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Analysis of the different maximum power point tracking strategies in a load-connected photovoltaic system

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Abstract: *For the past few years, solar energy has been widely applied in renewable energy systems. Maximum Power Point Tracking (MPPT) indicates one of the essential techniques for enhancing the efficiency of photovoltaic (PV) systems. Therefore, a high-efficiency method that can be accurate and fast-track the maximum power point (MPP) of PV is eagerly desired. In this paper, four different MPPT methods are compared in MATLAB/Simulink, which include two conventional methods: Perturbation and observation (P&O) and Incremental conductance (INC), one advanced intelligent method: Fuzzy logic (FLC), and one improved fuzzy logic-based variable step INC (FL-INC). The goal of this study is to find the more superior MPPT. According to the simulation result, FL-INC can enhance the output power by more than 6%, reducing the convergence time with fewer oscillations.*

Keywords: Control strategy; Fuzzy logic; Maximum power point tracking; Photovoltaic system; Variable step INC.

1. INTRODUCTION

Energy plays a vital role in the life and the economy of today's society. The demand for fossil fuels has increased considerably since the economy has grown. In recent years, a significant increase in the demand for energy leading to a shortage of fossil fuels. People are starting to turn their attention to renewable energy, because renewable energy can effectively solve the problem of energy security [1]. Renewable energy can be harnessed from nature, such as solar, wind, biological, and waves [2]. The most significant benefit of renewable energies is to generate electricity with zero carbon emissions, which aligns with the environmentally friendly concept of today's social development.

One of the most widely used forms of renewable energy is solar energy, which can be utilized by photovoltaics to generate electricity. The principle of photovoltaic power generation is based on the semiconductor properties of the P-N junction of silicon material. The best feature of photovoltaic electricity is that it can be generated in remote and isolated locations. With the development of technology, photovoltaics have been more widely used. Nowadays, we can find photovoltaics everywhere, such as on the home's roof and the electric light at the side of the road [3].

The output power of a solar PV varies on environmental conditions such as solar irradiance, wind, and ambient temperature. The maximum power point (MPP) is a working point of the system where the power delivered to the load is maximized [1-4]. Based on stochastic and non-predictable features of solar irradiation, Maximum PowerPoint Tracking (MPPT) strategies are used to keep the operating point working at the MPP to obtain more output power in a renewable energy system. The MPPT strategies can be divided into two main groups. The first group includes classic strategies, like incremental conductance (INC) and Perturb and Observe (P&O). The second group covers intelligent strategies, like Fuzzy Logic (FLC), Artificial Neural Networks (ANN) [5].

The main requirements for maximum power point tracking are simple implementation and lower cost, fast tracking speed under rapid changes in solar irradiation and temperature changes, and fewer oscillations for operating points [6]. The incremental conductance (INC) strategy is one of the fastest and most reliable conventional MPPT strategies. But it has a weakness of fixed step size to respond to the ambient condition changes, representing that the operating point will fluctuate around the Maximum Power Point (MPP) [7]. A fuzzy logic-based control method is considered as a brilliant MPPT since it tracks the MPP regardless of the possibility of losing sources of information. The FLC output will be a linguistic variable that defines the converter's duty ratio and interactively, making the error trend to zero [8].

This paper analyzes the technical performance of the different MPPT technologies, including the P&O, FLC, INC. It also introduces a primary analysis to a novel MPPT based on a combination of both INC and FLC methods to provide rapid control, small oscillations, and good performance under varying weather conditions [9]. The FLC-INC-based MPPT will be used for the first time with a buck DC-DC converter and tested using different solar irradiation and temperature conditions, and the results are also compared with the P&O method as the current existing MPPTs in the market. The rest of this article is organized as follows: Section 2 introduces the four different MPPT methods in a detailed algorithm and flow chart. This part also indicates the advantages and disadvantages of each method. Section 3 compares the simulation result of four methods and describes how efficient the new method is, using two case studies.

2. MPPT CONTROL TECHNIQUES

The commonly used structure of the MPPT system is shown in Fig. 1. MPPT controller obtains current and voltage from the PV module and, according to different control strategies, produces the control signals, usually the duty cycle for the DC-DC converter, by increasing or decreasing duty cycle to control the DC-DC converter's switch on or off to maintain the output voltage of PV system.

2.1 Perturb and Observe (P＆O)

The Perturb and Observe (P＆O) controller increase or decrease the duty cycle to carry the operating point (OP) close to the MPP on the PV curve. As shown in Fig. 2 [10]. The P&O method has a fixed step size, which causes this method will oscillate around the MPP. For example, if the P&O controller judges the operating point at the left side of MPP, the controller will decrease the duty cycle to increase the voltage to bring the OP close to MPP. When the OP is on the MPP's right side, the controller will produce a signal to reduce the voltage of the DC-DC converter. A flowchart of the P&O algorithm is shown in Fig. 3. This method is widely used because of its simple procedure and low cost.

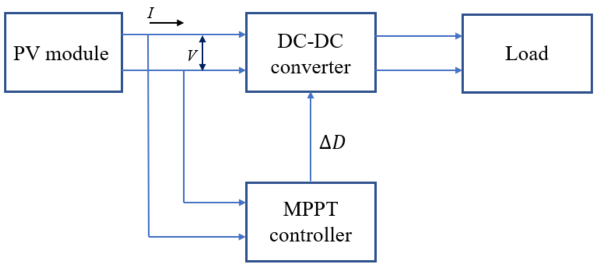


Fig. 1. Structure of MPPT.

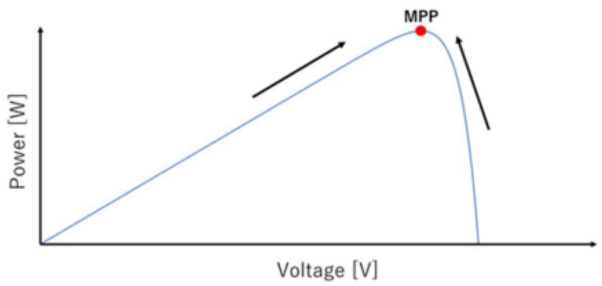


Fig. 2. PV characteristic curve [10].

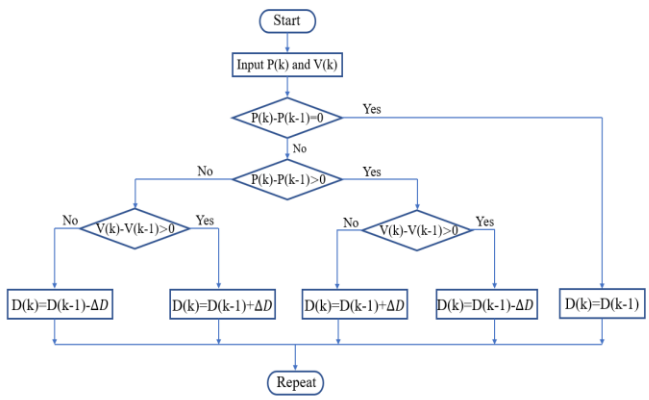


Fig. 3. Flow chart of P&O method.

However, P&O has some demerits. The tracking speed is a little slow, and its result has a lot of fluctuations. The fixed step size causes these defects. If the OP is located on the left side very close to the MPP, the OP gradually gets closer to the MPP at the same fixed step size. At the MPP, the OP passes by the MPP because of the same step size and then returns to the MPP at the fixed step size. This point oscillates around the MPP.

2.2 Incremental Conductance (INC)

The principle of the incremental conductance method is contrasting its conductance by calculating the operating point's slope on the P-V characteristic curve [11]:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} \tag{1}$$

Where P is the output dc power of the photovoltaic array, V represents output voltage at this moment, and I is the output current.
If the operating point's slope on the P-V curve is equal to 0, it means the OP is at the MPP. That can be expressed in the formula:

$$I + V\frac{dI}{dV} = 0 \tag{2}$$

$$-\frac{I}{V} = \frac{dI}{dV} \tag{3}$$

Where I/V is the instant conductance of the PV module, and dI/dV is the changed value in instant conductance or increments. According to these two indicators, the position of the current OP can be known [12].
Equations (4), (5), and (6) can be used to judge the position of the operating point and whether the PV module operates at the MPP:

$$\frac{dI}{dV} > -\frac{I}{V} \quad \text{At the left side of MPP} \tag{4}$$

$$\frac{dI}{dV} = -\frac{I}{V} \quad \text{At the MPP} \tag{5}$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad \text{At the right side of MPP} \tag{6}$$

A flowchart of the INC algorithm is shown in Fig. 4. This method is considered logically superior to the P&O method.

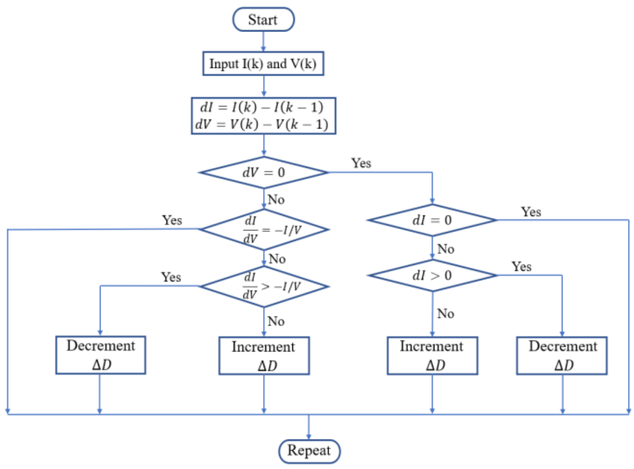


Fig. 4. Flowchart of INC method.

Although this strategy is theoretically better than the previous one, it has some disadvantages, like it's challenging to find the true MPP due to oscillations and losses caused by noise and measurement errors in practice. It also requires more time to track due to its complex calculations [10]. Therefore, nowadays, a faster and more accurate method is expected.

2.3 Fuzzy Logic (FLC)

Fuzzy logic emerged in the fuzzy set context, introduced by Lotfi Asker Zadeh (1965) at the University of California, Berkeley [13]. Fuzzy logic is a type of multi-valued logic that is different from P&O and INC, and its range is not limited from 0 to 1, like a truth value of the classical theory. Thus, Fuzzy logic can express linguistic variables by using values from 0 to 1. This is similar to the ways of human thinking. The fuzzy logic controller is based on this logic, so it has higher accuracy and is widely used for controlling electrical applications and machinery.
The fuzzy logic controller comprises fuzzification, rule inference interface, and defuzzification. Fig. 5. Shows the conceptual design of the FLC controller structure.

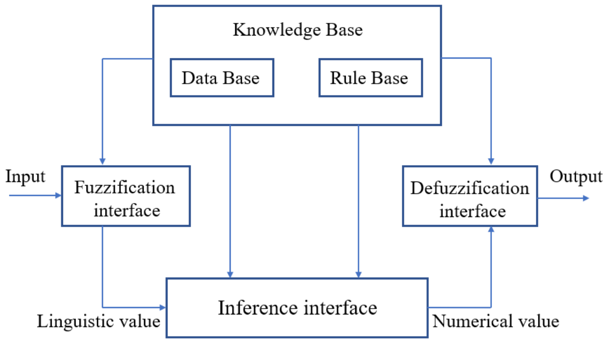


Fig. 5. Fuzzy logic controller structure.

From this structure, the working principle of FLC can be easily understood. First, the input variable will become a linguistic variable when passing through the fuzzification interface. Then based on the data and rule base, the linguistic variable will change to numerical value output to the next component.
The FLC used in this paper has two inputs which are the error $E(k)$ and the change of error $CE(k)$, and an output that represents the changed value in the duty cycle of the DC-DC converter [3]. $E(k)$ indicates the slope of the P-V curve, which shows the position of the operating point and $CE(k)$ shows the moving direction of the operating point. Equations (7) and (8) indicate the definition of inputs $E(k)$ and $CE(k)$ in sample times k:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} = \frac{\Delta P}{\Delta V} \tag{7}$$

$$CE(k) = E(k) - E(k-1) \tag{8}$$

The output ΔD of FLC works by adjusting the duty cycle of the DC-DC converter to track the maximum power point voltage:

$$D(k) = D(k-1) + \Delta D \tag{9}$$

The triangular membership function is used for both inputs and output in this FLC's fuzzification process. Fig. 6, Fig. 7, and Fig. 8 show the membership functions, and Table 1 shows the 25 important fuzzy rules divided into five categories: NB, NS ZE, PS, and PB.

The FLC works with specific membership functions and fuzzy rules which are created based on extensive experiments and expert's experience to mimic the human way of thinking as its core. That is why this method is better than conventional methods.

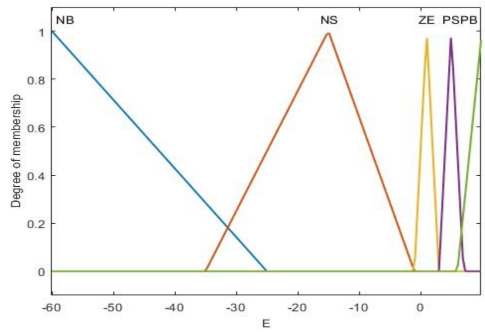


Fig. 6. Membership function of E(k)

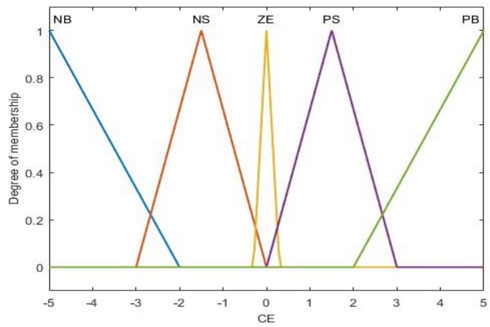


Fig. 7. Membership function of CE(k)

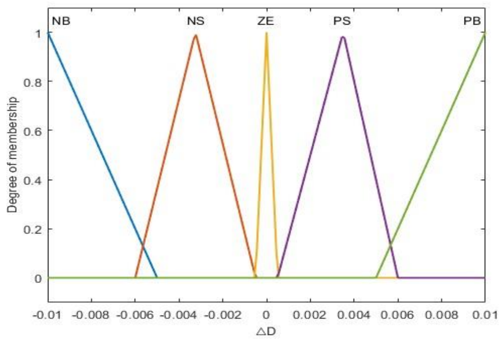


Fig. 8. Membership function of ΔD

Table 1. Fuzzy rules used in FLC [11]

		CE				
		NB	NS	ZE	PS	PB
E	NB	ZE	PB	PB	PB	PB
	NS	PB	PB	PS	ZE	ZE
	ZE	PS	ZE	ZE	ZE	NS
	PS	ZE	ZE	NS	NB	NB
	PB	ZE	NB	NB	NB	ZE

2.4 Fuzzy-Logic based variable-step INC (FL-INC)

As previously mentioned, the most widely used MPPT strategy is incremental conductance (INC) and perturbation and observation (P&O). INC is logically better than P&O. Recently, many researchers have considered how to improve the performance of P&O, and some unique methods have been formed. Such as, some techniques are used to vary the step size of P&O or improve its tracking speed. And these new technically improved P&O methods have a significant performance improvement.

As mentioned above, the INC method tracks the MPP with a fixed step size like P&O. Therefore, a lot of oscillations will inevitably be generated around the MPP. To solve this problem, a novel fuzzy-logic-based variable step size incremental conductance (FL-INC) will be introduced in this study. There are two inputs for the fuzzy-logic base INC: the instantaneous conductance (I/V) and the changed value of instantaneous conductance (dI/dV). And the desired output is the variable voltage step size applied to change the duty cycle of the DC-DC converter. The characteristic I-V curve and P-V curve can be divided into five regions according to their positions with respect to the maximum power point [9]. If $dP/dV \gg 0$, $I/V \gg -dI/dV$, which means the voltage of the operating point is much lower than the voltage of MPP from the left side, the proper voltage step size is positive big (PB). If $dP/dV > 0$, $I/V > -dI/dV$, which means the voltage of the operating point is a little lower than the MPP voltage at the left side of the MPP, the suitable step size should be positive small (PS). If $dP/dV \approx 0$, $I/V \approx -dI/dV$, the OP is very close to the MPP, so the step size needs to be very small (VS). And vice versa. According to the characteristics of the INC method, fuzzy rules for producing the variable step duty cycle of FL-INC can be shown below in Table 2 [9].

Table 2. Fuzzy rules for variable step size INC [9]

		dI/dV				
		VL	L	VC	H	VH
I/V	VL	PB	PS	PS	VS	NS
	L	PB	PS	VS	NS	NB
	VC	PB	PS	VS	NS	NB
	H	PB	PS	VS	NS	NB
	VH	PB	PS	PS	NS	NB

The important membership functions of inputs and output are shown in Fig. 9. The fuzzy inputs and output have been carefully designed at specific conditions [9]. When the solar irradiation and temperature change, the effective value for inputs and output will change, so, in simulating work, some gains may use for inputs and output to adjust the value of inputs and output to let the fuzzy system work smoothly. The gains value varies in different conditions, depending on the simulation scenarios. The structure of the load-connected PV array with the FLC-based variable step size INC is shown in Fig. 10.

This unique fuzzy logic-based INC method has an outstanding performance that will be demonstrated in the next section. This method not only enhances output dc power and has more minor fluctuations but also reduces the convergence time to reach the steady-state condition with instantly variable weather conditions.

3. SIMULATION MODEL

Three 160W parallel polycrystalline PV strings are used to assess the performance of above mentioned four MPPT methods. Table 3 shows the electrical characteristics of the PV module used in this research.

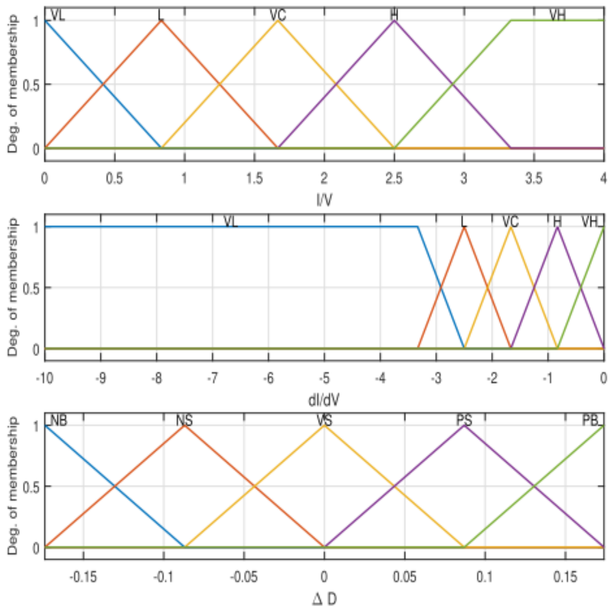


Fig. 9. Membership function for inputs and output of fuzzy logic-based INC [9].

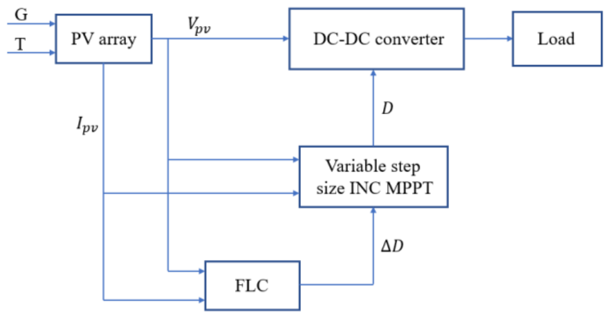


Fig. 10. Structure of variable step FL-INC.

Table 3. Electrical parameters of the PV module [10]

Maximum Power [W]	160
Voltage at MPP [V]	17.9
Current at MPP [A]	8.94
Open circuit voltage [V]	21.6
Short circuit current [A]	9.47
Temperature coefficient of Isc [%/deg.C]	0.10±0.01
Temperature coefficient of Voc [%/deg.C]	-(0.38±0.01)
The number of cells on the PV panel	36

A detailed simulation model was performed in MATLAB Simulink to assess the performance of the different MPPTs, which is shown in Fig. 11. The model consists of 3 parallel strings; each string includes one PV module composed of 36 cells, the MPPT controller, PV module, the DC-DC buck converter, one DC link, and the load. The input variables of the simulation model are solar irradiance and cell temperature. The subsystem of the new proposed fuzzy logic-based variable step INC is shown in Fig. 12. The fuzzy logic block produces the proper duty cycle step size, which can be used as the new step size of the incremental conductance method.

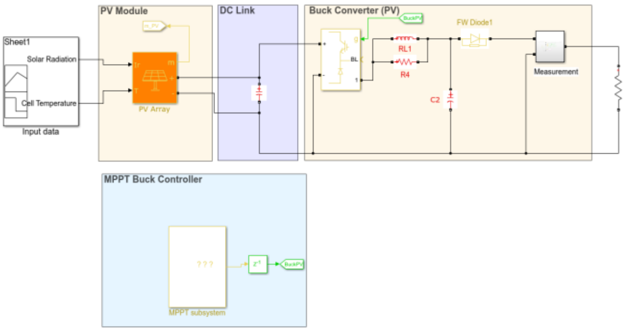


Fig. 11. PV Simulink model.

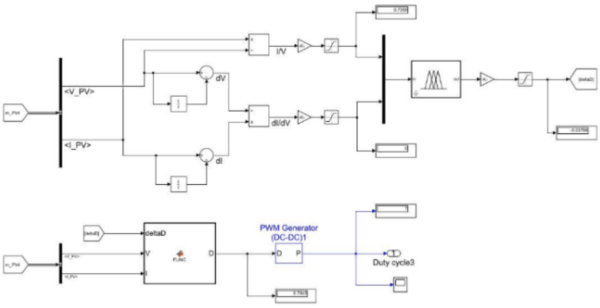


Fig. 12. Subsystem of FL-INC.

Considering the irradiation change is 0-0.06s: 1000W/m^2, 0.06s-0.12s: 800W/m^2, 0.12s-0.18s: 400W/m^2, and 0.18s-0.24s: 1000W/m^2. The cell temperature keeps at 25℃. The simulation result is shown in Fig. 13. below. It is obvious that, intelligent control techniques are superior to conventional control techniques. The red line represents INC, the blue one is P&O, the yellow line is fuzzy logic, and the violet one expresses the FL-INC method. When the simulation model starts working, the new FL-INC method can track the MPP at the fastest speed, followed by fuzzy logic, P&O, INC. In addition, FL-INC has less fluctuation and oscillation around MPP at the steady-state.

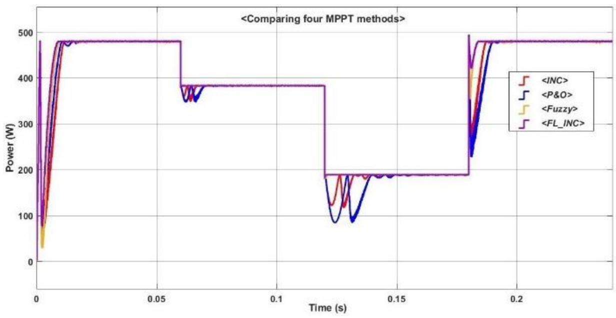
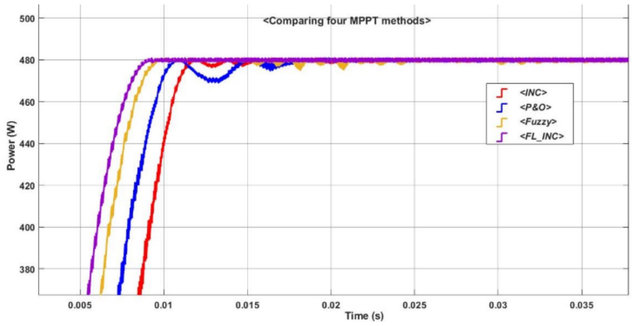


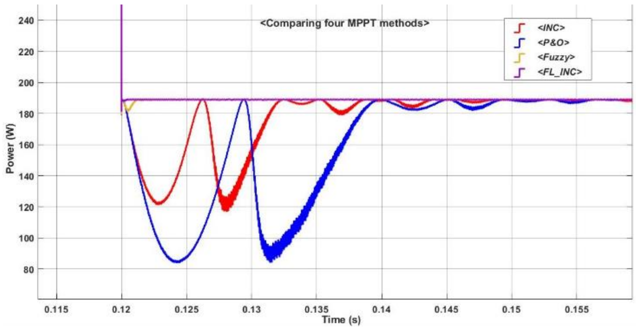
Fig. 13. Comparison of the simulation results of the four MPPT methods.

Fig. 14 shows a more transparent and precise comparison between MPPTs methods, considering different modes of steady state, the dramatic reduction in irradiation, and the sharp increase in irradiation.
The results emphasize the advantages of reducing the convergence time and improving tracking speed when applying the fuzzy logic variable step INC strategy.

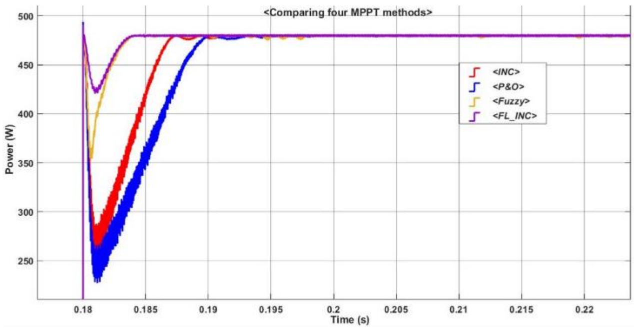
As shown in Fig. 14(a), the FL-INC technique can first find the MPP and then work on it with fewer oscillations. Fig. 14(b) shows that, the FL-INC method is capable of tracking the MPP quickly, in contrast to conventional methods, even when the solar irradiation suddenly declines from 800W/m^2 to 400W/m^2. As indicated in Fig 14(c), when the irradiation rises again to 1000W/m^2, the FL-INC can find the MPP quickly, unlike other methods, especially P&O and INC, which take more time on convergence.



(a)



(b)



(c)

Fig. 14. Comparison between the four methods (a)the first steady state; (b)the dramatic reduction in irradiation; (c)the sharp increase in irradiation.

The comparison between these four different MPPT control strategies indicates that FL-INC is better in fast and accurate tracking of the MPP, resulting in additional power out from the PV panel.
In order to estimate how good performance the new FL-INC-based MPPT has, the simulation model was carried out, considering the standard testing condition in which the solar radiation is assumed to be 1000W/m^2 at 25℃. The results are represented in Fig. 15. The simulation results revealed that all four methods gradually stabilized around the maximum power point after 0.025 seconds. But the higher speed and accurate tracking method used in FL-INC-based MPPT, provides a 6.29% extra output

power in the short time period, compared with the traditional P&O MPPTs. The extra power generated from the FL-INC-based MPPT at the standard test condition compared with other methods, is given in Table 4.

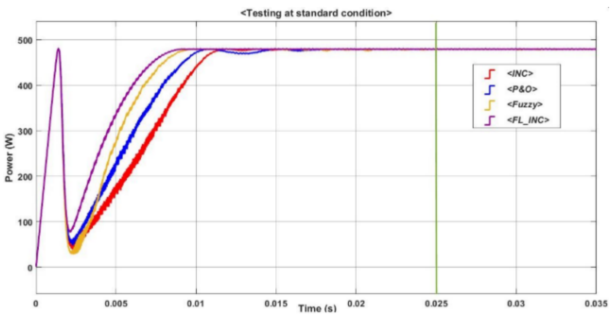


Fig. 15. Simulation result at standard condition.

Table 4. Estimation of the extra electricity generated in the 0-0.025s period from the different MPPTs studied in this research

Compare P&O with FL-INC	Cumulative Electricity generation	Extra Electricity generation
	P&O: 9.913 Ws FL-INC: 10.537 Ws	6.29%
Compare P&O with FLC	Cumulative Electricity generation	Extra Electricity generation
	P&O: 9.913 Ws FLC: 10.537 Ws	2.54%
Compare FLC with FL-INC	Cumulative Electricity generation	Extra Electricity generation
	FLC: 10.165 Ws FL-INC: 10.537 Ws	3.65%

When comparing the conventional P&O method with the intelligent fuzzy logic method, The FLC method can generate up to 2.54% more electricity than the P&O method. However, comparing conventional P&O methods with the new FL-INC, the FL-INC method surprisingly generates approximately 2.5 times the extra electricity generation in the general FLC during the testing time period.

4. CONCLUSION

The maximum power tracking control algorithms are essential to extract the maximum capable power of the solar photovoltaic with respective solar irradiance and temperature at a particular instant of time Point. Traditional methods like P&O and INC, which track MPP with the fixed step size, are widely used but suffer from slow tracking due to reduced utilization efficiency. Furthermore, intermittency and rapid changes in irradiation and temperature may cause the MMPT to oscillate around one of the multiple local power peaks. To overcome the drawbacks mentioned above, a new MPPT method based on a combination of FLC and INC methods was proposed, and its technical performance was compared with the currently existing methods. The results revealed a potential of 6.29% extra electricity generation from the proposed method compared to the other traditional MPPTs, such as the P&O MPPTs.

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