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An Efficient Fuzzy-Logic Based Variable-Step Incremental Conductance MPPT Method for Grid-Connected PV Systems

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ABSTRACT Recently, solar energy has been intensively employed in power systems, especially using the photovoltaic (PV) generation units. In this regard, this paper proposes a novel design of a fuzzy logic based algorithm for varying the step size of the incremental conductance (INC) maximum power point tracking (MPPT) method for PV. In the proposed method, a variable voltage step size is estimated according to the degree of ascent or descent of the power-voltage relation. For this purpose, a novel unique treatment is proposed based on introducing five effective regions around the point of maximum PV power. To vary the step size of the duty cycle, a fuzzy logic system is developed according to the locations of the fuzzy inputs regarding the five regions. The developed fuzzy inputs are inspired from the slope of the power-voltage relation, namely the current-voltage ratio and its derivatives whereas appropriate membership functions and fuzzy rules are designed. The benefit of the proposed method is that the MPPT efficiency is improved for varying the step size of the incremental conductance method, thanks to the effective coordination between the proposed fuzzy logic based algorithm and the INC method. The output DC power of the PV array and the tracking speed are presented as indices for illustrating the improvement achieved in MPPT. The proposed method is verified and tested through the simulation of a grid-connected PV system model. The simulation results reveal a valuable improvement in static and dynamic responses over that of the traditional INC method with the variation of the environmental conditions. Further, it enhances the output dc power and reduce the convergence time to reach the steady state condition with intermittent environmental conditions.

INDEX TERMS Maximum power point tracking, fuzzy logic, incremental conductance, PV system, dynamic responses.

I. INTRODUCTION

Globally, the integration of the photovoltaic (PV) system with the grid spreads progressively where the contribution of PV generation to the overall worldwide power generation is augmented. In this regard, the increase of the PV system efficiency is pivotal for optimal operation. This benefit can be achieved through continuous acquiring of the maximum power from the PV arrays as the environmental conditions vary. The maximum power point tracking (MPPT) is essential in the operation of the PV arrays to improve the overall system efficiency [1]–[3]. The solar irradiation (G) and the cell temperature (T_c) are considered to represent the environmental conditions change along the day hours. As G and T_c vary, the PV array voltage and power depart from the optimum point. Consequently, the PV array voltage is adjusted to match the maximum output power. The common way to adjust the PV voltage is via adjusting the duty cycle of the DC-DC boost converter.

The most widespread MPPT methods are the incremental conductance (INC), the perturb-and-observe, the fractional short-circuit current, the fractional open circuit voltage and the hill climbing [4]–[8]. Driven by the advancements in artificial intelligence techniques [9], [10], many variants are

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applied as control methods to the MPPT for PV systems [11]. The fuzzy logic control (FLC) and the artificial neural networks are widely used for MPPT, which are robust, accurate and fast methods [12]–[14]. Some optimization techniques are used to improve the MPPT accuracy, such as genetic algorithm [15], [16], ant colony optimization [17], and particle swarm optimization [18]. In [19]–[21], hybrid MPPT techniques, which comprise classical and artificial intelligence methods, are introduced. Due to the rapid development of metaheuristic optimizations, they are applied to the MPPT control of PV, e.g. intelligent fuzzy particle swarm optimizer [22], [23], modified sine-cosine optimizer [24], adaptive neuro-fuzzy inference system-particle swarm optimization [25], and Jaya optimizer [26]. An appraisal of different MPPT methods is presented in [27]–[31]. The INC method is one of the most robust and reliable classical MPPT method [32], [33]. It has a defect of fixed voltage step to react with the variation in the environmental conditions. Recent advancements to improve the INC method are presented in [34]–[36]. A fuzzy logic based control is used for improving the INC method was presented in [37]–[39]. A fuzzy logic based auto-scaling variable step-size MPPT method is presented in [40]. According to the authors' knowledge, different attempts have been implemented to solve the MPPT problem by traditional methods. However, none of them has applied fuzzy logic algorithm combined with the INC considering split regions, which is the main focus of this paper.

To cover the gap in the literature, a novel design of fuzzy logic control for varying the voltage step size is proposed in this paper to improve the operation of the conventional INC MPPT method. Five regions are suggested around the point of maximum power of PV. The voltage (duty cycle) step size is varied according to the locations of the fuzzy inputs regarding the five regions. The operation of the incremental conductance depends on the slope of the power-voltage relation. This relation is interpreted as the relation between the ratio of PV current and PV voltage (I/V) and the ratio of their derivatives (dI/dV). Therefore, the proposed fuzzy inputs are I/V and dI/dV. The fuzzy rule base and the membership functions of inputs and output are generated intuitively. The variation of the PV voltage is implemented by adjusting the duty cycle of the DC-DC boost converter. Thus, the fuzzy output is a variable step size of duty cycle. The application of this fuzzy logic based algorithm is presented to improve the MPPT performance during the constant environmental conditions (static performance) and during the switching of the environmental conditions (dynamic performance).

This paper is organized as follows. In Section II, the PV array modeling is presented and the effect of the variations of the environmental conditions on the maximum power point is declared. In Section III, a description of the proposed fuzzy logic controller (FLC) based variable step algorithm for incremental conductance MPPT method is presented. Section IV presents the results of the application of the proposed FLC based algorithm and illustrates the improvement achieved compared to the conventional fixed step INC method. Section V presents the conclusion.

II. MATHEMATICAL REPRESENTATION OF PV ARRAYS

PV arrays are composed of PV panels, which comprises PV cells connected in series or parallel. The panels are also connected in series and parallel to meet the required voltage, current and power. To present the mathematical model of a PV array, one diode model is adopted for modeling a PV cell as shown in Figure 1 [33], [41], [42].

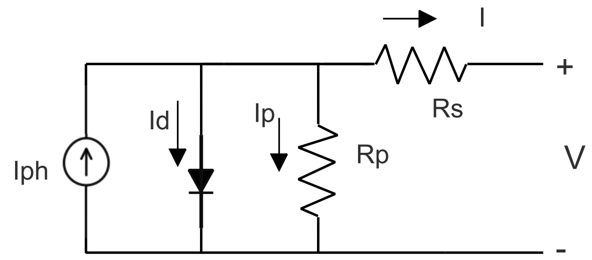


FIGURE 1. One diode model for modeling a PV cell.

The mathematical equations for representing PV panel, which has number of series cells (N_s) are presented as follows.

$$I = I_{ph} - I_s(exp(\frac{(V+IR_s)}{aN_sV_t}) - 1) - \frac{V+IR_s}{R_p} \quad (1)$$

$$V_t = \frac{kT_c}{q} \quad (2)$$

$$I_{ph} = \frac{G}{G_n}(I_{sc_n} + K_I(T_c - T_{c_n})) \quad (3)$$

$$I_s = I_{s_n}(\frac{T_c}{T_{c_n}})^3 exp(\frac{qE_g}{ak}(1/T_{c_n} - 1/T_c)) \quad (4)$$

$$I_{s_n} = I_{sc_n}/(exp(\frac{V_{oc_n}}{aN_sV_{t_n}}) - 1) \quad (5)$$

where I_{ph} is photo current of PV panel, I_s is saturation current, I_{sc} is short circuit current, V_{oc} is open circuit voltage, V_t is thermal voltage, G is solar irradiance, T_c is cell temperature, E_g is band gap of the semiconductor material, k is Boltzmann constant, q is electron charge, a is ideality factor, R_s is series resistance, R_p is parallel resistance, N_{p_s} is number of parallel strings, and N_{s_p} is number of series panels.

The standard test conditions are denoted by the subscript n, at which $G_n = 1000\ W/m^2, T_{c_n} = 25\ °C$. The series resistance (R_s) accounts for the internal cell resistance and the contact resistance, whereas the parallel resistance (R_p) accounts for the leakage current. The two resistances can be determined by solving nonlinear algebraic equations using the Newton-Raphson method or optimization methods.

For a PV array having number of parallel strings (N_{p_s}) and each string has number of series panels (N_{s_p}), the current-voltage equation is presented as follows:

$$I = N_{p_s} * I_{ph} - N_{p_s} * I_s(exp(\frac{(V+IR_s * N_{s_p}/N_{p_s})}{aN_sV_t}) - 1) - \frac{V+IR_s * N_{s_p}/N_{p_s}}{R_p * N_{s_p}/N_{p_s}} \quad (6)$$

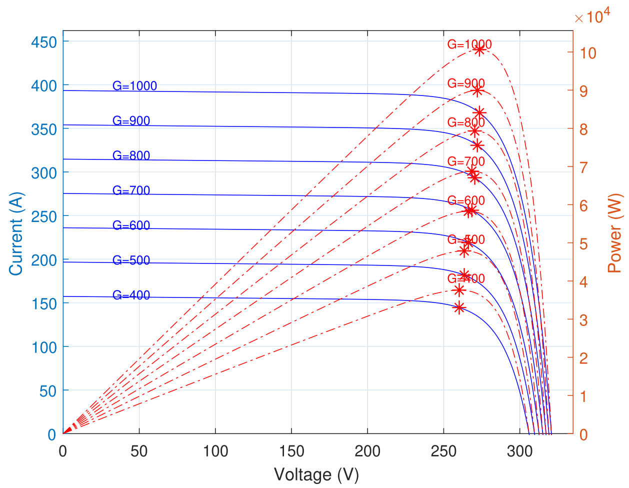


FIGURE 2. **The power-voltage and the current-voltage relations of a 100-kW PV array for different solar irradiance at $T_c = 25\,^\circ C$.**

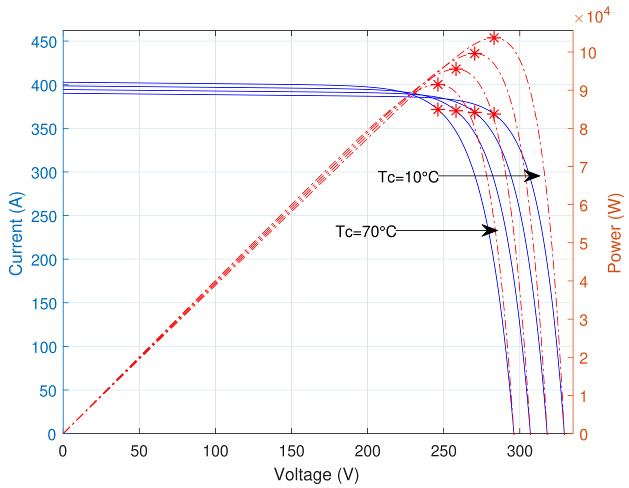


FIGURE 3. **The power-voltage and the current-voltage relations of a 100-kW PV array for different cell temperature at $G = 1000\ W/m^2$.**

To demonstrate the effect of change of the environmental conditions (G and T_c) on the maximum power point, a PV array is simulated using MATLAB/SIMULINK. The simulated array is a 100-kW PV array, which is composed of 5 parallel strings, each string consists of 66 series SUNPOWER 305 panel, which has 96 all back-contact solar cells. The current-voltage and the power-voltage relations are shown in Figure 2 and Figure 3 for different solar irradiance at $T_c = 25\,^\circ C$ and for different cell temperatures at $G = 1000\ W/m^2$, respectively.

As shown in these figures, the maximum power point changes continuously as the environmental conditions change. Therefore, it is indispensable to use MPPT systems to keep extracting the maximum power of PV panels/arrays.

III. DESCRIPTION OF THE FLC BASED VARIABLE STEP INC MPPT METHOD

A. CONVENTIONAL FIXED STEP INC MPPT METHOD

The incremental conductance method is one of the widely used conventional MPPT methods [32], [33]. It is based on the slope of the power-voltage relation. The maximum power occurs at zero slope, whereas negative slope requires voltage decrement and positive slope requires voltage increment to maintain the PV array voltage and power at their optimum values. The following equations summarize the incremental conductance method:

$$P = VI \tag{7}$$

$$dP/dV = I + VdI/dV \tag{8}$$

where P is the output dc power. At maximum power point $dP/dV = 0$, this leads to:

$$I/V = -dI/dV \tag{9}$$

When $dP/dV > 0$, i.e., $I/V > -dI/dV$, the voltage needs to be incremented, and when $dP/dV < 0$, i.e., $I/V < -dI/dV$, the voltage needs to be decremented. A flowchart of the incremental conductance method for MPPT is shown in Figure 4 [32]. For the conventional INC method, ϵ represents a fixed small amount of voltage for increment or decrement.

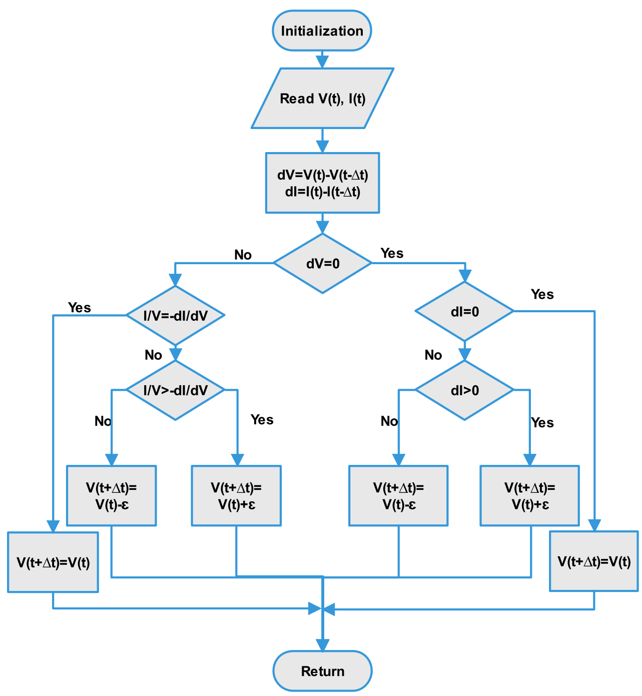


FIGURE 4. **A flowchart of the fixed step size incremental conductance MPPT method.**

B. FLC ALGORITHM FOR VARIABLE STEP INC MPPT METHOD

The basic functioning of fuzzy controller is shown in Figure 5, where crisp inputs are converted to fuzzy inputs according to their membership functions and degree of membership (the fuzzification process). Based on the degrees of the membership function and the rule base, the inference engine generate the fuzzy output using the implication and the aggregation methods. The fuzzy output is converted to

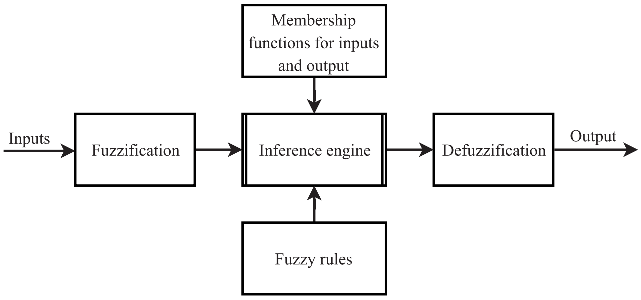


FIGURE 5. Overview of a fuzzy logic control system.

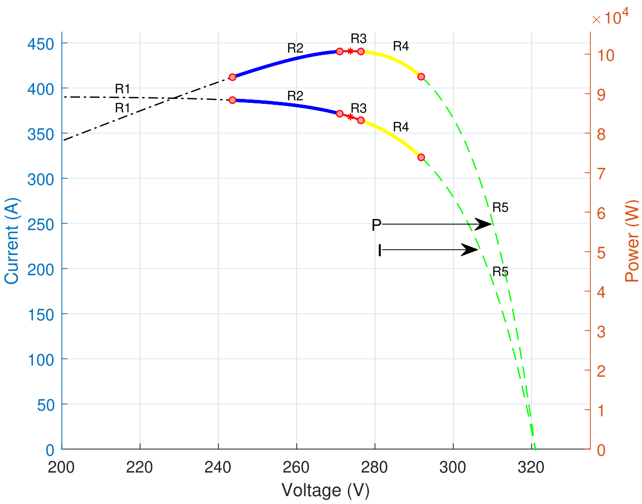


FIGURE 6. Representation of the five proposed regions on the power-voltage and current-voltage relations at the standard test conditions.

a crisp output using any method such as the center of area (the defuzzification process) [43].

The proposed algorithm employs FLC for varying the step size of voltage increment or decrement of the INC MPPT method. The algorithm assigns five regions according to their locations with respect to the point at maximum power. Figure 6 roughly shows the representation of the five regions on the power-voltage and current-voltage relations at the standard test conditions, where $R1$, $R2$, $R3$, $R4$, and $R5$ roughly represent these five regions. To clarify these regions, their ranges are represented on the voltage axis as follows:

- Region $R1$ represents the voltage range, which is much lower than V_{mpp}.
- Region $R2$ represents the voltage range lower than V_{mpp}.
- Region $R3$ represents the voltage range very close to V_{mpp}.
- Regions $R4$ and $R5$ represent the replica of regions $R2$ and $R1$, respectively, from the other side of V_{mpp}.

The proposed fuzzy inputs are the ratio between PV current and PV voltage (I/V) and the ratio between their derivatives (dI/dV). The desired output is the variable voltage step (increment or decrement). As the voltage is controlled through changing the duty cycle of the DC-DC boost converter, the variable voltage step is controlled through a variable duty cycle step (ΔD), which is considered as the fuzzy output. So, referring to the flowchart in Figure 7, the voltage step (V_{step}) is variable and is controlled through ΔD based on the two fuzzy inputs and the proposed intuitive decision rule base.

Figure 8 illustrates the relation between the fuzzy inputs (I/V and dI/dV) and the PV array voltage, at the standard test conditions, where the points representing the five regions are marked.

The intuitive rules to ensure accuracy and fast tracking to reach the point of maximum power are as follows;

- If $dP/dV \gg 0$, i.e., $I/V \gg -dI/dV$ (region $R1$), the suitable V_{step} is positive big (PB).
- If $dP/dV > 0$, i.e., $I/V > -dI/dV$ (region $R2$), the suitable V_{step} is positive small (PS).
- If $dP/dV \approx 0$, i.e., $I/V \approx -dI/dV$ (region $R3$), the suitable V_{step} is very small (VS).
- If $dP/dV < 0$, i.e., $I/V < -dI/dV$ (region $R4$), the suitable V_{step} is negative small (NS).
- If $dP/dV \ll 0$, i.e., $I/V \ll -dI/dV$ (region $R5$), the suitable V_{step} is negative big (NB).

TABLE 1. Fuzzy rules for generating the variable step duty cycle for INC method with the two inputs I/V and dI/dV.

I/V \ dI/dV	VL	L	VC	H	VH
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 fuzzy rules are proposed to generate suitable V_{step} based on the fuzzy inputs (I/V and dI/dV). Table 1 presents all the intuitive fuzzy rules. To explain how these rules are deduced, one rule is explained as follows;

If I/V and dI/dV are very low (VL) compared to their values at maximum power point (i.e., both are at region $R5$ as shown in Figure 8), then $I/V \ll -dI/dV$, which requires a negative big V_{step} (i.e., positive big (PB) step of the duty cycle). In other words, the suitable step size can be estimated based on the sum, $I/V + dI/dV$, and the region it belongs to as shown in Figure 8.

Note that the fuzzy output is the variable duty cycle step (ΔD), which can be related to V_{step} according to the following equations;

$$V = (1 - D) * V_{dc} \tag{10}$$

$$\Delta V = V_{step} = -\Delta D * V_{dc} \tag{11}$$

The dc link voltage (V_{dc}) is considered fixed in this study. V_{dc} dc link voltage.

In this table, the abbreviations are as follows; VL: very low, L: low, VC: very close, H: high, VH: very high, NB: negative big, NS: negative small, VS: very small, PS: positive small, PB: positive big. The membership functions of inputs and output are shown in Figure 9.

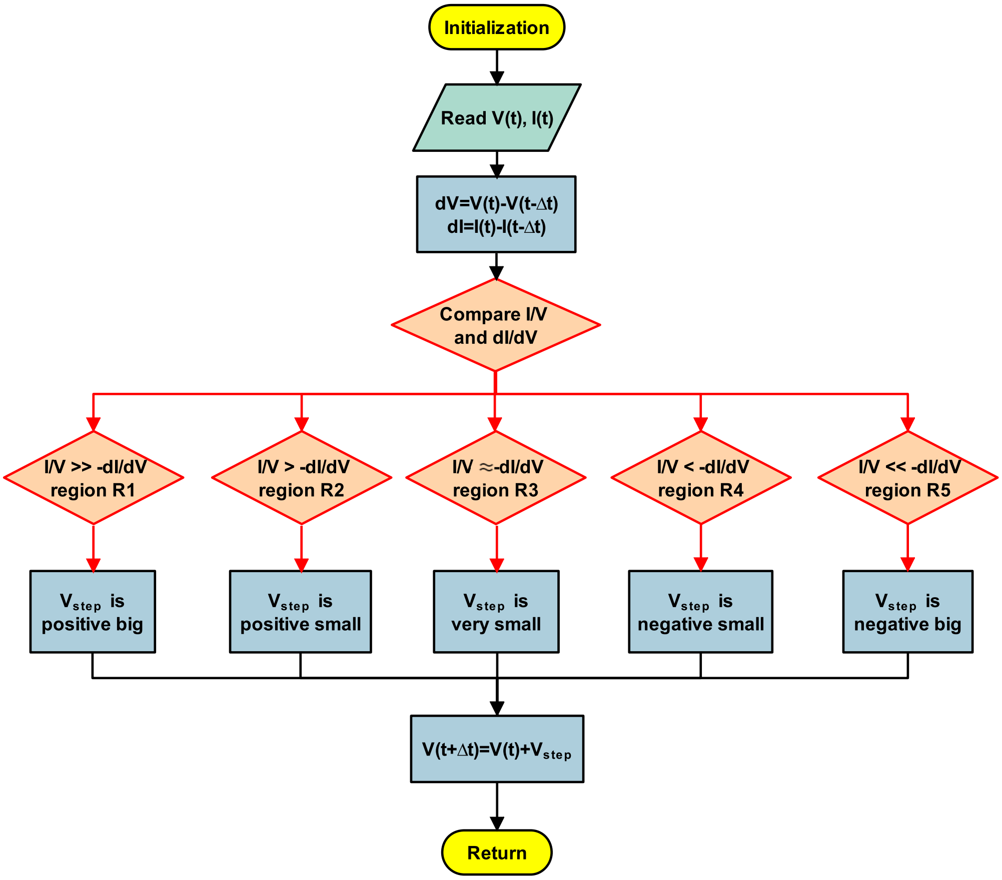


FIGURE 7. A flowchart of the proposed FLC based variable step size INC MPPT method.

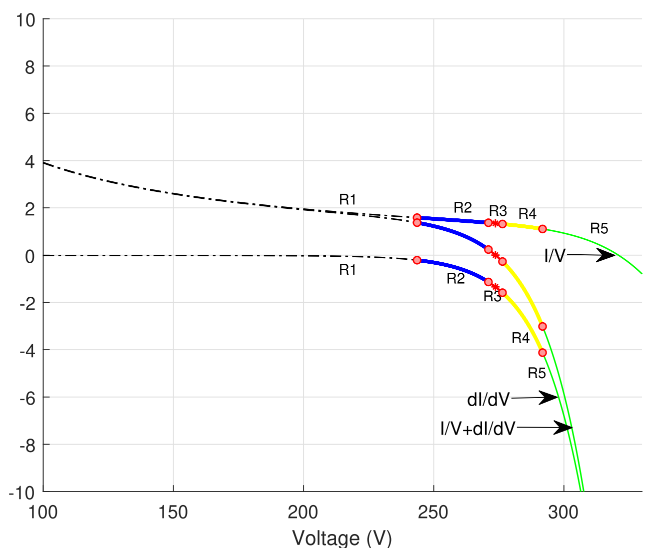


FIGURE 8. The relation between the fuzzy inputs (I/V and dI/dV) and the PV array voltage at the standard test conditions indicating the five regions.

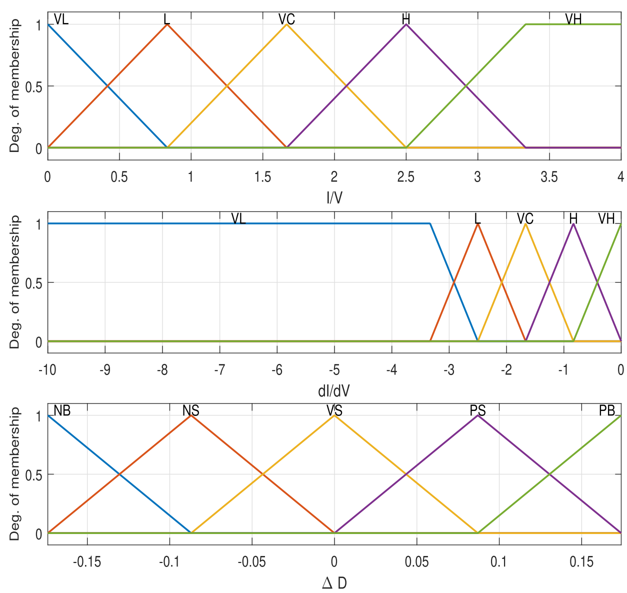


FIGURE 9. The membership functions of inputs and output of FLC based variable step INC method.

The universes of discourse for the fuzzy inputs and output are based on their effective values at the standard test conditions as shown in Figure 8. Nevertheless, as G and T_c vary, the effective values of the fuzzy inputs and output vary. So, some gains are used with the inputs and the output of the fuzzy system to adjust their values to be suitable for the

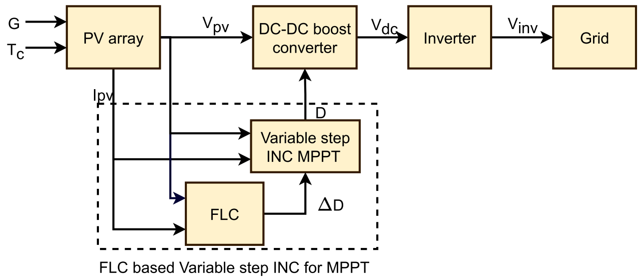
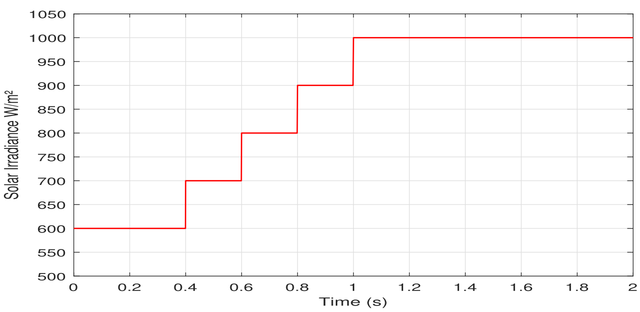
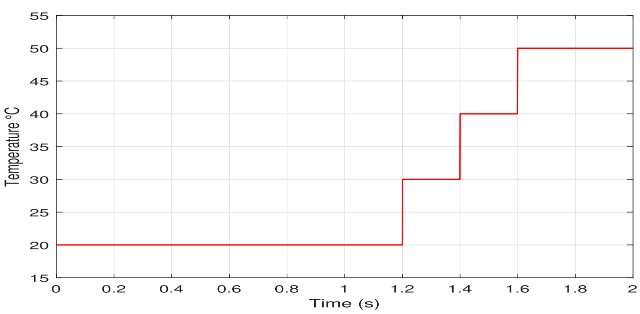


FIGURE 10. An overview of the grid-connected PV array with the proposed FLC based variable step INC MPPT method.

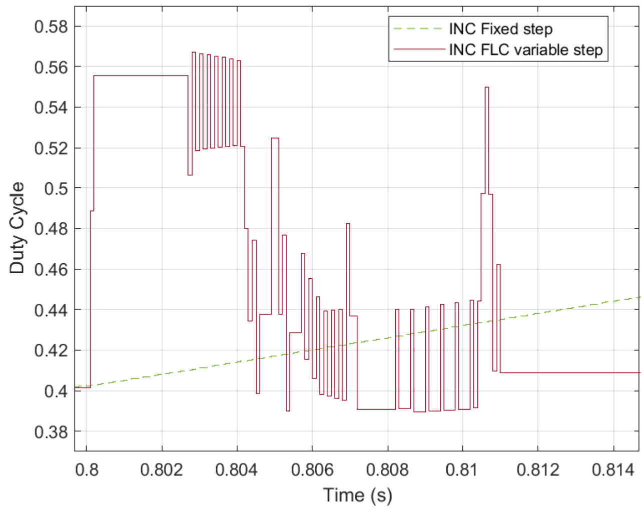


(a)

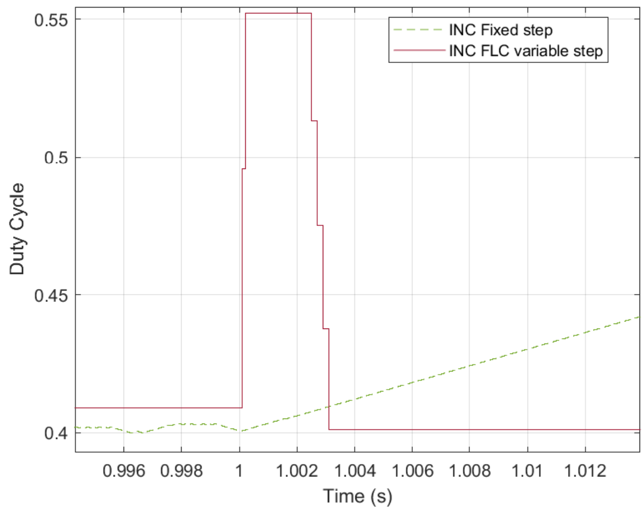


(b)

FIGURE 11. Testing the FLC based algorithm through the step variations of (a) the solar irradiance (G) (b) the cell temperature (T_C).



(a)



(b)

FIGURE 12. Comparisons of FLC based and fixed duty cycle of the INC MPPT method (fixed step=0.0003 s) for step variations of G and T_C: (a) for the step change at 0.8 s; (b) for the step change at 1 s.

designed universes of discourse. The gains are optimized to get the best suitability to be used with fuzzy logic variable step INC MPPT.

IV. APPLICATION OF THE FLC BASED VARIABLE STEP ALGORITHM

To apply the proposed FLC based variable step INC MPPT method, a modified MATLAB model of 100-kW grid-connected PV array is used. This model is composed of 5 parallel strings, each string consists of 66 series SUNPOWER 305 Panel as mentioned in Section II. An overview of the grid-connected PV array model, including the proposed algorithm for MPPT, is shown in Figure 10. It comprises the PV array, the dc-dc boost converter, the variable step INC MPPT, the inverter and the grid. The FLC block provides the INC method with a variable change of duty cycle at each step according to the fuzzy inputs. The variable step INC MPPT produces the duty cycle to adjust the PV voltage to its optimum value.

For the simulation purpose, the environmental variables taken into consideration are the solar irradiation (G) and the cell temperature (T_c). Two simulation cases are studied to highlight the effectiveness of the proposed method to improve the MPPT efficiency and to increase the output DC power. The first simulation case study deals with the step variations of G and T_c, while the second one deals with their ramp variations.

A. STEP VARIATIONS OF G AND T_c

The proposed step variations of G and T_c are shown in Figure 11, which are used for testing the proposed FLC based variable step INC MPPT method.

The feasibility of the application of such FLC based algorithm to improve the conventional INC MPPT method is

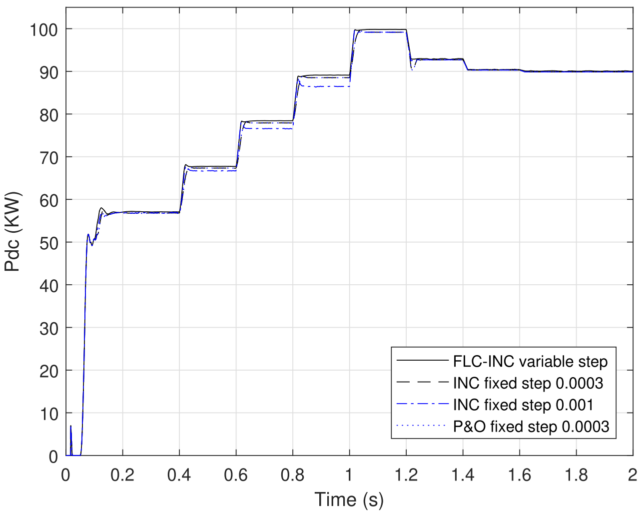


FIGURE 13. The output dc power comparison when applying the conventional fixed step INC method, the fixed step *P&O* method and the FLC based variable step INC method for MPPT.

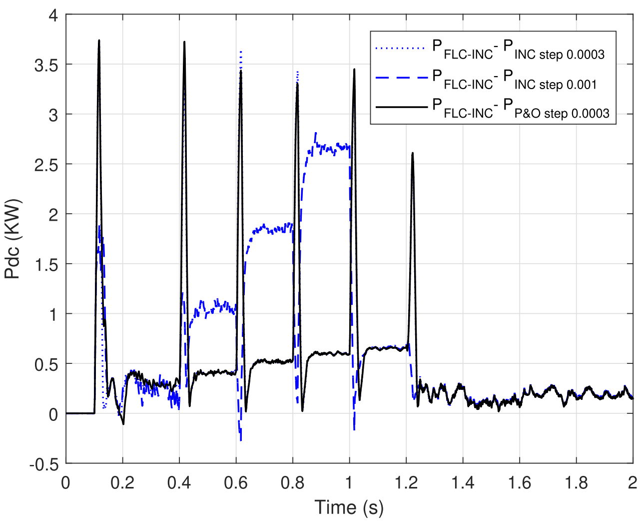


FIGURE 14. The difference between the output dc power when applying the FLC based algorithm and these of the conventional fixed step INC and P&O methods for MPPT.

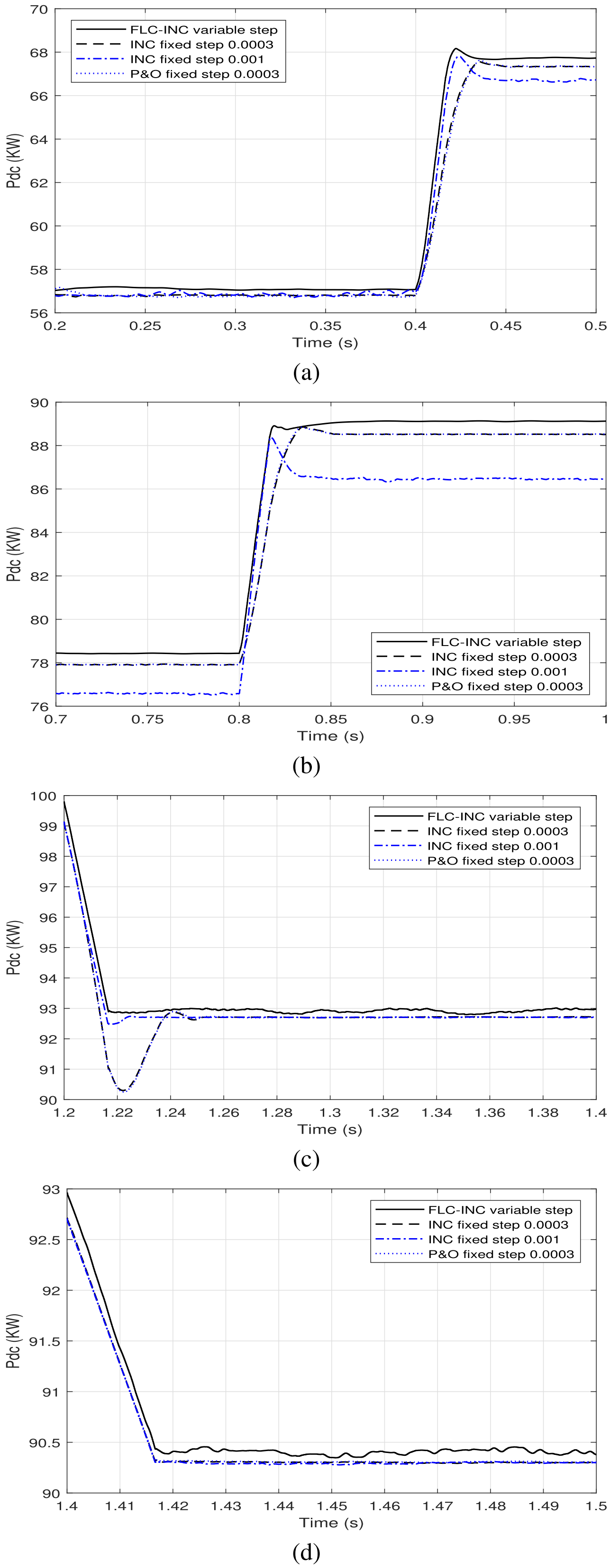


FIGURE 15. Proximate views of the output dc power comparison when applying the FLC based algorithm and these of the conventional fixed step INC and P&O methods for MPPT: (a) from 0.2 to 0.5 s; (b) from 0.7 to 0.95 s; (c) from 1.2 to 1.4 s; (d) from 1.4 to 1.5 s.

declared through the simulation of the grid-connected PV array. Figure 12 presents sample of comparisons between the fixed duty cycle step and the FLC based duty cycle step at different time periods. Two remarks can be extracted; The first one that the FLC based duty cycle step changes accordingly as G or T_c to improve the response of the MPPT system, where the fixed step is always of constant magnitude added or subtracted from the previous duty cycle value. The second remark that the fixed step cannot be zero even if the optimal point is very close, where the FLC based duty cycle step adapts its size according to its nearness to the maximum power point is reached.

To illustrate the efficacy of the proposed FLC variable step MPPT method, it is compared to two conventional methods.

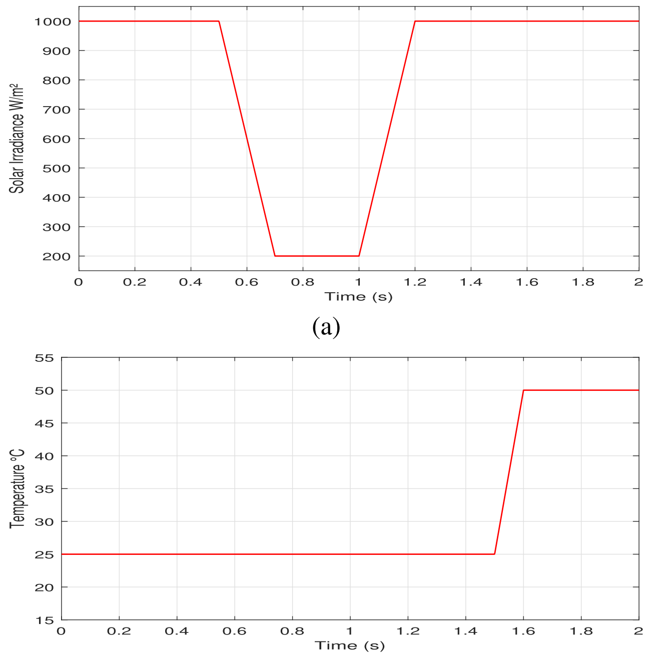


FIGURE 16. Testing the FLC based algorithm through the ramp variations of: (a) the solar irradiance (*G*); (b) the cell temperature (T_c).

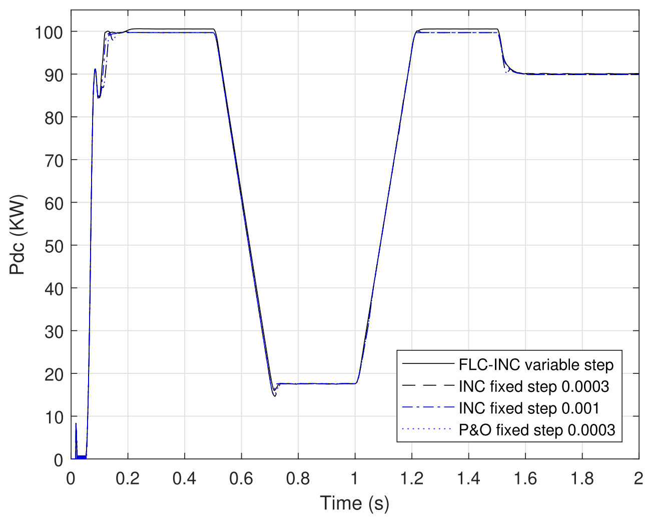


FIGURE 17. The comparison of output dc power when applying the conventional INC and the conventional P&O MPPT methods when using fixed step size and that of the FLC based variable step size for ramp variations of *G* and T_c.

The first one is the conventional INC method with fixed step sizes of 0.0003 s and 0.001 s. The second one is the conventional perturb and observe (P&O) method with fixed step of 0.0003 s. The comparison between these methods is considered from two points of view. The first one is the output dc power, which is relevant to the PV system efficiency. The second point is the tracking speed. This comparison is shown in Figure 13. The improvement achieved is declared in Figure 14, where it represents the output dc power difference between the compared methods.

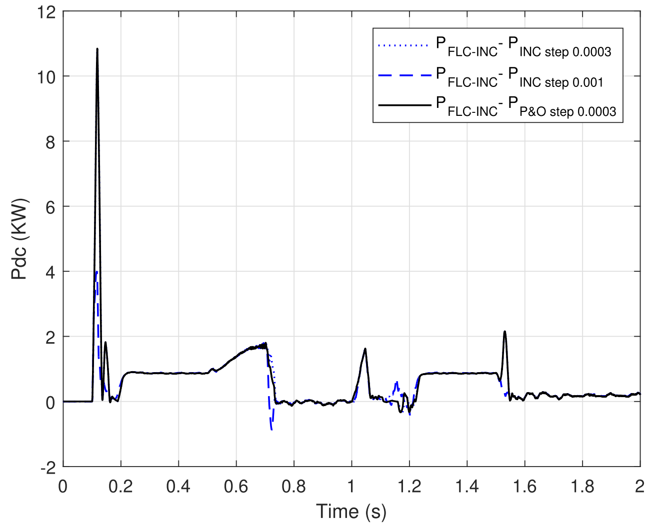


FIGURE 18. The improvement of the output dc power when applying the FLC based algorithm over these of the conventional fixed step INC and P&O methods for MPPT.

To focus on this comparison, proximate views of Figure 13 are presented in Figure 15 to emphasize the improvement achieved in the amount of the output dc power and the tracking speed when using the proposed method. It is shown from Figures 13, 14 and 15 that using the FLC based variable step INC method for MPPT improves the static and dynamic performance of the output dc power of the PV array. The static performance improvement is emphasized through the increase of the amount of the output dc power during the periods of constant G and T_c. The dynamic performance improvement is declared through fast tracking when G or T_c vary.

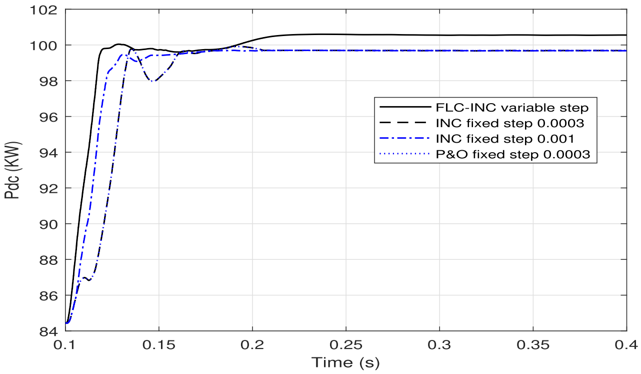
B. RAMP VARIATIONS OF G AND T_c

The proposed ramp variations of G and T_c are shown in Figure 16, which are used to emphasize the ability of the proposed algorithm to deal with different variations in the considered atmospheric conditions.

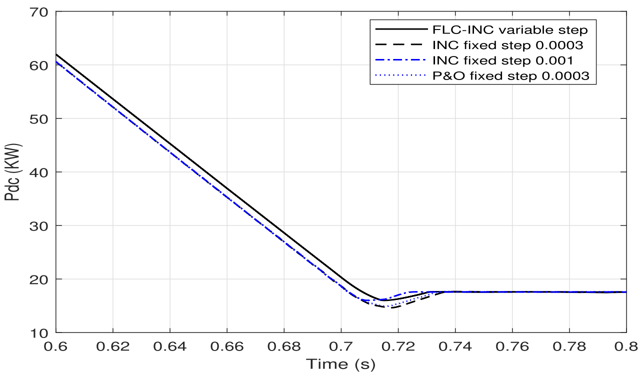
The comparison between the output DC power when using the fixed step INC method, the fixed step P&O method and the FLC based variable step based MPPT systems is shown in Figure 17. The improvement in the output DC power is presented in Figure 18.

Close views of Figure 17 are presented in Figure 19 to precisely illustrate the improvement in the output dc power.

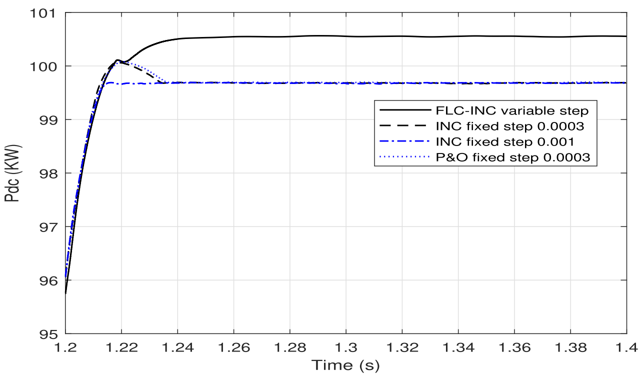
Table 2 present a quantitative comparison between the output dc power responses when applying the proposed FLC based variable step size and these of the fixed step size INC and P&O MPPT methods. The first quantitative index is the produced energy over the simulation period, which is the integration under the power-time curve. The second index is the average rise time at different step variations of the response. The first index is given for the two simulation cases (step and ramp variations of G and T_c), while the second index is presented only for the step variation of G and T_c.



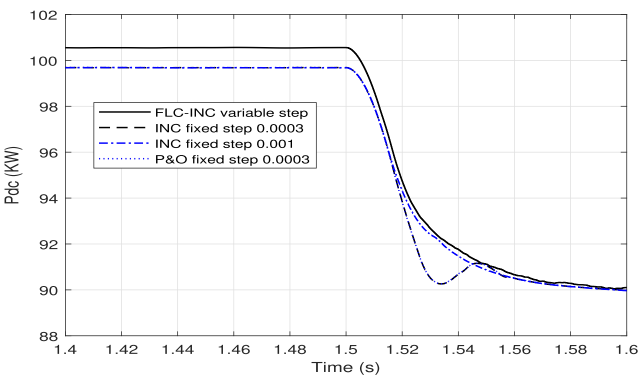
(a)



(b)



(c)



(d)

FIGURE 19. Close views of the output dc power comparison when applying the FLC based algorithm and these of the conventional fixed step INC and P&O methods for MPPT: (a) from 0.1 to 0.4 s; (b) from 0.6 to 0.8 s; (c) from 1.2 to 1.4 s; (d) from 1.4 to 1.6 s.

TABLE 2. A quantitative comparison of the produced energy and the average rise time when applying the proposed FLC based and the conventional INC and P&O MPPT methods.

MPPT method	Step variation in G and Tc		Ramp variation in G and Tc
	output Energy(KJ)	avg. Rise time (s)	output Energy(KJ)
INC fixed step 0.0003	155.53	0.0207	142.82
INC fixed step 0.001	155.055	0.0152	143
P&O fixed step 0.0003	155.52	0.0207	142.84
FLC variable step	156.45	0.0133	144.03

These two simulation cases of study emphasize the efficacy of the proposed FLC design to improve the INC based MPPT system for different environmental conditions through varying the duty cycle step size.

V. CONCLUSION

The PV system efficiency is a crucial index to evaluate the performance of grid-connected PV systems where the MPPT performance is a keynote. The conventional fixed step INC method for MPPT is widely used but it lacks some accuracy and speed of convergence. To tackle this issue, the proposed improvement of the INC method is introduced to employ a fuzzy logic algorithm to generate a variable step voltage increment or decrement, which is executed through decrement or increment of the duty cycle of the dc-dc boost converter. The voltage (duty cycle) step has five different sizes according to proposed five regions of the fuzzy inputs. The simulation results demonstrate that the proposed FLC based variable step INC method for MPPT enhances the output dc power and reduce the time of convergence to reach the steady state when switching of the environmental conditions. To illustrate the efficacy of the proposed MPPT method, it is compared to two conventional methods. The first one is the INC method with fixed step sizes of 0.0003 s and 0.001 s. The second method is the conventional P&O method with fixed step of 0.0003 s. In future work, the experimental application of the proposed FLC variable step method will be studied in a grid-connected PV systems.

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