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A Combination of INC and Fuzzy Logic-Based Variable Step Size for Enhancing MPPT of PV Systems

Ouassa Mohammed Lamine [a,1], Noureddine Bessous [a,2], Borni Abdelhalim [b,3], Fahd A. Banakhr [c,4], Mohamed I. Mosaad [c,5], Mammeri Oussama [d,6], Mohamed Metwally Mahmoud [e,7,*]

[a] El-Oued Electrical Engineering and Renewable Energy Laboratory, El-Oued University, El-Oued 39000, Algeria
[b] Centre de Développement des Energies Renouvelables. CDER Unité de Recherche Appliquée en Energies Renouvelables URAER, Ghardaïa Université, Ghardaïa 47000, Algeria
[c] Department of Electrical and Electronics Engineering, Yanbu Industrial College, Yanbu Industrial City 41912, Saudi Arabia
[d] Electrical Engineering Department, Faculty of Technology, El-Oued University, El-Oued 39000, Algeria
[e] Electrical Engineering Department, Faculty of Energy Engineering, Aswan University, Aswan 81528, Egypt
[1] ouassa-mohammedlamine@univ-eloued.dz; [2] nbessous@yahoo.fr; [3] borniabdelhalim77@gmail.com; [4] banakhrf@RCJY.EDU.SA, [5] m_i_mosaad@hotmail.com, [6] mammerioussama@yahoo.fr, [7] metwally_m@aswu.edu.eg
* Corresponding Author

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ABSTRACT

The significance of using the variable step Incremental Conductance (INC) technique in Maximum Power Point monitoring (MPPT) of photovoltaic (PV) systems resides in its capacity to improve the efficiency of energy conversion. This is accomplished through the constant measurement and comparison of incremental changes in current and voltage, precisely monitoring the maximum power point amidst changing environmental conditions. This traditional INC-MPPT approach has two primary disadvantages. Initially, it employs a predetermined scaling factor that necessitates human adjustment. Furthermore, it adjusts the inclination of the PV characteristics curve to modify the step size. This implies that even little changes in PV module voltage will have a substantial impact on the total step size. As a result, it shifts the operating point away from the intended reference maximum power point. The objective of this work is to improve the efficiency of traditional INC by overcoming the constraints associated with step size modifications. This is achieved by using a fuzzy logic (FL) technique to adjust the step size adaptively in response to environmental changes. The presented INC-FL-MPPT successfully achieves MPPT for a PV system under enhanced steady-state and transient-state settings. The results demonstrate the superiority of the suggested approach compared to three distinct MPPT strategies, namely Perturb and Observe (P&O), Classical INC, and P&O-FL technique.

1. Introduction

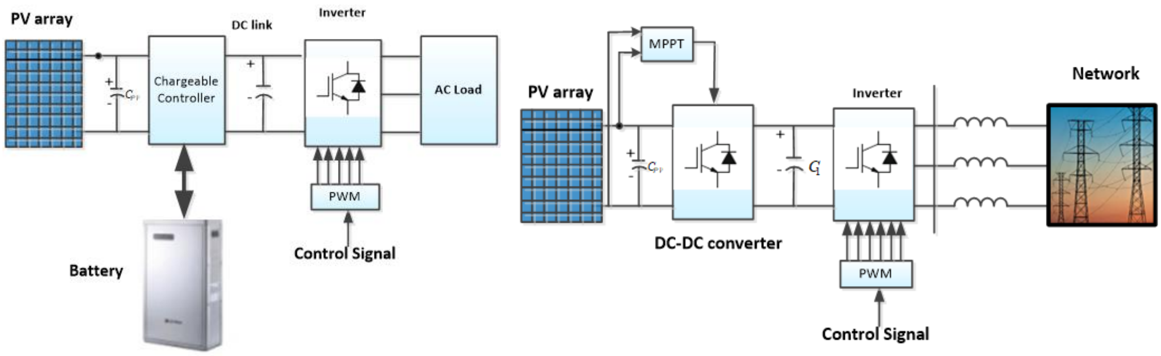
1.1. Motivations and Background

The surging adoption of renewable energy sources (RESs) is a direct response to the profound environmental repercussions wrought by the unrestrained consumption of fossil fuels (FFs) [1], [2]. The adverse effects of widespread fossil fuel use extend beyond a mere environmental concern; they encompass a multifaceted array of issues that imperil the delicate balance of our planet. Foremost among these concerns is the relentless increase in greenhouse gas emissions, primarily carbon dioxide and methane, emanating from the combustion of fossil fuels [3], [4]. This upward trajectory in emissions has been a key driver of climate change, triggering a cascade of detrimental effects such as rising global temperatures, altered weather patterns, and more frequent and severe natural disasters. The ramifications of climate change are felt worldwide, affecting ecosystems, communities, and economies alike. In addition to the climate crisis, the pervasive use of FFs begets significant pollution challenges. The release of pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter into the atmosphere contributes to air pollution, with repercussions for human health and the environment. Ground-level ozone formation, acid rain, and the degradation of air quality are among the consequences that pose tangible threats to public well-being. Furthermore, the reliance on FFs as a primary energy source introduces an element of economic instability. Vulnerability to fluctuations in FF prices and geopolitical tensions surrounding the control and distribution of these resources can lead to economic volatility on both national and global scales. The interplay between energy markets, geopolitical events, and economic stability underscores the urgent need for diversification and transition towards more sustainable and resilient energy sources [5]-[8].

Within this spectrum of RESs, photovoltaic (PV) has emerged as a particularly promising and captivating solution. Its ascendancy is attributed to its status as one of the newest and most economically viable technologies available today [9], [10]. The rapid advancements in PV solar technology have garnered substantial research attention in recent years, underscoring the pivotal role it plays in addressing the pressing global energy challenges. The attractiveness of PV lies not only in its promise as a clean and sustainable power source but also in its versatility and scalability. PV systems can be deployed across a wide range of applications, from small-scale residential installations to large-scale utility projects, contributing to their widespread adoption. Additionally, the declining costs associated with PV technology have further accelerated its acceptance as a feasible and cost-effective solution for meeting the burgeoning energy demands of the twenty-first century. As nations and industries seek to transition away from environmentally detrimental energy practices, the multifaceted benefits of PV make it a linchpin in the pursuit of a cleaner and more sustainable energy future. The collective emphasis on RESs reflects a global commitment to mitigating the adverse impacts of climate change and fostering a harmonious coexistence between energy consumption and environmental preservation. In essence, the heightened demand for green energy, with PV at its forefront, signifies a transformative step towards a more sustainable and resilient energy paradigm [11]-[13].

Two main categories of PV systems can be classed based on their connection to the network. The first option is the on-grid system, while the second option is the off-grid system. The off-grid PV systems operate independently from the public grid and necessitate the use of battery storage to retain surplus energy for times when solar production is insufficient. These systems are well-suited for isolated areas that lack grid connectivity, providing independence but typically requiring a greater upfront cost due to the inclusion of batteries and supplementary equipment [14]. On the other hand, the on-grid PV systems are directly linked to the public electrical grid, enabling any surplus energy generated to be transferred back to the grid. This typically leads to financial credits or incentives. These systems depend on the grid to provide electricity when solar energy is inadequate, such as during periods of darkness or overcast weather. On-grid PV systems have numerous benefits compared to off-grid systems, making them the preferable option in various situations. They offer enhanced reliability by establishing a connection with the public electrical grid, guaranteeing a consistent power supply even during periods of poor solar production [15]. This obviates the necessity for expensive and labor-intensive battery storage, hence decreasing the overall cost of the system. This can result in financial credits or a reduction in electricity costs. The typical configurations of on and off-grid systems are given in Fig. 1 [14].

A typical arrangement of a grid-connected PV system, shown in Fig. 1-b comprises many essential components [16]. The system starts with PV panels whose output is DC power, characterized by its unregulated DC voltage and current waveforms. The DC voltage is connected to the DC-DC converter, which can function as either a boost or buck converter. This converter regulates the PV DC voltage level. Furthermore, it demonstrates a crucial characteristic of voltage regulation to effectively track the maximum output of the photovoltaic system. The DC-AC inverter is essential in on-grid PV systems as it converts the DC voltage from the converter into AC. This conversion is crucial for the smooth integration of solar power into the grid, enabling surplus energy to be returned to the system and used in other locations. In addition, the inverter harmonizes the phase and frequency of the converted power with the AC power of the grid, guaranteeing a steady and effective flow of energy [17], [18].



Off-grid System (a) On-grid System (b)

Fig. 1. Typical configurations of PV systems

1.2. Literature Analysis

The PV solar cell has two primary attributes known as P-V and I-V. Their primary influences are mostly determined by external factors such as irradiance and temperature. The photovoltaic (PV) system reaches its maximum power output at a certain voltage point, which is determined by the degree of irradiance and temperature. This is seen in Fig. 2. Any changes in these factors will result in a shift of this point from the highest point, necessitating a special control mechanism to adjust the PV DC voltage level to match the new maximum power point. This voltage is managed by regulating it via the duty cycle control signal of the DC-DC converter, which is referred to as the Maximum Power Point Tracking (MPPT) technique [19], [20].

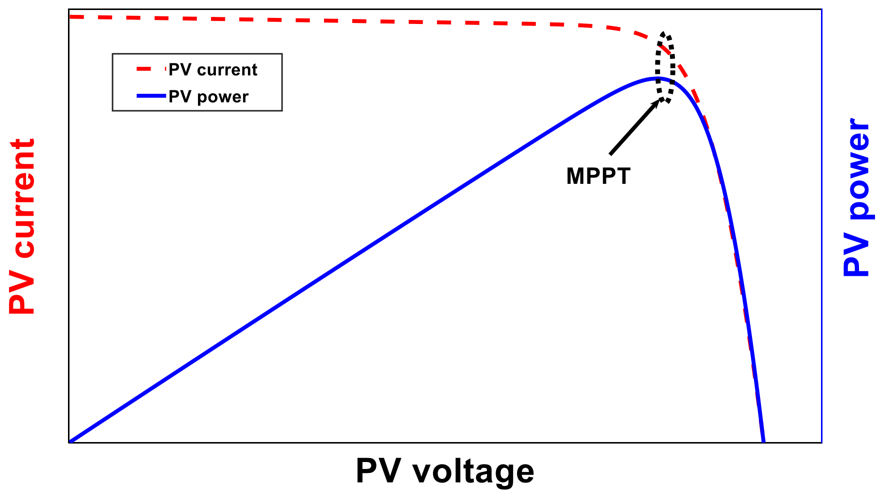


Fig. 2. PV and IV characteristics of PV cell

To ensure that the PV features can operate at the maximum power point despite the environmental variations, several MPPT algorithms were developed [21]-[23]. These algorithms vary in several respects, such as the rate at which they track, the expenses involved, and the required equipment for installation and use.

The introduction of the modified perturb and observe (M-P&O) MPPT algorithm with a variable step size based on fuzzy logic (FL) marks a significant stride in the evolution of PV technology. This innovative approach stands out for its ability to tackle and overcome several shortcomings inherent in traditional incremental conductance (INC) MPPT tracking techniques. Firstly, the M-INC algorithm addresses the issue of a gradual rise in the MPP, a common challenge encountered in conventional INC-MPPT methods. This gradual increase in MPP can result in suboptimal energy harvesting and reduced overall system efficiency. The M-INC algorithm, with its M-P&O strategy, introduces a more dynamic and responsive approach, ensuring a swifter and more precise tracking of the MPP. Moreover, the M-INC algorithm mitigates the problem of slow convergence associated with traditional INC techniques. Slow convergence can impede the MPPT process, especially during sudden changes in environmental conditions. The variable step size based on FL in M-INC enables adaptive adjustments, allowing for a faster convergence to the optimal operating point, thereby enhancing the overall efficiency of the PV system [24]-[27].

Another critical improvement offered by the M-INC algorithm is its ability to address power oscillations around the MPP in steady-state conditions. Power oscillations can lead to energy losses and instability in the system. By incorporating FL into the variable step size mechanism, M-INC minimizes oscillations, ensuring a more stable and consistent power output under varying operating conditions. Additionally, the M-INC algorithm effectively handles rapid MPP location changes triggered by varying meteorological conditions. Traditional MPPT algorithms may struggle to adapt swiftly to these changes, resulting in suboptimal performance. The FL-based variable step size in M-INC enhances the algorithm's adaptability, enabling it to respond rapidly to shifts in solar irradiance, temperature, or other meteorological factors [28]-[30].

1.3. Contributions

The incorporation of FL into the M-INC MPPT algorithm not only rectifies these deficiencies but also provides a more intelligent and adaptive control strategy. FL allows the algorithm to make nuanced decisions based on imprecise or incomplete information, further enhancing its robustness in real-world applications. The M-INC MPPT algorithm represents a groundbreaking advancement in PV technology, addressing and overcoming the limitations of traditional INC techniques. Its dynamic and adaptive nature, empowered by FL, positions it as a valuable tool for optimizing energy harvesting in PV systems, contributing significantly to the ongoing efforts to improve the efficiency and reliability of renewable energy technologies. The research methodology incorporates a test system designed to expedite the development of control algorithms within a real-time environment (RTE), leveraging the capabilities of MATLAB® and Simulink® 2016a. This test system serves as a crucial tool in the iterative process of refining and enhancing the proposed M-P&O algorithm.

The PC-based simulation platform provided in the study plays a pivotal role in the validation and optimization phases of the M-INC algorithm. This platform allows researchers to simulate and analyze the algorithm's performance under various conditions, providing valuable insights into its robustness, efficiency, and adaptability. By utilizing a virtual environment, researchers can systematically assess the algorithm's behavior and make necessary adjustments to ensure its reliability and effectiveness in real-world applications. Furthermore, the research presents a comprehensive overview of the mathematical PV emulator, shedding light on its intricacies and functionalities. This emulator serves as a computational model that mimics the behavior of a physical PV system, allowing researchers to conduct simulations and experiments in a controlled setting. The detailed exposition of the mathematical PV emulator aids in understanding its role in the research methodology and highlights its significance in validating the M-INC algorithm. Additionally, the study delves into the electrical properties of the model and the intricate circuit connections involved in the PV system. This comprehensive exploration provides a foundational understanding of the system's components, emphasizing the importance of considering electrical characteristics in the development and optimization of MPPT algorithms. In summary, the deployment of a PC-based simulation platform for validation and optimization, as well as the detailed presentation of the mathematical PV emulator and electrical properties collectively contribute to the robustness and credibility of the research. These components form a cohesive framework that not only advances the understanding of the proposed M-INC MPPT algorithm but also establishes a solid foundation for future research and practical implementation in the field of PV systems.

2. PV Panel and Boost Converter Modeling

2.1. PV Panel Simulation

The PV cell's equivalent circuit when exposed to radiation. It is equivalent to an Ipv current generator linked in parallel to a diode. There are two new parasite resistances. The characteristics of the cell, I = f(V) Fig. 3, are somewhat influenced by these resistors. The cell's internal resistance is measured in series resistance (Rs). The leakage current at the junction is the cause of the shunt resistor (Rp) [31], [32].

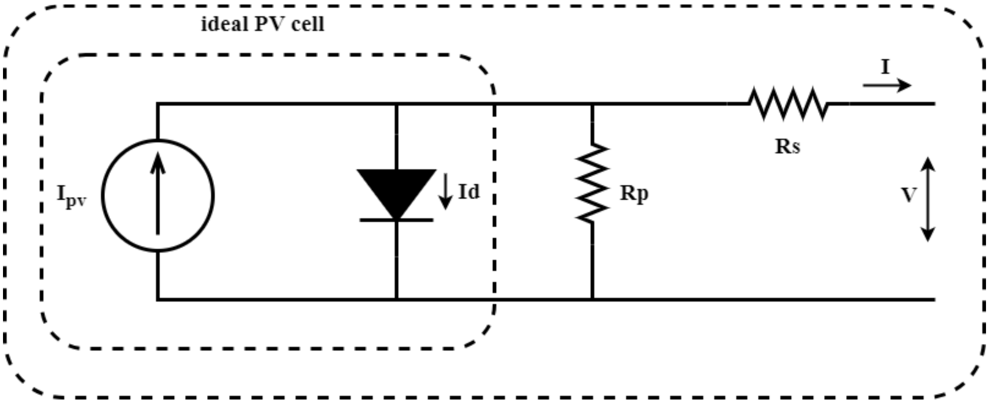


Fig. 3. An equivalent solar cell circuit

The following formulas represent the mathematical expression of the current-voltage characteristic of the ideal PV cell and this is fully analyzed and described in [33]:

$$I = I_{PV.cell} - I_{0.cell}\left[exp\left(\frac{qV}{akT}\right) - 1\right] \tag{1}$$

$$I = I_{PV} - I_0\left[exp\left(\frac{V + R_s I}{N_s V_t}\right) - 1\right] - \frac{V + IR_s}{R_p} \tag{2}$$

The technical specifications of the PV panel utilized in this application, under standard test conditions (STCs), are presented in Table 1. It should be noted that, under the specified fixed or variable conditions, the PV panel is capable of producing the most energy at one point. Both of the I-V and P-V characteristics at different irradiances and constant temperature of 25°C are presented in Fig. 4 and Fig. 5.

Table 1. The solar panel's user-defined settings at STC

Maximum rating for power	178.068 W
Open-circuit Voltage (Voc)	42.1 V
Short circuit Current (Isc)	5.423 A
Maximum voltage for power (Vmp)	35.5 V
Maximum current power (Imp)	5.016 A
Number of cells	60
Typical operating cell temperature	25

2.2. The Boost Converter

The MPP should be matched by the voltage or current used in MPPT techniques. The provided power is rarely at its peak when the PV module is connected directly to the load. Consequently, it is recommended to combine the PV panel with a DC-DC converter controlled by the MPPT tracker for it to operate at the MPP [31]. Examine a PV panel with a resistive load that is coupled to a boost-type converter Fig. 6. Table 2 lists the design parameter of the implemented DC-DC converter. The relationship between the input and output voltages of the converter is as follows and is fully described in [34], [35]:

$$V_{out} = \frac{1}{1-\alpha} V_{pv} \tag{3}$$

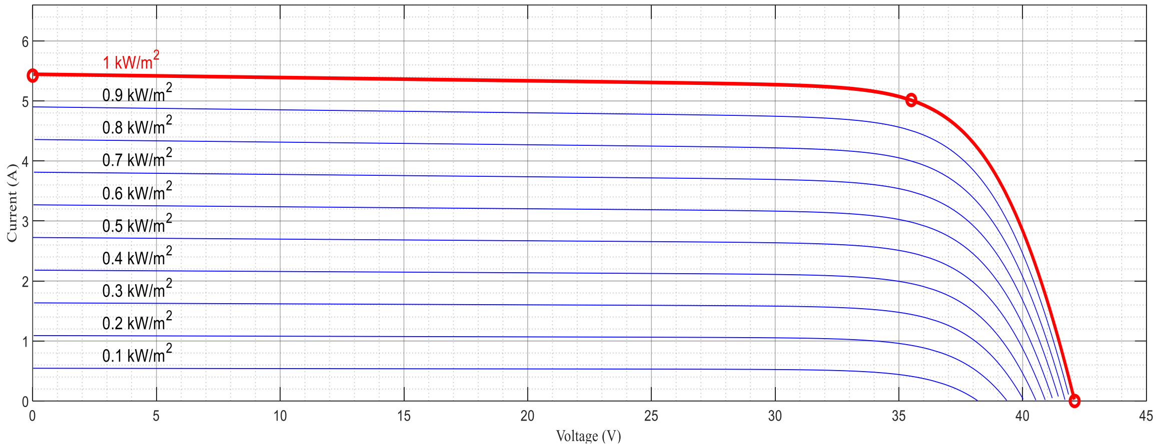


Fig. 4. I-V characteristics at different irradiances and constant temperature of 25°C

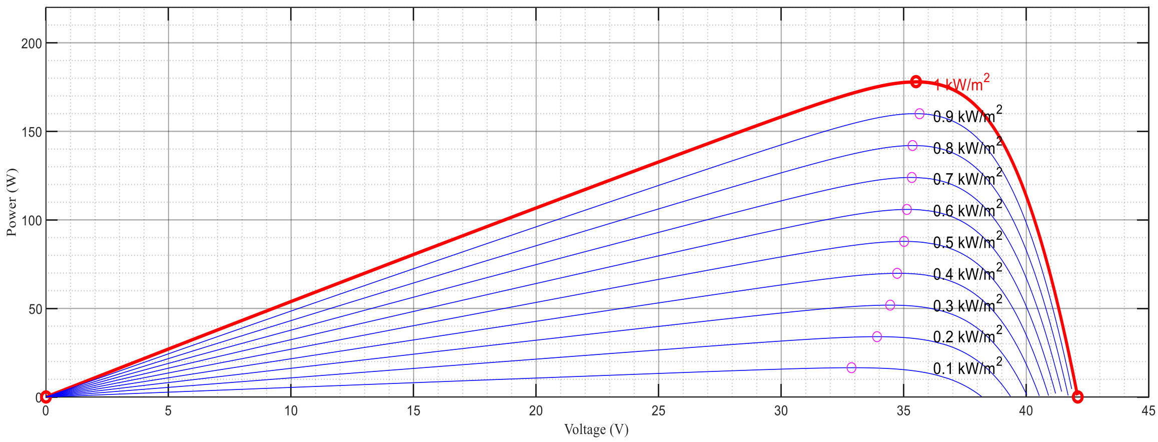


Fig. 5. P-V characteristics at different irradiances and constant temperature of 25°C

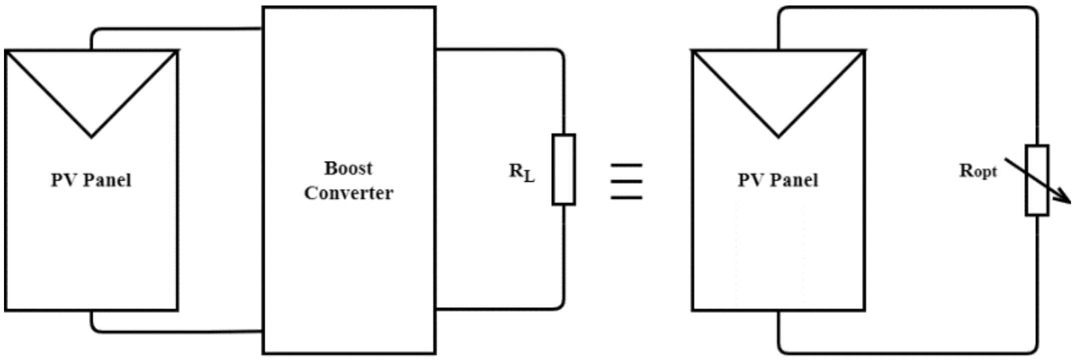


Fig. 6. Boost acts as resistance emulator

If we consider the converter to function at 100% efficiency when connected to a resistive load (R), the power output from the PV panel would be:

$$P_{pv} = \frac{V_{out}^2}{R_L} = \left(\frac{1}{1-\alpha}\right)^2 \frac{V_{pv}^2}{R_L} \tag{4}$$

By correctly changing the duty ratio command of the converter, maximum power may be obtained [6]. The following equation describes the relationship in continuous conduction mode between the simulated resistance (Ropt) and the load resistance (RL):

$$R_{opt} = R_L(1-\alpha)^2 \tag{5}$$

The following equation can be used to express RL:

$$R_{opt} = R_L(1-\alpha)^2 \tag{6}$$

The following equation can be used to express RL:

$$R_{opt} = R_L(1-\alpha)^2 \tag{7}$$

The load resistance RL value needs to be:

$$R_{opt} = R_L(1-\alpha)^2 \tag{8}$$

Assumedly, the PV panel runs under STC circumstances. The optimal resistance Ropt to reach the MPP is:

Table 2. Boost the design parameter of a DC-DC converter.

Boost parameter for DC-DC converter	
Inductor	110 µH
Input capacitor	200 µF
Output capacitor	420 µF
Switching frequency	20 Hz

3. Investigated MPPT Methodologies

One of the most important methods for increasing the effectiveness of PV systems is MPPT. The point on the current-voltage (I-V) curve where the PV produces the most power is known as the MPP. The MPP is affected by many variables, including temperature, shade, and sun irradiation. The goal of MPPT techniques is to track the MPP in response to changing environmental factors and modify the PV's operating point to maximize power extraction [36]-[38].

3.1. The Principle of INC MPPT Techniques

INC-MPPT technology is used to monitor and maintain the MPP of a PV panel. This is accomplished by adjusting the I-V in order to extract the most power under various environmental conditions. The output I-V of the PV is measured using INC MPPT technology, which then compares the results with historical data to determine the direction of the power change [39], [40]. The graphic in Fig. 7 illustrates the fundamental concept of the approach. By relying on a fixed delta cycle step, this method allows us to track the MPP, but the tracking is slow in response time and fluctuating in value. To improve this method, it has become dependent on a variable step size that automatically adjusts the operating points intending to improve the response time and reduce Oscillation.

3.2. Proposed MPPT Technique

The limiting oscillation of PV array output power around MPP and the convergence of rising step size perturbation are incompatible with each other because the conventional INC approach usually works on fixed step size perturbation. Reaching MPP takes a long time when using the INC technique with a fixed step size. This is because once it reaches a specific operational point, the PV system will go in a planned step to reach MPP. We employ a variable step when the operational point is close to the MPP and a large step when it is far from the MPP in order to reach the MPP in less time. To overcome the drawbacks of the traditional fixed step size INC MPPT, this study used the FL technique to modify the step size for an INC MPPT algorithm. The suggested FL-based variable step size INC MPPT algorithm's flowchart is shown in Fig. 8.

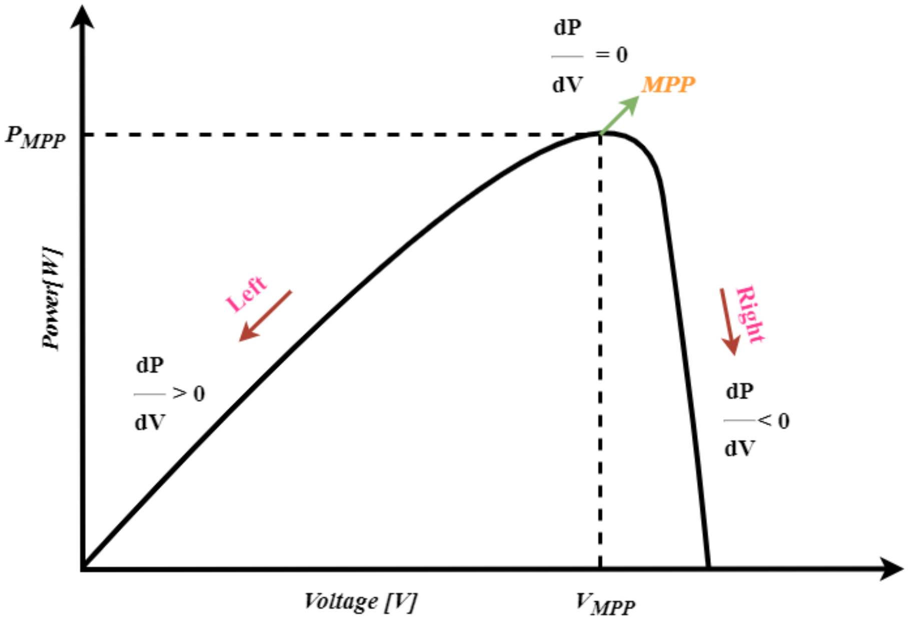


Fig. 7. P-V characteristics curve

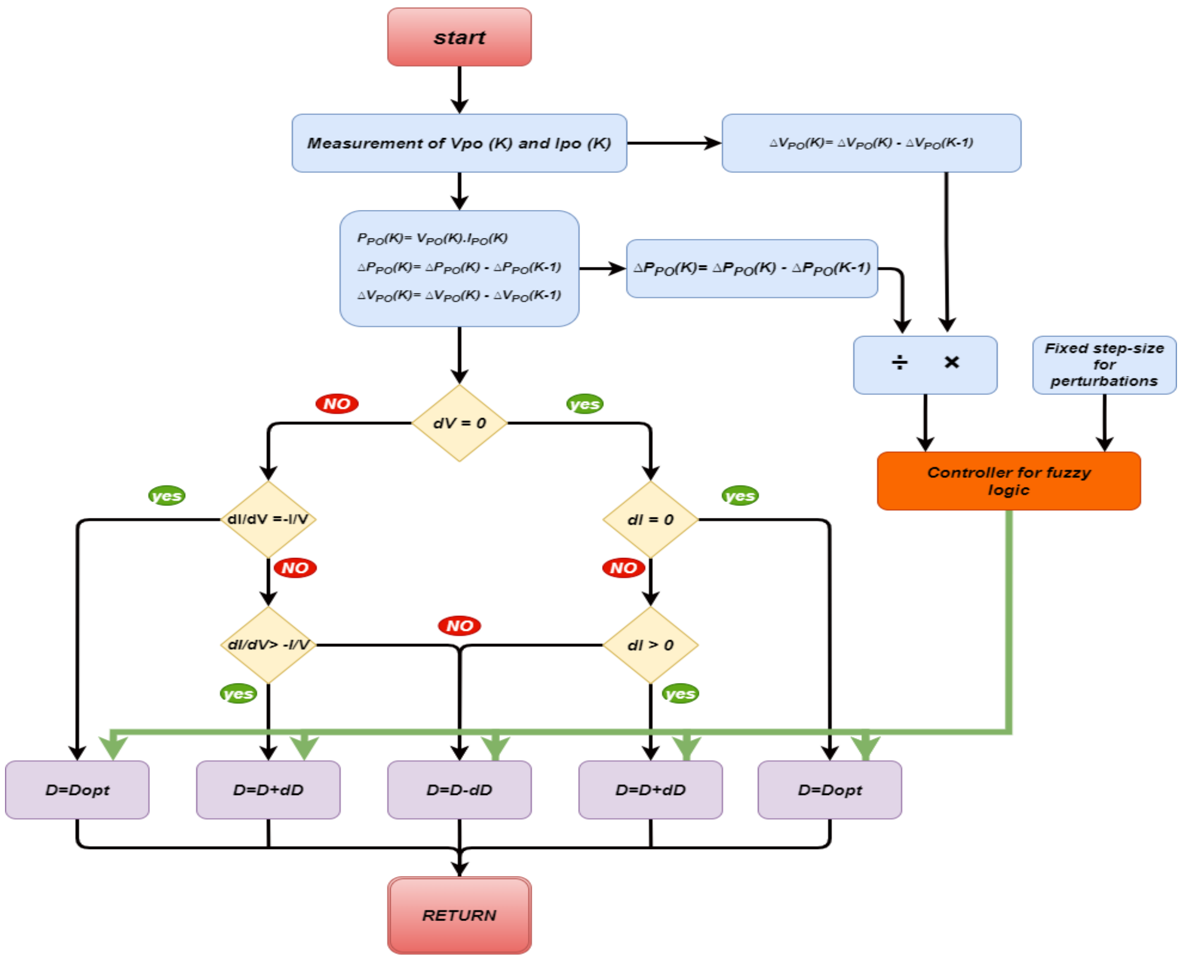


Fig. 8. Flowchart of FL-based variable step size INC-MPPT algorithm

The FL technique used to compute the variable step size in the proposed variable step size INC-MPPT algorithm may enable automatic updating of the PV array operating point by giving a variable step size reference. The variable step size control action was determined using Mamdani's FL rule-based technique and a Max-Min operation structure. As seen in Fig. 9, the FL controller is composed of five parts. Twenty-five rules with "if" and "then" syntax was used in the controller's design. Moreover, positive medium (PA), positive small (PL), and positive extremely tiny (PVL) were the designations assigned to the fuzzy. Table 3 displays these values as positive high (PH) and positive very high (PVH), respectively.

The associated power converter may automatically modify the PV array's operating point following the recommended variable step size INC MPPT algorithm, which uses an FL method to determine the variable step size. This is accomplished by providing a variable step size reference voltage, or Vpv, to the associated power converter. Using a Max-Min operation structure and Mamdani's FL rule-based method, the variable step size control action was identified. The FL controller is made up of five components, as shown in Fig. 10. Twenty-five regulations and the operators "if" and "then" were used to develop the controller. Additionally, as Table 3 shows, positive average (PA), positive low (PL), and positive very low (PVL).

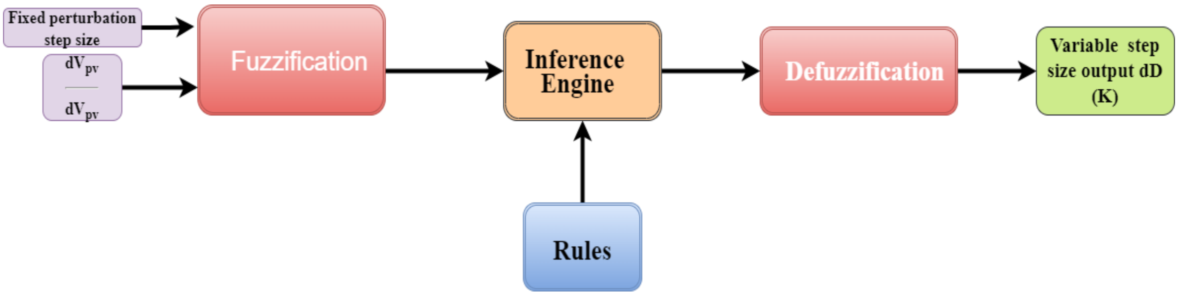
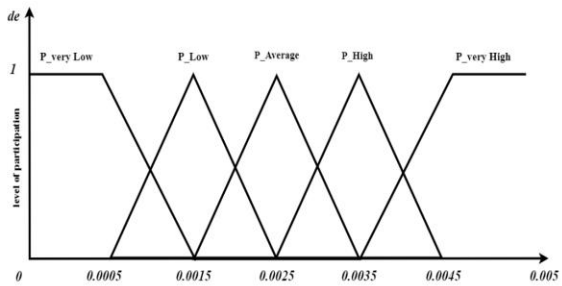
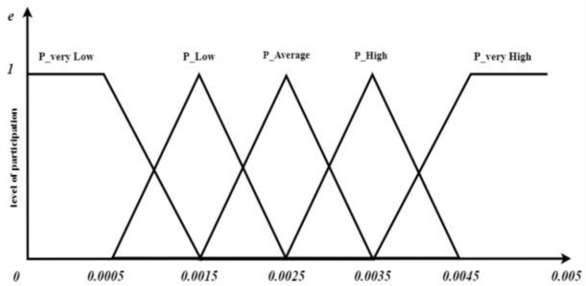


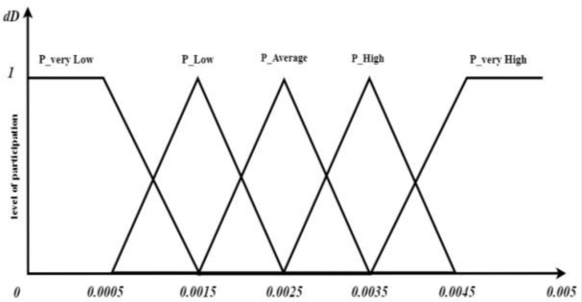
Fig. 9. Block schematic of a FL controller



Modification of Error S(k) (a)



Voltage step (Error) (b)



variable step size variation (c)

Fig. 10. The membership function of the proposed FL controller for the variable step size MPPT algorithm

The output variable step size, denoted as ΔD(k), is the required result of every one of the twenty-five FL controller rules. The input-output mapping of a FL controller with two inputs and one output is shown on a surface called the control viewer Fig. 11.

Table 3. FL rules for the proposed MPPT technique.

E = Voltage step / Δe = S(k)	PVL	PL	PA	PH	PVH
PVL	PVH	PVL	PVL	PL	PL
PL	PVH	PVL	PVL	PL	PL
PA	PL	PL	PL	PVH	PVH
PH	PL	PVH	PL	PVL	PVH
PVH	PVL	PVL	PVH	PH	PVH

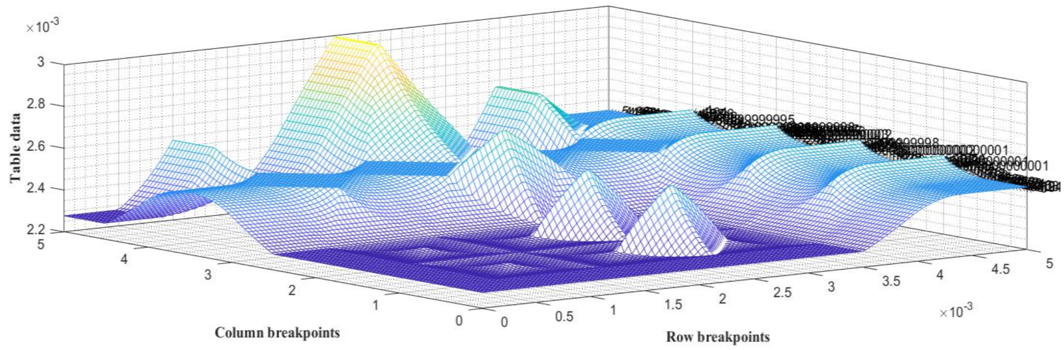


Fig. 11. The relationship between the output variable step ΔDpv(k), the fixed perturbation voltage step size, and the measured PV curve slope S(k) is shown by an input-output mesh plot

4. Simulation Results

MATLAB Simulink is used to simulate and compare two distinct MPPT approaches: a fixed step size INC MPPT and a variable step size INC MPPT employing a suggested FL controller. The investigated system is depicted in Fig. 12. This system is tested under change in solar irradiance (1000, 700,900 W/m2) to show the efficacy of the proposed technique as seen in Fig. 13. There is a moderate efficiency difference favoring the conventional INC with fixed step size voltage in steady state when comparing the suggested modified INC based on FL and variable step size to the traditional INC with fixed step size voltage utilization. A comparison of the two investigated MPPT techniques in Fig. 14, shows the efficacy of the proposed method in boosting the output power in terms of settling time, rise time, and under\overshoot. Both output voltage as in Fig. 15 and output current as in Fig. 16 prove the effectiveness, reliability, and accuracy of the proposed method. A comparison with the other three published techniques is presented in Table 4 to show the role of the suggested method.

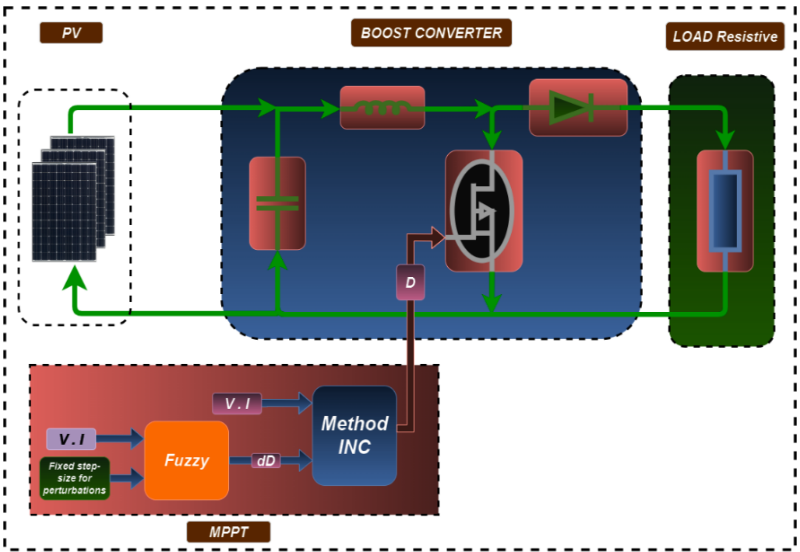


Fig. 12. Block diagram of the MPPT algorithm testing experiment setup

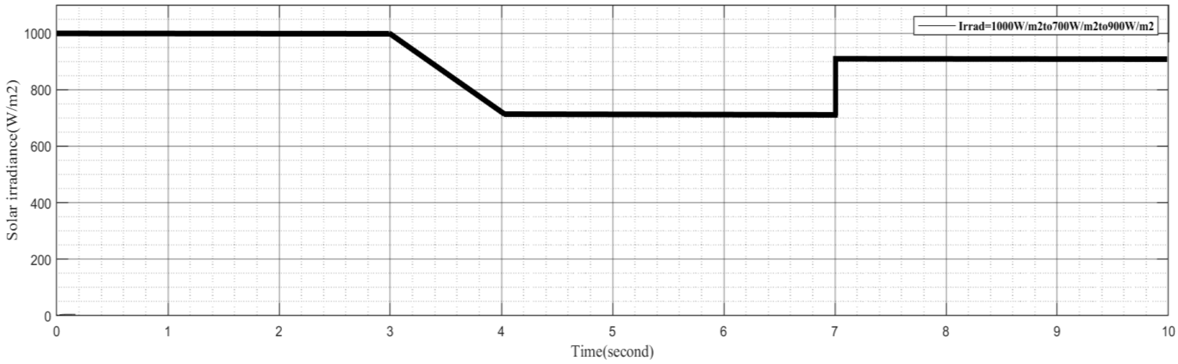


Fig. 13. Change in solar irradiance (1000, 700,900 W/m2)

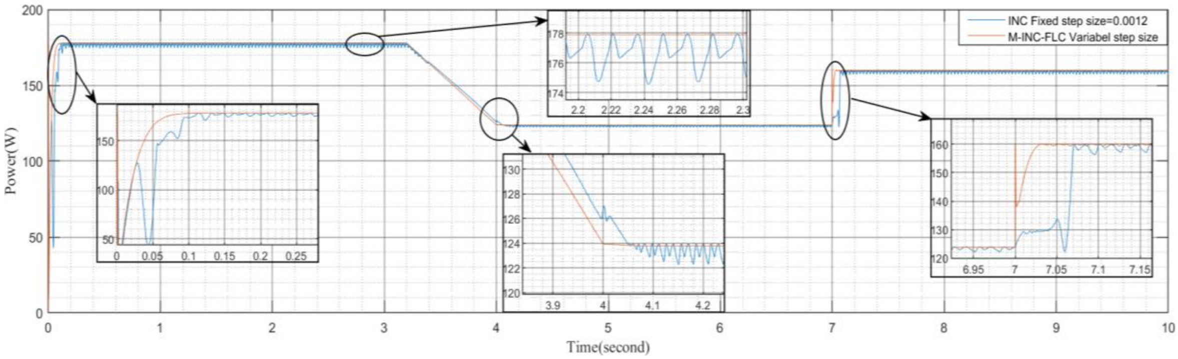


Fig. 14. Output power under the two investigated methods

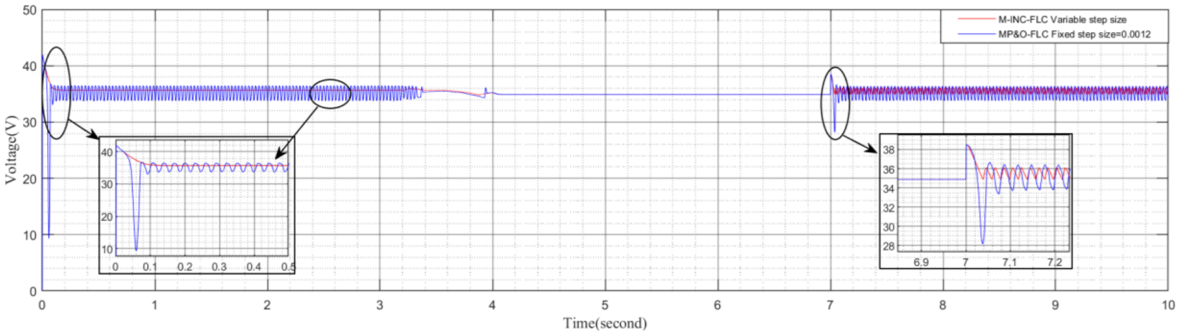


Fig. 15. Output voltage under the two investigated methods

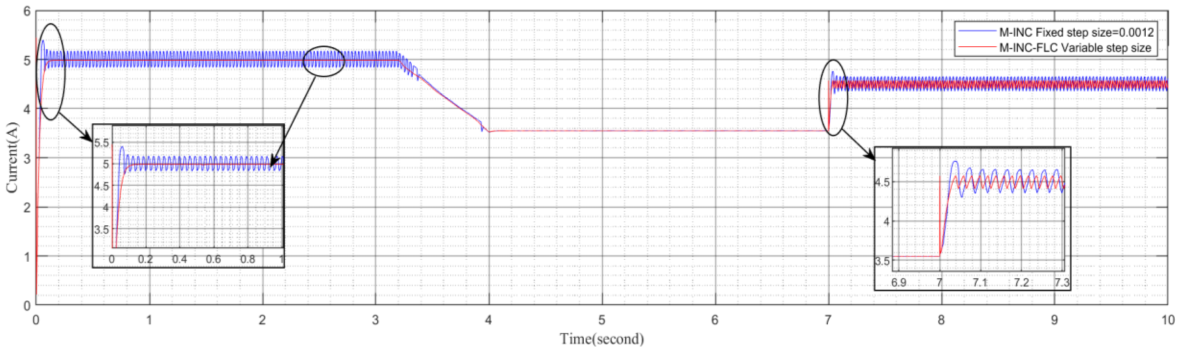


Fig. 16. Output current under the two investigated methods

These data were collected from the PEARL laboratory via SMA Sunny WebBox. The data was recorded from 12.00 am to 12.55 pm. For this research, the data was measured between 7.00 am to 7.00 pm. Table 5 below shows changes in Lighting intensity over time for a real sample. In this system, time intervals, denoted as T, are set at 5 minutes each, and the parameter G represents the level of lighting intensity associated with each time unit. Investigated real changes in irradiance over time are depicted in Fig. 17. Fig. 18, depicts the output power over time with the proposed method, where it effectively tracks the input irradiance.

Table 4. Comparison of several methods to determine the MPP

Methods / Standards	Traditional methods		Improved traditional methods	
	P&O [41]	**INC** [42]	**P&O-Fuzzy** [43], [44]	**INC-Fuzzy (proposed)**
Working principle	It relies on a fixed step in changing the voltage	It relies on a fixed step in changing the voltage	It is based on a variable step in changing the voltage ΔV(k)	It is based on a variable step in changing the ΔD(k)
tracking time	Slow response	Slow response	Quick response	Quick response
Oscillation	Significant	Significant	Low	Very low
Work in shade	Does not work	Does not work	It responds	It responds
control	/	/	Indirect control	Direct control

Table 5. Historical irradiance data from PEARL grid-connected PV system

T	G	T	G	T	G	T	G	T	G	T	G
1	1	23	63.4	45	284	67	1000.06	89	493.5	112	11.56
2	1	24	63.62	46	327.19	68	953.65	90	699.56	113	11
3	1	25	66.64	47	471.75	69	1070.37	91	629.25	114	15.38
4	1.63	26	72.96	48	481.29	70	1066.48	92	643.16	115	21.96
5	2.31	27	73.56	49	506.63	71	971	93	678.97	116	28.04
6	5.41	28	76.35	50	586.7	72	412.76	97	845.81	117	38.36
7	11.46	29	232.79	51	627.81	73	421.33	98	736.59	118	47.46
8	16.76	30	380.19	52	644.32	74	584.52	99	824.97	121	58.15
9	21.65	31	395.44	53	451.31	75	424.31	100	521.42	122	54.5
10	25.56	32	382.5	54	357.23	76	418.77	101	234.28	123	54.12
11	28.96	33	363.9	55	476.41	77	437.44	102	190.1	124	51.35
12	31.2	34	404.16	56	762.65	78	332.84	103	154.52	138	37.42
13	33.36	35	494.69	57	812.56	79	281.71	104	68.66	139	39.88
14	37.08	36	502.32	58	799.55	80	336	105	38.7	140	41.44
15	42.12	37	526.78	59	709.53	81	375.73	106	20.22	141	40.88
16	49.32	38	557.32	60	564.22	82	406.23	107	8.33	142	37.31
17	56.4	39	595.19	61	348	83	489.21	108	4.63	143	30.77
18	61.6	40	629	62	352.61	84	490.29	97	845.81	144	24.24
19	64.36	41	630.61	63	389.48	85	383.5	98	736.59	145	17.29
20	65.23	42	536.03	64	520.32	86	394.9	109	4.33		
21	68	43	287.94	65	989.97	87	402.59	110	6.94		
22	64.92	44	323.25	66	1065.25	88	405.26	111	11.46		

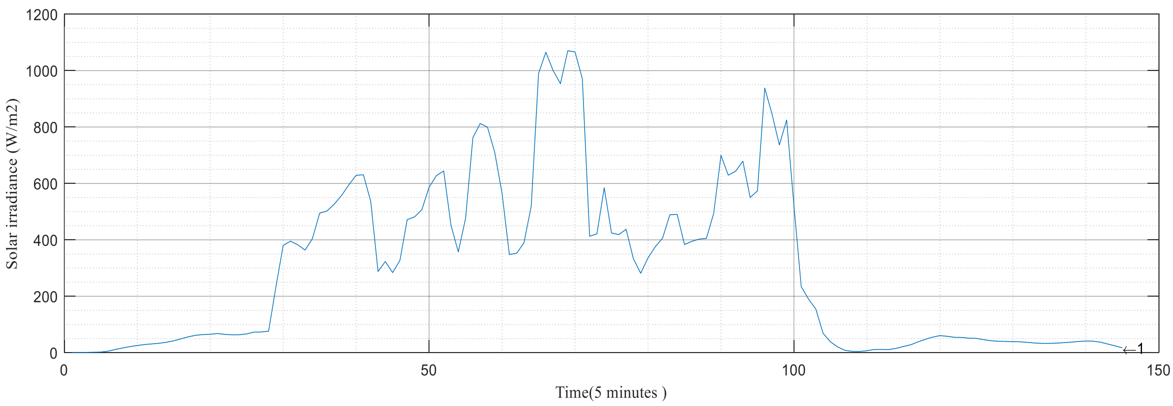


Fig. 17. Changes in irradiance over time

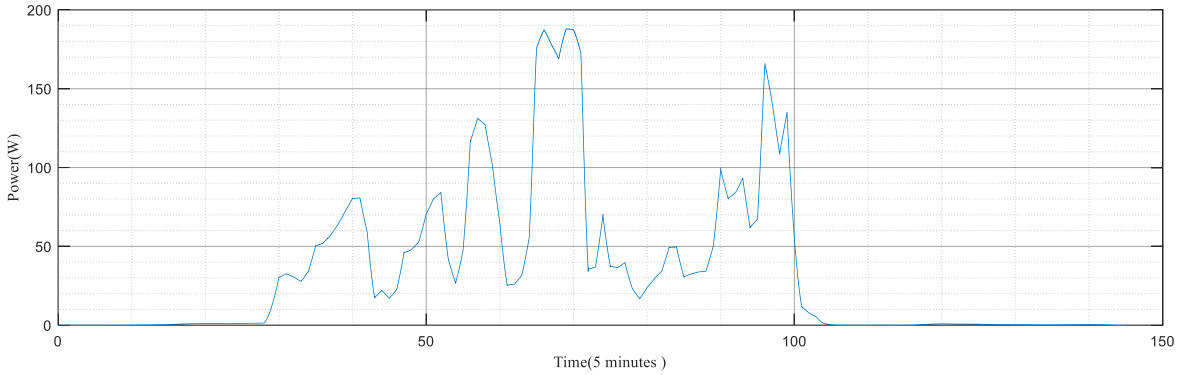


Fig. 18. Output power over time with the proposed method

5. Conclusions

This paper introduces a new approach to implementing the MPPT algorithm. The approach used an FL controller with a variable step size, which is referred to as M-INC. The goal is to overcome the limitations of traditional MPPT approaches, which are defined by fixed step sizes. A simulation circuit was used to propose and validate an FL-INC MPPT approach. Based on the simulation findings, the suggested technique provides a faster reaction time and decreases the steady-state oscillation around the MPP. The FL-based Variable Step Size INC MPPT algorithm, which has been advocated, offers the possibility of properly balancing the trade-off between minimizing variability in PV array output power around the MPP and accelerating convergence to it. This strategy effectively mitigates certain constraints associated with fixed step size MPPT methods. An authentic specimen is used to evaluate the system, and the accuracy of the system's response is confirmed by comparing it to the sample data. In addition, a comparative analysis was performed between the proposed FL-INC MPPT method and three other MPPT approaches: P&O, INC, and P&O-fuzzy for the PEARL grid-connected PV system. The comparisons demonstrate that the suggested MPPT approach effectively tracked the MPP in comparison to the three other methods. Furthermore, the MPP was achieved rapidly and with little power fluctuations.

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