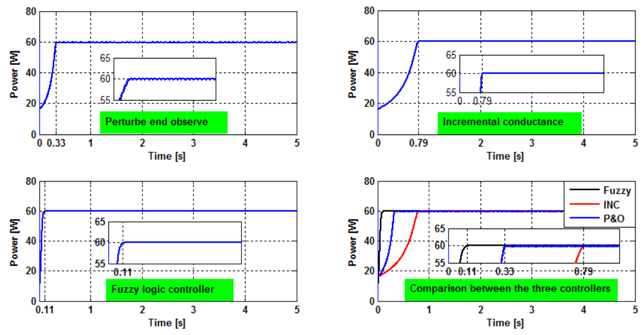

Fig. 11. Simulation results in atmospheric conditions 25C° and 1000 W\m^2

B. *Case II*

For a constant temperature of 25C°and radiation varies from 500 W\m^2 to 1000 W\m^2, the simulation results of the proposed controllers are given in Fig. 12. From Fig. 12, we can see that the P&O grasps the MPP after a time of 0.25s and stays around the MP. At the same time, in the case of irradiation, a change from 500 W\m^2 to 1000 W\m^2 takes a time of 0.06s to reach the MPP. Still, in the INC, we can see that the time to get the MP is 0.57s, and in irradiation, change takes a time of 0.17s and stays very close to the MPP. We can see that the FLC has a virtuous RS of 0.16s and 0.06s to reach the MPP in irradiation change from 500 W\m^2 to 1000 W\m^2. The figure shows the comparison between the three controllers proves the efficiency of the FLC and that the increase of the irradiation generates an increase in the power.

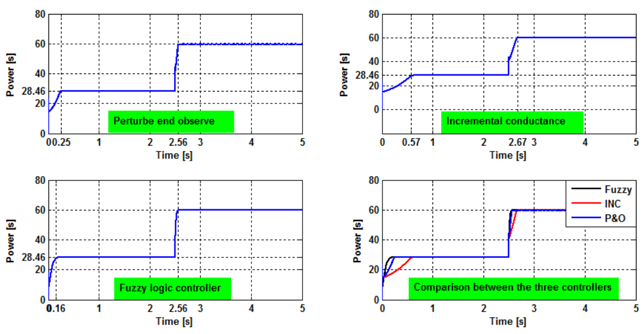

Fig. 12. Simulation results in atmospheric conditions 25C° and radiation varies from 500 W\m^2 to 1000 W\m^2

C. *Case III*

For constant irradiation 1000 W\m^2 and temperature varies from 25C° to 50C°, Fig. 13 displays the computer simulation outcomes for the suggested MPPT methods. In the temperature variation test we notice a good time of reaching the MPP but with an overshoot in all the controls, but still, the FLC-MPPT control is a good choice. The comparison made proves the efficiency of the FLC-MPPT.

TABLE IV. TIME RESPONSE AND PRECISION

	Algorithms		
The conditions	**P&O**	**INC**	**FLC**
25C° and 1000 W/m^2	0.33s	0.79s	0.11s
25C° and 500 W/m^2 to 1000 W/m^2	0.25s and 0.09s	0.57s and 0.17s	0.16s and 0.06s
25C°to 50C° and 1000 W/m^2	Good time	Good time	Good time
Precision	Middle	Good	Very good

TABLE V. PERFORMANCE COMPARISON OF STUDIED METHODS

Methods	**RS**	**TA**	**Stability**
P&O	Medium (M)	H	M
INC	High (H)	H	M
FLC (proposed)	Very H (VH)	VH	VH

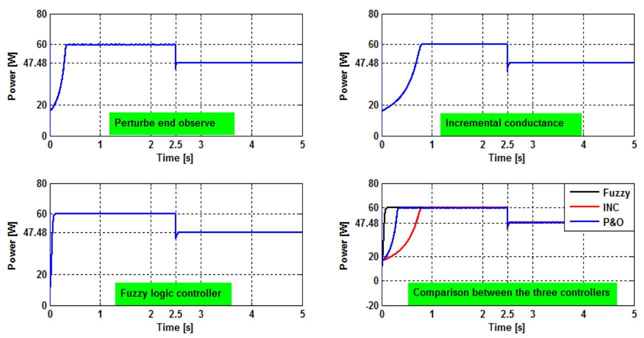

Fig. 13. Simulation results in atmospheric conditions temperature vary from 25C° to 50C° and 1000 W\m^2

V. CONCLUSION

Three approaches (P&O, INC, and FLC) to carrying out MPPT in PV systems were examined in this research. The FLC-MPPT method's performance was assessed and contrasted with that of other algorithms, including INC and P&O. The FLC-MPPT performed better than the formerly discussed methods and continuously showed outstanding tracking abilities in every situation. Additionally, it demonstrated a significant drop in power fluctuations, the lowest average tracking time of 0.06%, and a reduction of more than 60% in convergence time. Future research will focus on improving metaheuristic techniques to distinguish between patterns that are evenly and partly shaded.

ACKNOWLEDGMENT

Authorship contribution: All authors have equally contributed to every facet of this research. Their joint efforts encompassed: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing—original draft; and Writing—review and editing. Data Availability: The data used to support the findings of this study are available at reasonable request from the corresponding author. Conflicts of Interest: The authors declare that they have no conflicts of interest. Funding: The author(s) received no specific funding for this work.

REFERENCES

[1] M. Awad *et al.*, “A review of water electrolysis for green hydrogen generation considering PV/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application,” *Alexandria Engineering Journal*, vol. 87, pp. 213-239, 2024.

[2] J. P. Chaves-Avila, F. Banez-Chicharro, and A. Ramos, “Impact of support schemes and market rules on renewable electricity generation and system operation: The Spanish case,” *IET Renewable Power Generation*, pp. 238-244, 2017.

[3] A. Uzzaman, I. Adam, S. Alam, and P. Basak, “Review on the Safety and Sustainability of Autonomous Vehicles : Challenges and Future Directions,” *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 103-109, 2025.

[4] I. E. Maysse *et al*., "Nonlinear Observer-Based Controller Design for VSC-Based HVDC Transmission Systems Under Uncertainties," *IEEE Access*, vol. 11, pp. 124014-124030, 2023.

[5] N. F. Ibrahim *et al*., “Multiport Converter Utility Interface with a High-Frequency Link for Interfacing Clean Energy Sources (PV\Wind\Fuel Cell) and Battery to the Power System: Application of the HHA Algorithm,” *Sustainability*, vol. 15, no. 18, p. 13716, 2023.

[6] S. C. Ariadita and A. Ma’arif, “Development of an IoT-Monitoring and Control System for Solar Panel Surface Temperature Regulation Utilizing Water-Cooling Techniques,” *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 174–180, 2023.

[7] F. Menzri *et al*., “Applications of Novel Combined Controllers for Optimizing Grid-Connected Hybrid Renewable Energy Systems,” *Sustainability*, vol. 16, no. 16, p. 6825, 2024.

[8] M. M. H. Swarup Kumar, M. M. R. Neidhe, and F. Ahmed, “Enhancing Solar Cell Performance: The Impact of Microstructure in Nanostructured Perovskites,” *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 8-13, 2025.

[9] H. M. H. Farh, A. Fathy, A. A. Al-Shamma’a, S. Mekhilef, and A. M. Al-Shaalan, “Global research trends on photovoltaic maximum power extraction: Systematic and scientometric analysis,” *Sustainable Energy Technologies and Assessments*, vol. 61, p. 103585, 2024.

[10] F. Ahmed, A. Uzzaman, I. Adam, M. Islam, M. Rahman, and A. M. Islam, “AI-Driven Microgrid Solutions for Enhancing Energy Access and Reliability in Rural and Remote Areas : A Comprehensive Review,” *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 110-116, 2025.

[11] N. F. Ibrahim *et al*., "Operation of Grid-Connected PV System With ANN-Based MPPT and an Optimized LCL Filter Using GRG Algorithm for Enhanced Power Quality," *IEEE Access*, vol. 11, pp. 106859-106876, 2023.

[12] N. Benalia *et al*., “Enhancing electric vehicle charging performance through series-series topology resonance-coupled wireless power transfer,” *PLoS One*, vol. 19, no. 8, p. e0309545, 2024.

[13] H. Boudjemai *et al*., “Design, Simulation, and Experimental Validation of a New Fuzzy Logic-Based Maximal Power Point Tracking Strategy for Low Power Wind Turbines,” *International Journal of Fuzzy Systems*, vol. 5, no. 1, pp. 296-310, 2025.

[14] C. Biswas, A. Sharma, and Y. M. Prianka, “Enhancing Energy Flexibility : A Case Study on Peer-to-Peer (P2P) Energy Trading Between Electric Vehicles and Microgrid,” *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 28-35, 2025.

[15] IEA, “Global Energy Review 2021 Assessing the effects of economic recoveries on global energy demand and CO2 emissions in 2021,” *International Energy Agency*, 2021.

[16] Y. M. Prianka, A. Sharma, and C. Biswas, “Integration of Renewable Energy , Microgrids , and EV Charging Infrastructure : Challenges and Solutions,” *Control Systems and Optimization Letters*, vol. 2, no. 3, pp. 317-326, 2024.

[17] N. F. Ibrahim, A. Alkuhayli, A. Beroual, U. Khaled, and M. M. Mahmoud, “Enhancing the Functionality of a Grid-Connected Photovoltaic System in a Distant Egyptian Region Using an Optimized Dynamic Voltage Restorer: Application of Artificial Rabbits Optimization,” *Sensors*, vol. 23, no. 16, p. 7146, 2023.

[18] A. F. A. Ahmed, I. M. Elzein, M. M. Mahmoud, S. A. E. M. Ardjoun, A. M. Ewias, and U. Khaled, “Optimal Controller Design of Crowbar System for DFIG-based WT: Applications of Gravitational Search Algorithm,” *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 7, no. 2, pp. 122-137, 2025.

[19] O. M. Kamel, A. A. Z. Diab, M. M. Mahmoud, A. S. Al-Sumaiti, and H. M. Sultan, “Performance Enhancement of an Islanded Microgrid with the Support of Electrical Vehicle and STATCOM Systems,” *Energies*, vol. 16, no. 4, p. 1577, 2023.

[20] T. Aziz, Z. Al Dodaev, M. A. Halim, and M. Y. A. Khan, “A Review on Integration Challenges for Hybrid Energy Generation Using Algorithms,” *Control Systems and Optimization Letters*, vol. 2, no. 2, pp. 162-171, 2024.

[21] N. F. Ibrahim *et al*., “A new adaptive MPPT technique using an improved INC algorithm supported by fuzzy self-tuning controller for a grid-linked photovoltaic system,” *PLoS One*, vol. 18, no. 11, p. e0293613, 2023.

[22] A. H. Elmetwaly *et al*., “Modeling, Simulation, and Experimental Validation of a Novel MPPT for Hybrid Renewable Sources Integrated with UPQC: An Application of Jellyfish Search Optimizer,” *Sustainability*, vol. 15, no. 6, p. 5209, 2023.

[23] N. Hussain, K. A. Kader, S. Ali, A. Ullah, and Z. Al Dodaev, “An Extensive Analysis of the Significance and Difficulties of Microgrids Based on Renewable Energy in Wireless Sensor Networks,” *Control Systems and Optimization Letters*, vol. 2, no. 2, pp. 178-183, 2024.

[24] M. Awad, M. M. Mahmoud, Z. M. S. Elbarbary, L. Mohamed Ali, S. N. Fahmy, and A. I. Omar, “Design and analysis of photovoltaic/wind operations at MPPT for hydrogen production using a PEM electrolyzer: Towards innovations in green technology,” *PLoS One*, vol. 18, no. 7, p. e0287772, 2023.

[25] R. Zaman, S. Sarker, A. Halim, S. Ibrahim, and A. Haque, “A Comprehensive Review of Techno-Economic Perspective of AC / DC Hybrid Microgrid,” *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 36-42, 2024.

[26] R. Kassem *et al*., “A Techno-Economic-Environmental Feasibility Study of Residential Solar Photovoltaic / Biomass Power Generation for Rural Electrification : A Real Case Study,” *Sustainability*, vol. 16, no. 5, p. 2036, 2024.

[27] M. M. Islam, M. T. Akter, H. M. Tahrim, N. S. Elme, and M. Y. A. Khan, “A Review on Employing Weather Forecasts for Microgrids to Predict Solar Energy Generation with IoT and Artificial Neural Networks,” *Control Systems and Optimization Letters*, vol. 2, no. 2, pp. 184-190, 2024.

[28] S. Ashfaq *et al*., "Comparing the Role of Long Duration Energy Storage Technologies for Zero-Carbon Electricity Systems," *IEEE Access*, vol. 12, pp. 73169-73186, 2024.

[29] Y. Maamar *et al*., “Design, Modeling, and Simulation of A New Adaptive Backstepping Controller for Permanent Magnet Linear Synchronous Motor: A Comparative Analysis,” *International Journal of Robotics and Control Systems*, vol. 5, no. 1, pp. 296-310, 2025.

[30] F. Menzri, T. Boutabba, I. Benlaloui, H. Bawayan, M. I. Mosaad, and M. M. Mahmoud, “Applications of hybrid SMC and FLC for augmentation of MPPT method in a wind-PV-battery configuration,” *Wind Engineering*, vol. 48, no. 6, pp. 1186-1202, 2024.

[31] M. N. Hussain, M. R. Zaman, M. A. Halim, M. S. Ali, and M. Y. A. Khan, “A Comprehensive Review of Renewable and Sustainable Energy Sources with Solar Photovoltaic Electricity Advancement in Bangladesh,” *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 1-7, 2024.

[32] A. T. Hassan *et al*., “Adaptive Load Frequency Control in Microgrids Considering PV Sources and EVs Impacts: Applications of Hybrid Sine Cosine Optimizer and Balloon Effect Identifier Algorithms,” *International Journal of Robotics and Control Systems*, vol. 4, no. 2, pp. 941-957, 2024.

[33] M. M. Mahmoud *et al*., “Voltage Quality Enhancement of Low-Voltage Smart Distribution System Using Robust and Optimized DVR Controllers : Application of the Harris Hawks Algorithm,” *International Transactions on Electrical Energy Systems*, vol. 2022, no. 1, pp. 1-18, 2022.

[34] O. M. Lamine *et al*., “A Combination of INC and Fuzzy Logic-Based Variable Step Size for Enhancing MPPT of PV Systems,” *International Journal of Robotics and Control Systems*, vol. 4, no. 2, pp. 877-892, 2024.

[35] M. N. A. Hamid *et al*., “Adaptive Frequency Control of an Isolated Microgrids Implementing Different Recent Optimization Techniques,”

International Journal of Robotics and Control Systems, vol. 4, no. 3, pp. 1000-1012, 2024.

[36] K. Karthick, “Comprehensive Overview of Optimization Techniques in Machine Learning Training,” *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 23-27, 2024.

[37] S. P. Ye, Y. H. Liu, C. Y. Liu, K. C. Ho, and Y. F. Luo, “Artificial neural network assisted variable step size incremental conductance MPPT method with adaptive scaling factor,” *Electronics*, vol. 11, no. 1, p. 43, 2022.

[38] L. Farah, A. Haddouche, and A. Haddouche, “Comparison between proposed fuzzy logic and anfis for MPPT control for photovoltaic system,” *International Journal of Power Electronics and Drive System*, vol. 11, no. 2, pp. 1065-1073, 2020.

[39] A. Raj *et al*., “Wavelet Analysis- Singular Value Decomposition Based Method for Precise Fault Localization in Power Distribution Networks Using k-NN Classifier,” *International Journal of Robotics and Control Systems*, vol. 5, no. 1, pp. 530-554, 2025.

[40] B. A. Numan, A. M. Shakir, and A. L. Mahmood, “Photovoltaic array maximum power point tracking via modified perturbation and observation algorithm,” *International Journal of Power Electronics and Drive System*, vol. 11, no. 4, pp. 2007-2018, 2020.

[41] P. Singh, B. Mangu, and S. Saho, “A New Dragonfly Optimized Fuzzy Logic-based MPPT Technique for Photovoltaic Systems,” *International Journal of Electrical and Electronics Research (IJEER)*, vol. 11, no. 4, pp. 1097-1102, 2023.

[42] T. Hai, A. Rezvani, and B. N. Le, “Improved design and analysis of MPPT technique for photovoltaic power systems to increase accuracy and speed under different conditions,” *Environment, Development and Sustainability*, vol. 26, no. 4, pp. 9759-9781, 2024.

[43] D. Naamane, H. Benbouhenni, A. Chebabhi, Z. Laid, D. Zellouma, and I. Colak, “A new nonlinear control to improve the efficiency of the PV-SAPF system,” *Energy Reports*, vol. 11, pp. 3096-3116, 2024.

[44] M. Hanhart *et al*., "An Integrated 50 V Boost Controller With Digitally-Assisted MPPT for Submodule PV Applications," *IEEE Open Journal of Power Electronics*, vol. 4, pp. 221-236, 2023.

[45] E. Heydari and A. Y. Varjani, "Combined modified P&O algorithm with improved direct power control method applied to single-stage three-phase grid-connected PV system," *2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC)*, pp. 347-351, 2018.

[46] M. H. Ibrahim, S. P. Ang, M. N. Dani, M. I. Rahman, R. Petra and S. M. Sulthan, "Optimizing Step-Size of Perturb & Observe and Incremental Conductance MPPT Techniques Using PSO for Grid-Tied PV System," *IEEE Access*, vol. 11, pp. 13079-13090, 2023.

[47] A. Bouchakour, A. Borni, and M. Brahami, “Comparative study of P&O-PI and fuzzy-PI MPPT controllers and their optimisation using GA and PSO for photovoltaic water pumping systems,” *International Journal of Ambient Energy*, vol. 42, no. 15, pp. 1746-1757, 2021.

[48] H. Rezk, M. Aly, M. Al-Dhaifallah and M. Shoyama, "Design and Hardware Implementation of New Adaptive Fuzzy Logic-Based MPPT Control Method for Photovoltaic Applications," *IEEE Access*, vol. 7, pp. 106427-106438, 2019.

[49] J. M. Riquelme-Dominguez and S. Martinez, "Comparison of Different Photovoltaic Perturb and Observe Algorithms for Drift Avoidance in Fluctuating Irradiance Conditions," *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1-5, 2020.

[50] A. Gupta and S. K. Jain, “An Improved Time-Sharing Control of Multiport Converter for Solar-Powered EVs Application,” *IETE Journal of Research*, vol. 70, no. 1, pp. 531-541, 2024.

[51] J. C. Kim, J. H. Huh, and J. S. Ko, “Improvement of MPPT control performance using fuzzy control and VGPI in the PV system for micro grid,” *Sustainability*, vol. 11, no. 21, p. 5891, 2019.

[52] A. Nouri, A. Lachheb, and L. El Amraoui, “Optimizing efficiency of Vehicle-to-Grid system with intelligent management and ANN-PSO algorithm for battery electric vehicles,” *Electric Power Systems Research*, vol. 226, p. 109936, 2024.

[53] N. Priyadarshi, S. Padmanaban, J. B. Holm-Nielsen, F. Blaabjerg and M. S. Bhaskar, "An Experimental Estimation of Hybrid ANFIS–PSO-Based MPPT for PV Grid Integration Under Fluctuating Sun Irradiance," *IEEE Systems Journal*, vol. 14, no. 1, pp. 1218-1229, 2020.

[54] A. S. Mohammed and A. Dodo, “Load Frequency Control of One and Two Areas Power System Using Grasshopper Optimization Based Fractional Order PID Controller,” *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 32-40, 2023.

[55] A. Loukriz, M. Haddadi, and S. Messalti, “Simulation and experimental design of a new advanced variable step size Incremental Conductance MPPT algorithm for PV systems,” *ISA Transactions*, vol. 62, pp. 30-38, 2016.

[56] V. V. Martynyuk, M. P. Voynarenko, J. M. Boiko, and O. Svistunov, “Simulation of photovoltaic system as a tool of a state’s energy security,” *International Journal of Engineering: Basics, Applications and Aspects*, vol. 34, no. 2, pp. 487-492, 2021.

[57] A. Juaidi *et al*., “A comparative simulation between monofacial and bifacial PV modules under palestine conditions,” *Solar Compass*, vol. 8, p. 100059, 2023.

[58] F. Listyantoro, A. Ma’arif, A.-N. Sharkawy, and H. M. Marhoon, “DC to AC Inverter Prototype for Small Scale Power Supply with SPWM Method,” *Control Systems and Optimization Letters*, vol. 1, no. 2, pp. 87-92, 2023.

[59] A. Loukriz, D. Saigaa, A. Kherbachi, M. Koriker, A. Bendib, and M. Drif, “Prediction of Photovoltaic Panels Output Performance Using Artificial Neural Network,” *International Journal of Energy Optimization and Engineering*, vol. 11, no. 2, pp. 1-19, 2022.

[60] A. Fatah *et al*., “Design, and dynamic evaluation of a novel photovoltaic pumping system emulation with DS1104 hardware setup: Towards innovative in green energy systems,” *PLoS One*, vol. 19, no. 10, p. e0308212, 2024.

[61] M. Premkumar, C. Kumar, and R. Sowmya, “Mathematical modelling of solar photovoltaic cell/panel/array based on the physical parameters from the manufacturer’s datasheet,” *International Journal of Renewable Energy Development*, vol. 9, no. 1, pp. 7-22, 2020.

[62] H. N. Kadeval and V. K. Patel, “Mathematical modelling for solar cell, panel and array for photovoltaic system,” *Journal of Applied and Natural Science*, vol. 13, no. 3, pp. 937-943, 2021.

[63] A. Hysa, M. M. Mahmoud, and A. Ewais, “An Investigation of the Output Characteristics of Photovoltaic Cells Using Iterative Techniques and MATLAB ® 2024a Software,” *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 46-52, 2025.

[64] S. Heroual *et al*., “Enhancement of Transient Stability and Power Quality in Grid- Connected PV Systems Using SMES,” *International Journal of Robotics and Control Systems*, vol. 5, no. 2, pp. 990-1005, 2025.

[65] H. Zhang, Y. Li, R. Xie, J. Song, B. Liang, and Y. Huangfu, "Adaptive Model Predictive Control of an Interleaved Boost Converter Using Real-Time Updated Model," *IEEE Transactions on Power Electronics*, vol. 38, no. 2, pp. 1720-1731, 2023.

[66] Y. Li, S. Sahoo, T. Dragičević, Y. Zhang, and F. Blaabjerg, "Stability-Oriented Design of Model Predictive Control for DC/DC Boost Converter," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 1, pp. 922-932, 2024.

[67] T. Boutabba, I. Benlaloui, F. Mechnane, I. M. Elzein, M. Ammar, and M. M. Mahmoud, “Design of a Small Wind Turbine Emulator for Testing Power Converters Using dSPACE 1104,” *International Journal of Robotics and Control Systems*, vol. 5, no. 2, pp. 698-712, 2025.

[68] H. Alnami, S. A. E. M. Ardjoun, and M. M. Mahmoud, “Design, implementation, and experimental validation of a new low-cost sensorless wind turbine emulator: Applications for small-scale turbines,” *Wind Engineering*, vol. 48, no. 4, pp. 565-579, 2024.

[69] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of Perturb and Observe MPPT Algorithm Implementation Techniques for PV Pumping Applications," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 1, pp. 21-33, 2012.

[70] L. Piegari, R. Rizzo, I. Spina, and P. Tricoli, “Optimized adaptive perturb and observe maximum power point tracking control for photovoltaic generation,” *Energies*, vol. 8, no. 5, pp. 3418-3436, 2015.

[71] D. Remoaldo and I. S. Jesus, “Analysis of a traditional and a fuzzy logic enhanced perturb and observe algorithm for the mppt of a photovoltaic system,” *Algorithms*, vol. 14, no. 1, p. 24, 2021.

[72] I. Al-Wesabi, Z. Fang, H. M. Hussein Farh, A. A. Al-Shamma’a, and A. M. Al-Shaalan, “Comprehensive comparisons of improved incremental conductance with the state-of-the-art MPPT Techniques

for extracting global peak and regulating dc-link voltage," *Energy Reports*, vol. 11, pp. 1590-1610, 2024.

[73] M. V. da Rocha, L. P. Sampaio, and S. A. O. da Silva, "Comparative analysis of MPPT algorithms based on Bat algorithm for PV systems under partial shading condition," *Sustainable Energy Technologies and Assessments*, vol. 40, p. 100761, 2020.

[74] G. D. Eddine, N. Abdellatif, and S. Abdelkader, "Power System Stabilizer Design using Genetic Algorithms and Particle Swarm Optimization," *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 52-57, 2023.

[75] A. Safari and S. Mekhilef, "Simulation and Hardware Implementation of Incremental Conductance MPPT With Direct Control Method Using Cuk Converter," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1154-1161, 2011.

[76] N. Bouarroudj *et al*., "Fuzzy Logic Controller Based Maximum Power Point Tracking and its Optimal Tuning in Photovoltaic Systems," *Serbian Journal of Electrical Engineering*, vol. 18, no. 3, pp. 351-384, 2021.

[77] M. Aly, E. A. Mohamed, H. Rezk, A. M. Nassef, M. A. Elhosseini, and A. Shawky, "An Improved Optimally Designed Fuzzy Logic-Based MPPT Method for Maximizing Energy Extraction of PEMFC in Green Buildings," *Energies*, vol. 16, no. 3, p. 1197, 2023.

[78] R. Ghasemi and N. A. Hazaveh, "Ultimately Bounded TSK Fuzzy Management in Urban Traffic Stream Mechanism: Multi-Agent Modeling Approach," *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 58-63, 2023.

[79] H. Abidi, L. Sidhom, and I. Chihi, "Systematic Literature Review and Benchmarking for Photovoltaic MPPT Techniques," *Energies*, vol. 16, no. 8, p. 3509, 2023.

[80] S. Jalali Zand, S. Mobayen, H. Z. Gul, H. Molashahi, M. Nasiri, and A. Fekih, "Optimized Fuzzy Controller Based on Cuckoo Optimization Algorithm for Maximum Power-Point Tracking of Photovoltaic Systems," *IEEE Access*, vol. 10, pp. 71699-71716, 2022.