



# A Comprehensive Study on Maximum Power Point Tracking Techniques Based on Fuzzy Logic Control for Solar Photovoltaic Systems

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Maximum power point tracking (MPPT) methods based on fuzzy logic control (FLC) is a popular application in recent years. However, different kinds of fuzzy control methods lack comparative study, which led to confusion in practice. Hence, a comprehensive study on these methods is essential. Unfortunately, very few attempts have been made in this regard. In this paper, four FLC methods are selected for comparative analysis. Furthermore, the design details and experimental result will also be given to help choose and measure these methods, which presents a clear image of the technology of FLC based MPPT to readers.

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## 1 INTRODUCTION

Due to the increasingly serious environmental problems, low carbon economy has received people's attention. Photovoltaic (PV) energy becomes a promising alternative as it is omnipresent, environment friendly, and has less operational and maintenance costs. An efficient maximum power point tracking (MPPT) technique is necessary that is expected to track the maximum power point (MPP) at all environmental conditions and then force the PV system to operate at that MPP (Sivakumar et al., 2015; Saravanan and Ramesh Babu, 2016; Kandemir et al., 2017; Al-Dhaifallah et al., 2018; Yang et al., 2018a; Yang et al., 2018b; Li X. et al., 2019a; Yang et al., 2019a; Li X. et al., 2019b; Yang et al., 2019b; Yang et al., 2019c; Li S. et al., 2020; Yang et al., 2020b; Eltamaly, 2021; Li F. et al., 2021).

In recent years, many advanced control techniques have been associated with the MPPT control such as fuzzy logic control (FLC) in order to increase the efficiency of solar panels. Several FLC methods are compared and reviewed in the literature (Dounis et al., 2013; Boukenoui et al., 2016; Kwan and Wu, 2016; Ouchen et al., 2016; Mohamed et al., 2017; Nabipour et al., 2017; Yilmaz et al., 2018; Youssef et al., 2018; Li X. et al., 2019c; Loukil et al., 2020; Verma et al., 2020; Jin et al., 2021; Rajesh et al., 2021; Tang et al., 2021). In this paper, four FLC methods are selected for comparative analysis. Then, comprehensive study has been made to compare the FLC methods regarding their features of input variables. Furthermore, the control effect has also been studied. Finally, the correctness of the conclusion is verified by simulation and experiment.

The paper is organized as follows. In **Section 2**, FLC MPPT techniques are extracted from a vast literature survey. Then, the comparative analysis of the four methods will be verified by experiments in **Section 3**. The concluding remarks are presented in **Section 4**.

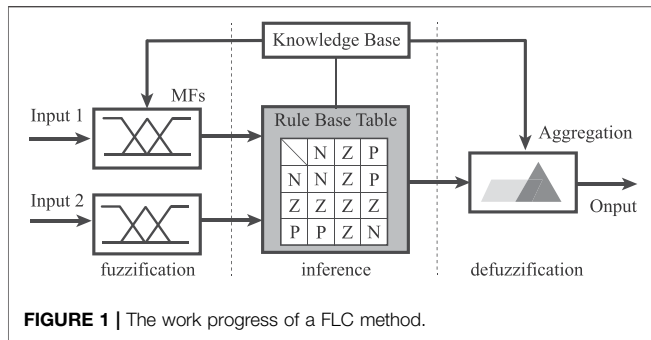


FIGURE 1 | The work progress of a FLC method.

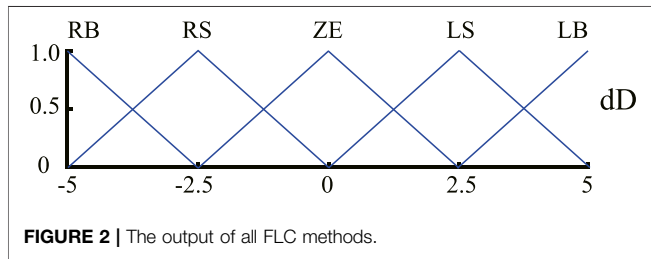


FIGURE 2 | The output of all FLC methods.

## 2 REVIEW OF MPPT ALGORITHMS BASED ON FUZZY LOGIC CONTROL

Generally, three stages can be identified in FLC MPPT's control **Figure 1**. In the first stage, the numerical input variables are converted into equivalent linguistic variables as input fuzzy sets. In the second stage, the input fuzzy sets are calculated into output fuzzy sets through the inference with the fuzzy rule base table. In the last stage, the output fuzzy sets are converted back to numerical variables as the output.

On the other hand, the design of FLC method is also divided into three stages. Firstly, the input variables should be selected to identify the position of work power point (WPP) related to MPP, and the output variable should be chosen to execute the command of the controller. After that, the rules of FLC methods should be set based on the study of PV characteristics. Finally, the parameters of FLC methods should be configured on the basis of the variable characteristic.

In FLC, the values of variable are expressed of linguistic variables such as PB (positive big), PS (positive small), ZE (zero), NS (negative small), and NB (negative big) using basic fuzzy subset. Each of these acronyms is defined by mathematical membership functions (MFs). Moreover, the setting of parameters involves two aspects: ranges and adjustments.

According to the consultation of other literature data and personal summary, four extant methods of fuzzy controls are compared. In addition, for ease of comparison, the output variable of the four methods should be consistent. The difference of duty cycle ( $dD$ ) is the universal choice, and the range and parameters of  $dD$  are same in different methods (Rezk and Eltamaly, 2015). And boost circuit is chosen as the DC-DC converter.  $dD$  are expressed of linguistic variables such as LB (left big), LS (left small), ZE (zero), RS (right small), and RB (right big) using basic fuzzy subset, as shown in **Figure 2**.

TABLE 1 | The rules of dP&dV method.

		dP				
		NB	NS	ZE	PS	PB
dV	NB	RB	RS	ZE	LS	LB
	NS	RS	RS	ZE	LS	LS
	ZE	RS	ZE	ZE	ZE	LS
	PS	LS	LS	ZE	RS	RS
	PB	LB	LS	ZE	RS	RB

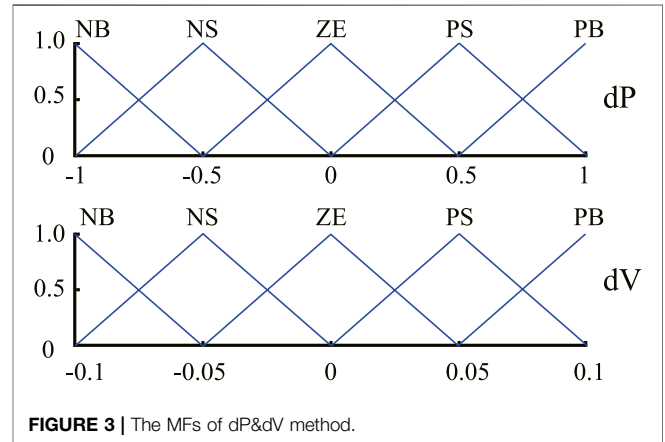


FIGURE 3 | The MFs of dP&dV method.

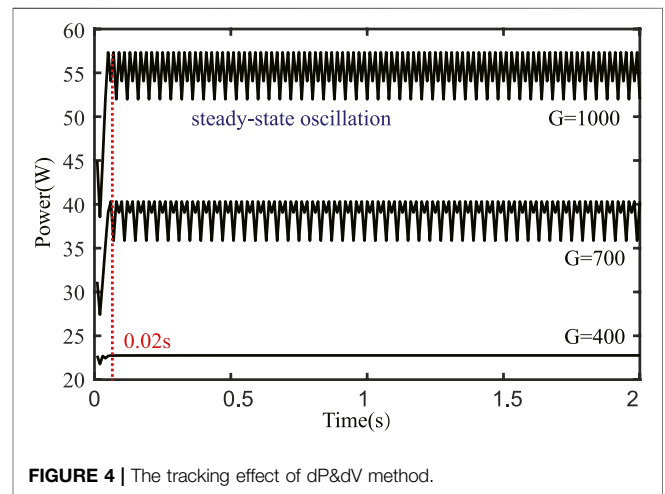


FIGURE 4 | The tracking effect of dP&dV method.

### 2.1 dP&dV Method and dP&dI Method

The dP&dV method is one of the most widely used in the industry (Boukenoui et al., 2017; Farajdadian and Hassan Hosseini, 2019). For the dP&dV method, the first and second inputs refer to **Eqs. 1, 2**, respectively.

$$dP(k) = P(k) - P(k - 1) \tag{1}$$

$$dV(k) = V(k) - V(k - 1) \tag{2}$$

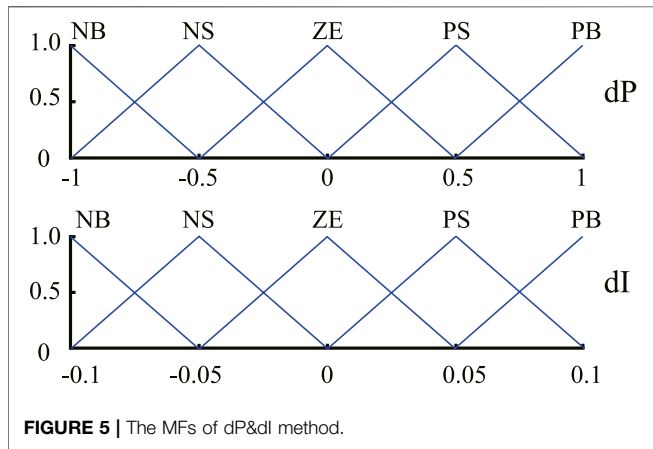
where  $P(k)$  and  $V(k)$  are PV output power and voltage, respectively at time  $k$ . According to the principle of dP&dV method, the basic operation principle can be expressed by:

**TABLE 2** | The rules of dP&dI method.

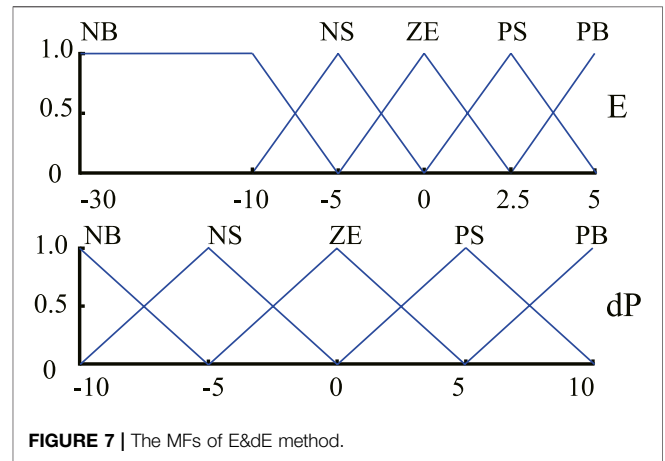
		dP				
		NB	NS	ZE	PS	PB
dI	NB	LB	LS	ZE	RS	RB
	NS	LS	LS	ZE	RS	RS
	ZE	LS	ZE	ZE	ZE	RS
	PS	RS	RS	ZE	LS	LS
	PB	RB	RS	ZE	LS	LB

**TABLE 3** | The rules of E&dE method.

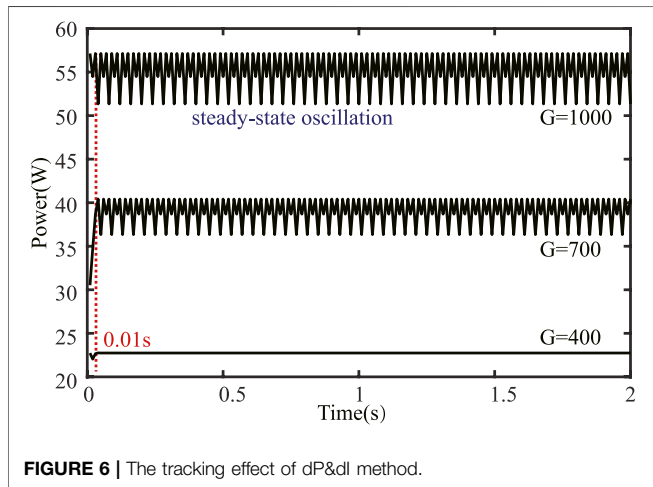
		E				
		NB	NS	ZE	PS	PB
dE	NB	ZE	ZE	ZE	ZE	ZE
	NS	LS	LS	ZE	RS	RS
	ZE	LB	LS	ZE	RS	RB
	PS	LS	LS	ZE	RS	RS
	PB	ZE	ZE	ZE	ZE	ZE



**FIGURE 5** | The MFs of dP&dI method.



**FIGURE 7** | The MFs of E&dE method.



**FIGURE 6** | The tracking effect of dP&dI method.

$$\begin{cases} dP > 0, dV > 0 \text{ or } dP < 0, dV < 0 & \text{Left of MPP} \\ dP > 0, dV < 0 \text{ or } dP < 0, dV > 0 & \text{Right of MPP} \end{cases} \quad (3)$$

Based on Eqs. 1–3, fuzzy rules are summarized in Table 1, and the MFs of dP and dV is shown as Figure 3.

As shown in Figure 4, the steady-state oscillation is significant when the irradiation is large. On the contrary, the steady-state oscillation disappears when the solar irradiance level is low. The tracking speed of this method is relatively fast, which helps to keep up with PV changes quickly.

The dP&dI method is another popular method, which is similar to the dP&dV method. For the dP&dV method, the first and second inputs refer to Eqs. 4, 5, respectively.

$$dP(k) = P(k) - P(k - 1) \quad (4)$$

$$dI(k) = I(k) - I(k - 1) \quad (5)$$

where  $P(k)$  and  $I(k)$  are PV output power and voltage, respectively at time  $k$ . According to the principle of dP&dI method, the operation principle can be expressed by:

$$\begin{cases} dP > 0, dI < 0 \text{ or } dP < 0, dV > 0 & \text{Left of MPP} \\ dP > 0, dI > 0 \text{ or } dP < 0, dI < 0 & \text{Right of MPP} \end{cases} \quad (6)$$

Based on Eqs 4–6, fuzzy rules are summarized in Table 2, and the MFs of dP and dI is shown as Figure 5.

As shown in Figure 6, the steady-state oscillation is hard when the irradiation is large. On the contrary, the steady-state oscillation disappears when the irradiance decreases. The tracking speed of this method is relatively faster, which help to keep up with PV changes quickly.

The characteristics of the two methods can be summarized as follow:

- The control logic is simple and rules are easy to design.
- It is easy to produce steady-state oscillation.
- The tracking speed of the two methods is faster.

## 2.2 E&dE Method

For the E&dE method, the first and second inputs refer to Eqs. 7, 8, respectively (Danandeh and Mousavi G, 2018; Bhukya and Nandiraju, 2020).

$$E(k) = \frac{dP}{dV} = \frac{P(k) - P(k - 1)}{V(k) - V(k - 1)} \quad (7)$$

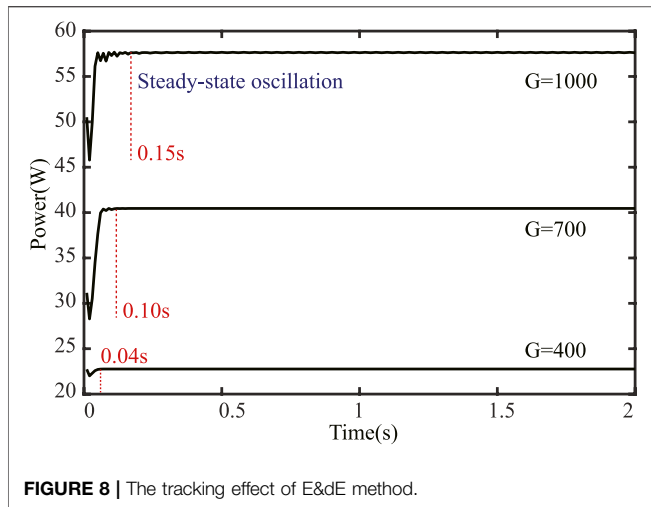


FIGURE 8 | The tracking effect of E&dE method.

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

where  $P(k)$  and  $V(k)$  are PV output power and voltage respectively at time  $k$ . According to the principle of E&dE method, the operation principle can be expressed by:

$$\begin{cases} E > 0 & \text{Left of MPP} \\ E < 0 & \text{Right of MPP} \end{cases} \tag{9}$$

Based on Eqs. 7–9, fuzzy rules are summarized in Table 3, and the MFs of  $E$  and  $dE$  is shown as Figure 7.

As shown in Figure 8, the steady-state oscillation still exists and is mainly decided by the solar exposure level. The tracking speed of this method is relatively slower, which is not suitable to cope with the rapid change of irradiation.

The characteristics of E&dE method can be summarized as follow:

- The tracking speed of the two methods is faster. The control logic is simple and rules are easy to design.
- The steady-state oscillation is slight.
- The tracking speed of E&dE method is slow.

### 2.3 G&F Method

For the G&F method, the first and second inputs refer to Eq. 10 (Chen Y.-T. et al., 2016).

$$\begin{cases} G = 1 - \left| \frac{dI}{dV} \right| / \left| \frac{I}{V} \right| \\ F = 1 - \left| \frac{I}{V} \right| / \left| \frac{dI}{dV} \right| \end{cases} \tag{10}$$

According to the principle of G&F method, the operation principle can be expressed by:

$$\begin{cases} G > 0 \text{ and } F < 0 & \text{Left of MPP} \\ F > 0 \text{ and } G < 0 & \text{Right of MPP} \end{cases}$$

According to the above formulas, fuzzy rules can be designed, as shown in Table 4, and the MFs of  $G$  and  $F$  is shown as Figure 9.

TABLE 4 | The rules of G&F method.

		G				
		NB	NS	ZE	PS	PB
F	NB			ZE	RS	RB
	NS			ZE	RS	RS
	ZE	ZE	ZE	ZE	ZE	ZE
	PS	LS	LS	ZE		
	PB	LB	LS	ZE		

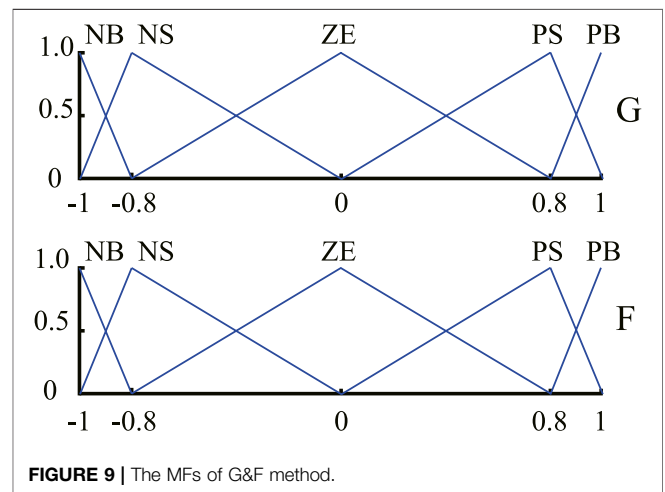


FIGURE 9 | The MFs of G&F method.

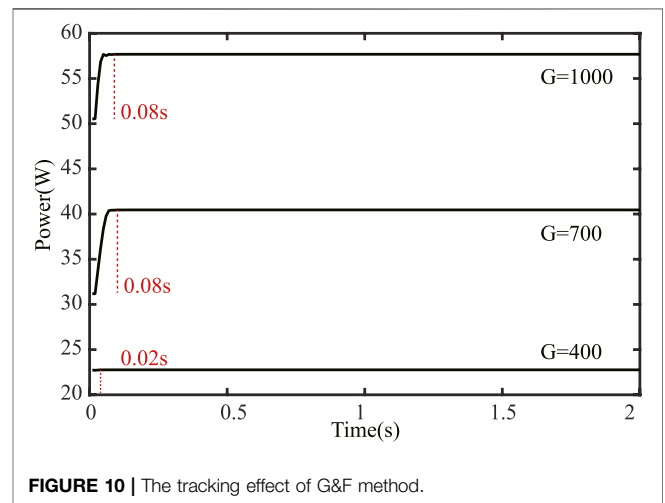


FIGURE 10 | The tracking effect of G&F method.

As shown in Figure 10, the steady-state oscillation is well canceled in this scheme. The tracking speed of this method is appropriate, which is enough to cope with the rapid change of irradiation.

The characteristics of E&dE method can be summarized as follow:

- The control logic is ingenious and rules are less.
- The steady-state oscillation is not found.
- The tracking speed of E&dE method is moderate.

**TABLE 5** | The rules of  $\beta$  method.

$\beta_{min}$	PB			
$\beta_{mid}$	dP	dV		
$\beta_{max}$				
	NS	NS	ZE	PS
	ZE	ZE	ZE	PS
	PS	PS	ZE	ZE
	NB			NS

### 2.4 The Composite Methods

After the combination of other control techniques, many FLC methods have been developed based on the above methods.

The beta-parameter based MPPT algorithm are derived from E&dE method (Li X. et al., 2019c). This method adds an input variable,  $\beta$ , to E&dE method, and changes the fuzzy rule based on the value of  $\beta$ , as shown in **Table 5**. The dilemma between the rules number and the universality for various operating conditions can be effectively solved with this new algorithm. In addition, it can simplify the Fuzzy rule membership functions since the number of fuzzy rules can be reduced.

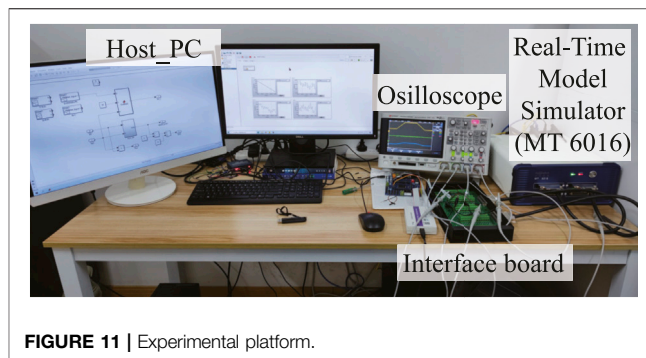
The FLC-MPPT based on genetic algorithm and small-signal analysis are derived from dP&dV method (Mohamed et al., 2017). Then, proper FLC-MPPT control design was performed by means of combining genetic algorithm and the analytical design formulas. This method use the small-signal model with combination of a stochastic searching technique based on genetic algorithm to get the accurate design parameters of dP&dV method.

The FLC MPPT based on firefly algorithm are derived from dP&dV method (Farajdadian and Hassan Hosseini, 2019) This method utilize the firefly algorithm to design fuzzy controller membership functions for a better effectiveness. After optimizing the parameters by firefly algorithm, the MPPT method will have better dynamic performance and perform well at all irradiation levels.

Another MPPT method which is well adapted with microcontrollers is Neural networks (NN) method. Artificial neural network (ANN) emerged at the same time that fuzzy logic emerged and both are considered a part of soft computation. In complex neural networks, higher number of hidden layers are used. Number of layers and neurons of each layer and the functions employed in layers depend on user’s knowledge. Input variables might be array parameters like V and I, weather information like temperature and solar irradiation or a combination of them. Output variable is usually duty cycle of the inverter.

## 3 SIMULATION RESULT AND EXPERIMENTAL EVALUATION

As shown in **Figure 11**, this experiment utilized Host PC, Real-Time Model Simulator (MT6016), Interface board, and Oscilloscope.



**FIGURE 11** | Experimental platform.

**TABLE 6** | Main parameters for EN50530 PV modules.

Parameter	Value
Maximum power, $P_{mpp}$	59.85 W
Voltage at MPP, $V_{mpp}$	17.1 V
Current at MPP, $I_{mpp}$	3.5 A
Open-circuit voltage, $V_{oc}$	21.1 V
Short-circuit current, $I_{sc}$	3.8 A
Temperature coefficient of $V_{oc}$	-80 mV/°C
Temperature coefficient of $I_{sc}$	0.065%/°C

**TABLE 7** | Main parameters for the PV system.

Parameter	Value
Boost converter inductor, $L$	10 <sup>-3</sup> H
PV-side capacitor, $C_{pv}$	470 <sup>-6</sup> F
DC-link capacitor, $C_{dc}$	470 <sup>-6</sup> F
Load resistance, $R_{load}$	20 $\Omega$
Switching frequency, $f$	20,000 Hz
Reference power, $P_{limit}$	40 W
Threshold power, $dP_{th}$	6 W
Simulation step size, $T_{control}$	10 <sup>-4</sup> s
Sampling step size, $dT_{sample}$	10 <sup>-2</sup> s

The PV model of EN50530 and boost converter are utilized in this experience (Chen P.-C. et al., 2015; Park and Choi, 2017; Ayop and Tan, 2018; Yang et al., 2020a; Li X. et al., 2021). **Table 6** lists main electrical parameters of the selected PV module in EN50530, and **Table 7** lists main electrical parameters of the PV system.

The results of the real-time simulation platform are consistent with the theoretical analysis. As shown in **Figure 12**, the tracking process of dP&dV method was successful in the whole process. However, with the irradiation intensifies, the oscillation becomes more obvious. This not only leads to the power loss, but also brings a large variation of voltage, which will seriously affect the power quality. Furthermore, the oscillation in E&dE and G&F methods is far smaller than the dP&dV method. The tracking speed of E&dE method is slower than that of the G&F method.



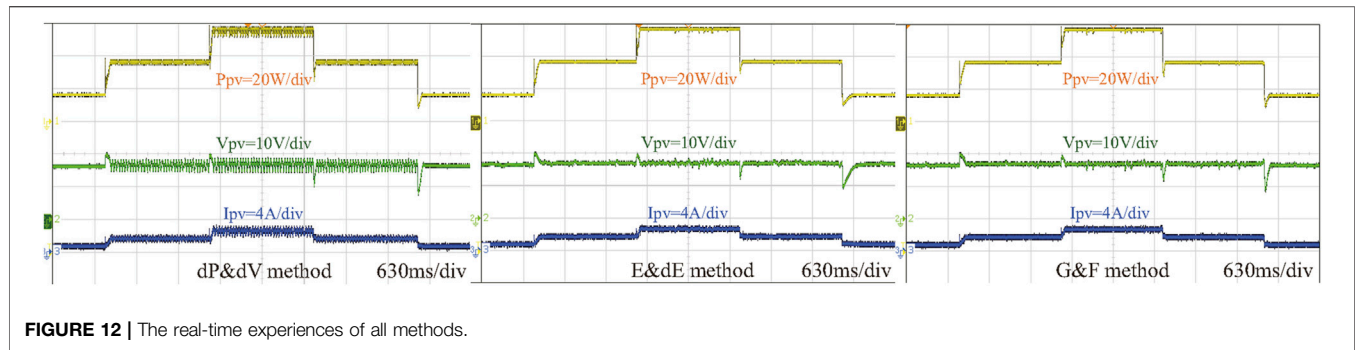


FIGURE 12 | The real-time experiences of all methods.

## 4 CONCLUSION

In this paper, four MPPT programs based FLC are compared. It can be concluded that, the selection of input variables determines the difficulty of the final control effects, based on the analysis of the design process and tracking effects. The correctness of the theoretical analysis is proved by simulation results and experiment evaluations.

However, this paper does not describes the MPPT progresses which combine FLC with other technologies in detail. Because, this paper focuses on the comparative analysis of the difference of basic FLC methods. The introduction of additional methods does not benefit comparative analysis.

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## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

TZ, JD, and XL contributed to conception and design of the study and wrote sections of the manuscript. TZ performed the statistical analysis and wrote the first draft of the manuscript. XL provides guidance. SD proof reading. All authors contributed to manuscript revision, read, and approved the submitted version.

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