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IMPROVED INCREMENTAL CONDUCTANCE MAXIMUM POWER POINT TRACKING ALGORITHM USING FUZZY LOGIC CONTROLLER FOR PHOTOVOLTAIC SYSTEM

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Key words: Photovoltaic energy, Maximum power point tracking (MPPT), Incremental conductance (INC), Improved INC, Fuzzy logic controller (FLC).

The hard nonlinearity of the electrical behavior, current-voltage output of a photovoltaic array considered a big issue in the designing of maximum power point tracking (MPPT) algorithms, furthermore changing with atmospheric condition temperature and irradiation. So it's more challenging to control both the time response and the accuracy. The most commonly algorithms discussed and used in practice are incremental conductance (INC) and perturb and observe (P&O), nevertheless failed to overcome the drawback of the trade-off between the elimination of oscillation around MPP in the steady state and quickness tracking, chiefly when sudden sharp environmental change occurs. Thus, this study suggests a revised incremental conductance combined with fuzzy logic controller (FLC), to enhance the efficiency of the conversion system and perfom it for practical operating conditions. The INC uses the step size generated from FLC. The performance of the dynamic response and the accuracy have optimized significantly compared with conventional methods (P&O, INC). Computer simulation has carried out under MATALB/Simulink environment to demonstrate the performance of the proposed method.

1. INTRODUCTION

The energy crisis, ongoing and getting worse due to the increasing requests, particularly in the last decade which witnessed sharp rising. The worldwide has been powered essentially by conventional fossil-fuel energy sources for long periods of time. The rising up environmental anxiety in recent years about global warming and the harmful effects of carbon rate emissions has led to looking for new alternative clean and sustainable energy sources, such as (solar energy, wind, biomass etc.) [1].

Among all these, solar photovoltaic (PV) technology has considered as one of the most attractive and promising renewable energy [2]. Many countries have been showing their interest to PV system through the immersion of new industrial moguls in this area and doubled the number of installations of PV system, due of the many merits that they have such as, green energy, free and available, no noise, pollution or moving parts and requires less maintenance [3]. However the high production cost and low efficiency of the PV system which include in the range between 12–20% [4], are the major disadvantages. The use of the maximum power point tracking (MPPT) control has become an important spot to extract the maximum power harvested from a PV panel; the main problem solved by the MPPT is to maintain the system to operating at the maximum power point MPP all times. In the view of the fact that the hard nonlinearity of the *I–V* (current-voltage) characteristics and *P–V* (power-voltage) characteristics clear to us that there is only one point which deliver the maximum power under uniform and particular weather conditions and this point continuously changing with ambient temperature and sunlight intensity. The electrical behavior is more complicated further by rapid changes in the environmental conditions, this challenging topic has been attracting many research to overcome these drawbacks.

Over the years, many MPPT algorithms have been reported in the literature [5]. The main difference between them is the degree of complexity, speed of convergence and cost.

Some of them have the same principle working and others used two stages [6]. Fractional open-circuit voltage and short-circuit current, there is a linear dependency between maximum power point (MPP) and open-circuit voltage (V_{oc}) or short-circuit current (I_{sc}). The computational of MPP is easy and does not require microcontroller [7]. Usually, the system disconnects the load periodically to measure (V_{oc}) or (I_{sc}) which results temporary power losses. Some methods have proposed to overcome this drawback like monitor cell, but have to be carefully chosen to determine the right open-circuit voltage. The most well-known MPPT methods and widely used in practice are perturb and observe P&O and incremental conductance (INC) due to their simplicity of implementation [8]. The perturb and observe method involves introducing a perturbation in the operating voltage, if the sign of the slope, maintain positive should be kept in the same direction, otherwise the next perturbation should be in the opposite direction [9]. The incremental conductance is based on the fact that the derivative of the power-voltage characteristic (slope) is zero at MPP, the main idea is to compare the incremental conductance to the instantaneous conductance. Depending on the result, the operating voltage is either increased, or decreased until the MPP is reached [10]. The main shortcoming of this algorithm is a trade-off between the dynamic response and the oscillation around MPP in the steady state. To solve this problem some algorithms with variable step size are proposed [11]. Heuristic methods considered recently as an alternating method in order to optimize the performance (fuzzy logic controller, neural network, genetic algorithms). Fuzzy logic controller (FLC) is a new emerging technology for the last two decades, which has become present in many fields as consumer, industrial process control, medical diagnostics and automotive applications [12]. The FLC has the ability to deal with nonlinear system or complex mathematical models and the possibility of exploiting tolerance for some inexactness and imprecision [13]. Moreover, simple to understand, and inexpensive to develop. Fuzzy logic controllers emulate

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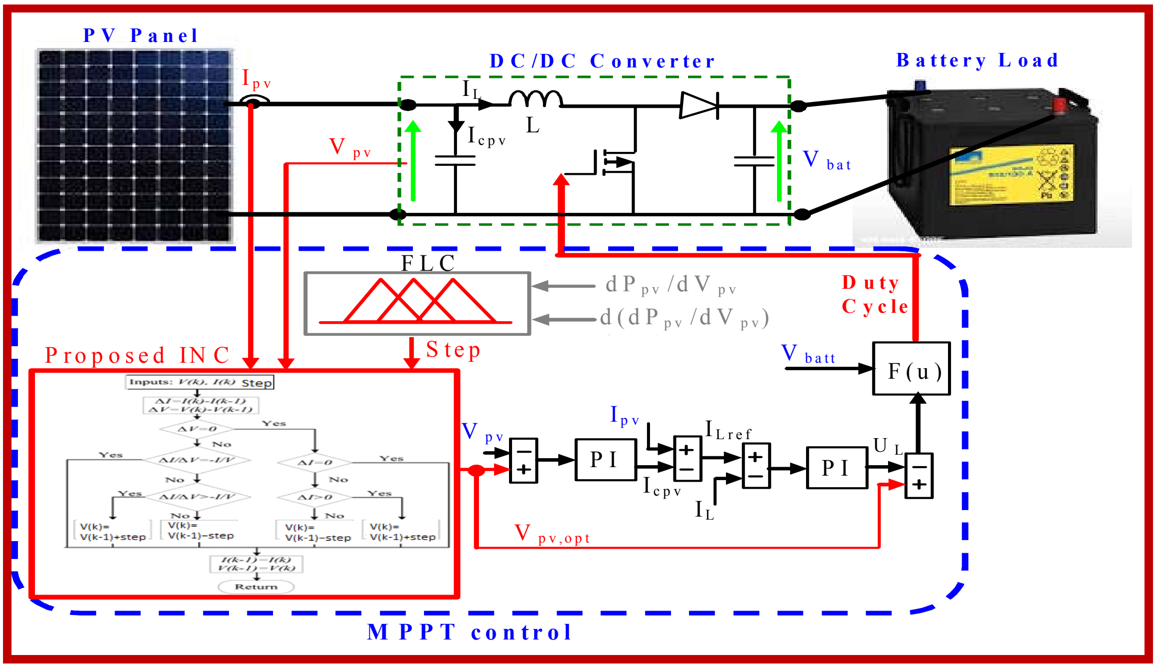


Fig. 1 – PV System with MPPT control.

human control strategies. However, the big issue that the effectiveness of FLC depend on the knowledge and experience of the designer. The performance of the behavior of FLC relies mainly on shape of membership functions and rule base [14].

In this paper, a revised incremental conductance method combined with FLC is proposed in order to optimize the efficiency of the PV system. The inputs of FLC are the error of power and change of error on the other hand the output is the step size of the perturbation. INC uses the step size generated from FLC to provide the operating voltage.

This suggested control could reduce significantly the oscillation around MPP and enhance the time response together. The results discussed in this work have been made under MTLAB/Simulink environment.

2. PV SYSTEM DESCRIPTION

Figure 1 depicts the block diagram of the standalone system consisting principally of three major parts battery load powered by a PV module equipped with a dc boost converter that transforms the voltage of the PV module to a desired voltage and an MPPT control each part will be discussed.

2.1. PV MODULE

Photovoltaic cells are the source of the power. In the literature, we can find several mathematical models that represent the electrical behavior. The PV cell consists of current source, diode representing the P–N semiconductor junction, series resistance Rs to modulate the energy losses, The value of the shunt resistance *Rsh* has assumed very big $R = \infty$ (no leakage to ground). The equivalent circuit is shown in Fig. 2.

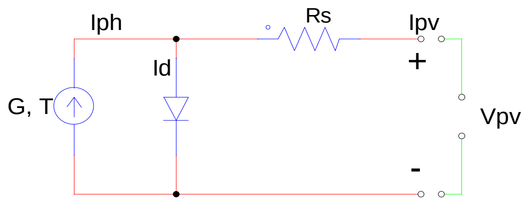


Fig. 2 – Equivalent circuit of a PV cell.

In this study, four parameter model is adopted [15]. The output photovoltaic current I_{pv} is described by the following equation:

$$I_{pv} = I_{sc}\cdot\{1 - C_1[\exp(C_2 V_{pv}^{C_3}) - 1]\}. \quad (1)$$

The coefficients C_1,C_2 and C_3 are given as follows:

$$C_1 = 0.01175,$$

$$C_2 = \frac{\ln\left[\frac{1+C_1}{C_1}\right]}{V_{oc}^{C_3}}, \quad (2)$$

$$C_3 = \left[\frac{\ln\left[\frac{I_{sc}(1+K_1) - I_{mpp}}{K_1 I_{sc}}\right]}{\ln\left[\frac{1+K_1}{K_1}\right]}\right] \Bigg/ \ln\left[\frac{V_{mpp}}{V_{oc}}\right], \quad (3)$$

where: V_{mpp} – maximum power point voltage; V_{oc} – open circuit voltage; I_{mpp} – maximum power point current; I_{sc} – short circuit current.

The above equation is useful only at standard test condition (STC) (G = 1 000W/m^2, T = 25^{o}C) when the temperature and irradiation change the voltage and current variation vary as follows:

$$V_{pv,new} = V_{pv} - \beta_{oc}\Delta T_c - R_s \Delta I_{pv}, \quad (4)$$

$$I_{pv,new} = I_{pv} + \alpha_{sc}\left(\frac{G}{G_{stc}}\right)\Delta T_c + \left(\frac{G}{G_{stc}} - 1\right) I_{sc,stc}. \quad (5)$$

In this study, we use SIEMENS SM 110 module [15]. Table 1 shows the electrical data of PV panel at STC conditions. Figure 3 shows the simulation of electrical characteristics (*I–V* and *P–V*) that prove to us, there is only one point which can deliver the maximum power.

Table 1

Parameters of the PV module SIEMENS SM110 [15]

P_{pv}	110 W
I_{mpp}	3.15 A
V_{mpp}	35 V
I_{sc}	3.45 A
V_{oc}	43.5 V
α_{sc}	1.4 mA/°C
β_{oc}	–152 mV/°C
P_{mpp}	110 W

Figure 3 represents the 3D *I–V–P* characteristic of the PV panel under respectively, different level of irradiation at 25°C and different level of temperature at 1 000 W/m².

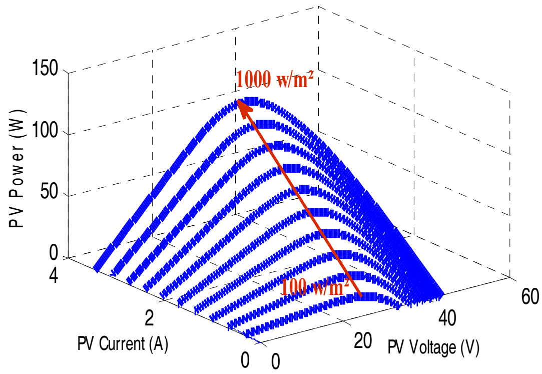


Fig. 3 – PV panel 3D *I–V* characteristic curves with different insolation and constant temperature (25 °C).

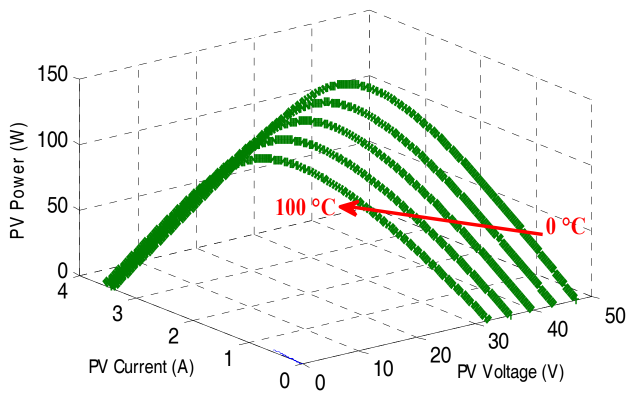


Fig. 4 – PV panel 3D *I–V–P* characteristic curves with different temperature and constant insolation (1 000 W/m²).

2.2. DC-DC BOOST CONVERTER

The switch-mode converter is mentioned to adapt the transform power from a PV panel to the load [16]. In our study, we intercalated a boost converter to achieve the maximum power point MPP as illustrated in Fig. 1. The basic topology consists of two semiconductor switch (Diode, Mosfet), inductor and capacitor, these latter must be chosen big enough to assure the continued conduction mode [16].

The relationship between current and voltage are given as follows:

$$V_{batt} = \frac{V_{pv}}{1-D}, \quad (6)$$

$$I_{pv} = \frac{I_{batt}}{1-D}, \quad (7)$$

where V_{batt} and I_{batt} are output battery voltage and current.

3. MPPT CONTROL

3.1. INCREMENTAL CONDUCTANCE METHOD

In this section, we will describe the incremental conductance (INC) method to calculate the optimum voltage of photovoltaic system by using a fixed step. The incremental conductance (INC) method is based on the fact that the derivative of the PV power (slope) *versus* voltage is zero at MPP. The derivative is positive on the left side and negative on the right side of the MPP [17] as given by :

$$\begin{cases} \frac{dP_{pv}}{dV_{pv}} = 0, & \text{at } MPP \\ \frac{dP_{pv}}{dV_{pv}} > 0, & \text{at left of MPP} \\ \frac{dP_{pv}}{dV_{pv}} < 0, & \text{at right of MPP} \end{cases}. \quad (8)$$

The power derivative can be also written as follows:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = \frac{I_{pv}dV_{pv}}{dV_{pv}} + \frac{V_{pv}dI_{pv}}{dV_{pv}} = $$
$$= I_{pv} + \frac{V_{pv}dI_{pv}}{dV_{pv}} \cong I_{pv} + \frac{V_{pv}\Delta I_{pv}}{\Delta V_{pv}}, \quad (9)$$

where $G = \frac{I_{pv}}{V_{pv}}$ represent the inductance and $\Delta G = \frac{\Delta I_{pv}}{\Delta V_{pv}}$ represent the variation of the inductance.

The main idea is to compare the incremental conductance d*G* to the instantaneous conductance *G*. Depending on the result; the panel operating voltage is either increased, or decreased until the MPP is reached. Figure 5 shows the flowchart of the operating INC.

3.2. IMPROVED INCREMENTAL CONDUCTANCE METHOD

The basic incremental conductance algorithm uses a fixed step size for the panel operating voltage updates. Using a bigger step size will speed up tracking, but may also cause the algorithm to oscillate around the MPP [18]. Improved INC (I-INC), correspond to the incremental conductance algorithm combined with a fuzzy logic controller (FLC), is proposed to track the MPP. The step size used is given form FLC to solve the problem of trade-off between the dynamic response and the oscillations

$$\begin{cases} E(k) = \dfrac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \\ \Delta E(k) = E(k) - E(k-1) \end{cases} . \quad (10)$$

The proposed FLC to optimize the tracking accuracy of MPPT is shown in the Fig. 1. The inputs of the FLC are error power (E) and change of error (ΔE); the output will be the step size (Step) of the perturbation voltage [19]. These inputs are varying according to the Eq. (10), where $P_{pv}(k)$ and $V_{pv}(k)$ are the power and voltage of PV panel at sample time k.

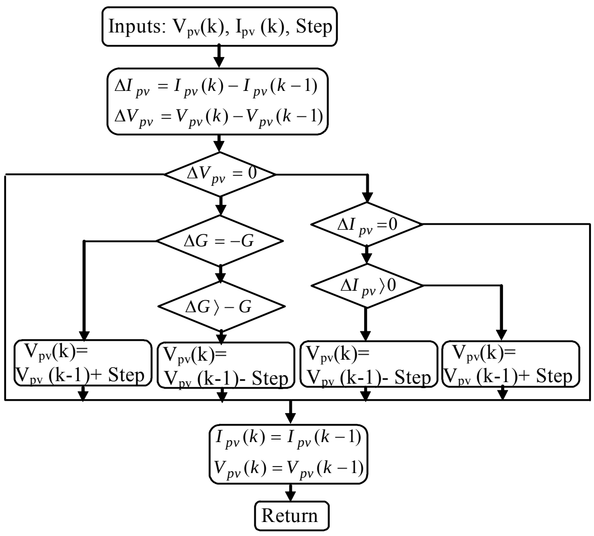


Fig. 5 – Flowchart of INC method.

As illustrated in Fig. 6 the FLC scheme works through three stages: fuzzification, rule-based table lookup and defuzzification [20]. The input variables are translated from numerical to linguistic variables based on membership function which scale into seven subsets, NB (negative big), NM (negative means), NS (negative small), Z (zeros), PS (positive small), PM (positive means), PB (positive big) [18]. The input variables are Z (zeros), PS (positive small), PBS (positive big small), PM (positive medium), PBM (positive big medium), PB (positive big), PH (positive huge). These variables are adjusted by the user, as presented in Fig. 7. The rule table of FLC indicated in Table 2 consists of 49 rules.

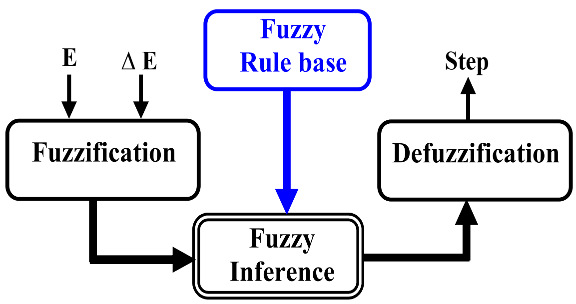


Fig. 6 – Structure of the fuzzy logic controller.

The fuzzy inference is carried out by Mamdani's method, in this paper a centered of gravity (COG) is adopted to defuzzifie the output (Step).

Practically its difficult to get zero error due to truncation error and noise, which causes continuous tracking operations that cause unnecessary oscillations around the MPP. This can be diminished by choosing tolerance (ε) close to zero as depicted in Eq. (11).

This value ε can be determined according to the sensitivity and a signal-to-noise ratio of measurements [21–22]

$$\left| \frac{dP_{pv}}{dV_{pv}} \right| \le \varepsilon. \quad (11)$$

Table 2

Fuzzy rules table [14]

E/ΔE	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PS	PS	PS	PS	PBS	PM	Z
NM	PS	PS	PS	PBS	PM	Z	PBM
NS	PS	PS	PBS	PM	Z	PBM	PB
Z	PS	PBS	PM	Z	PBM	PB	PH
PS	PBS	PM	Z	PBM	PB	PH	PH
PM	PM	Z	PBM	PB	PH	PH	PH
PB	Z	PBM	PB	PH	PH	PH	PH

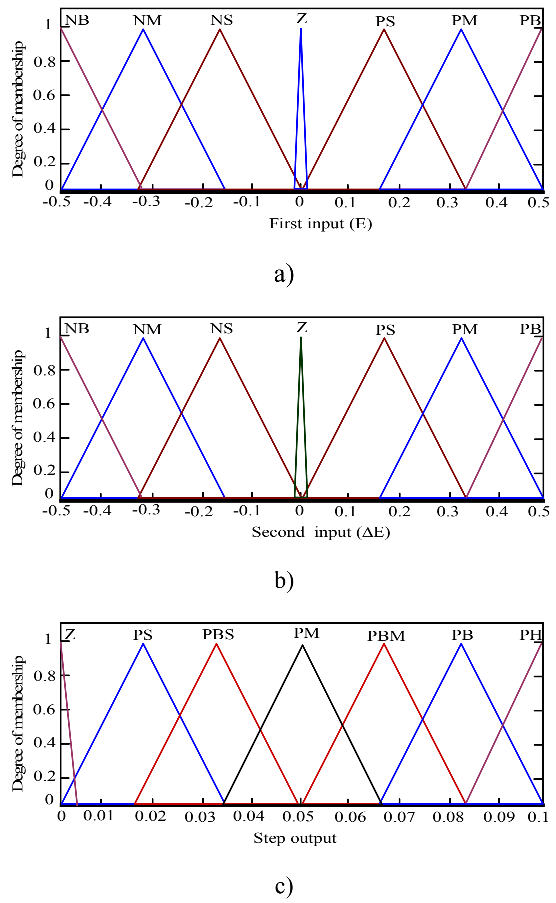


Fig. 7 – Membership function inputs and output: a) error E; b) error variation ΔE; c) step.

4. SIMULATION AND RESULTS

To test the performance of the proposed method and comparing it with conventional methods (P&O, INC) under sharp changes of solar irradiance levels. A step solar irradiance curve is generated, which change from 1 000 to 200 W/m² at 2 s then from 200 to 800 W/m² at 4 s and we assume the temperature constant at 25 °C. In this simulation the step size of conventional INC has taken two values (0.01 and 0.02). Figures 8–12 show the simulation results of the proposed method (I–INC) and conventional INC and P & O methods, which confirms that the proposed method is faster than conventional (INC and PO) methods to achieving MPP.

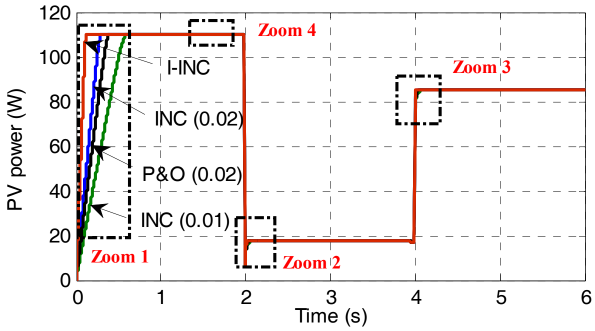
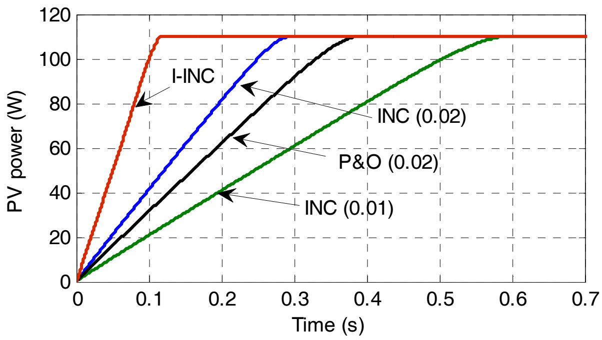
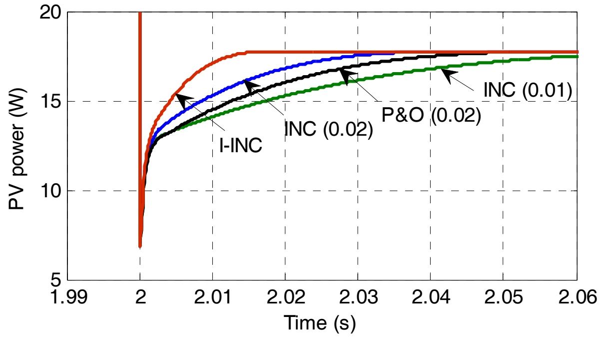


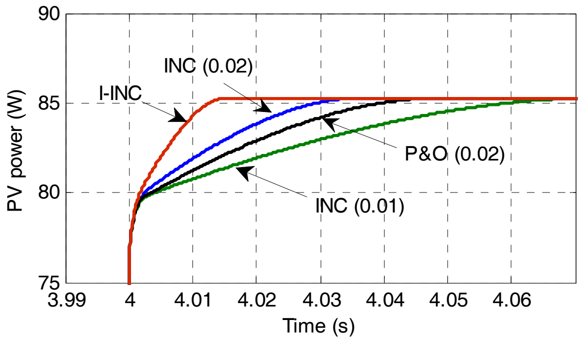
Fig. 8 – PV power with improved (I–INC) and conventional method.



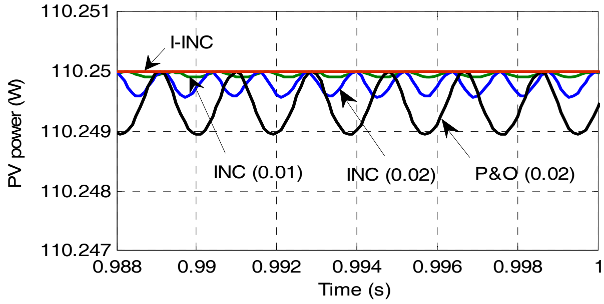
a) Zoom 1



b) Zoom 2



c) Zoom 3



d) Zoom 4

Fig. 9 – PV power zoom with improved (I–INC) and conventional methods: a, b, c) transitional state; d) steady state.

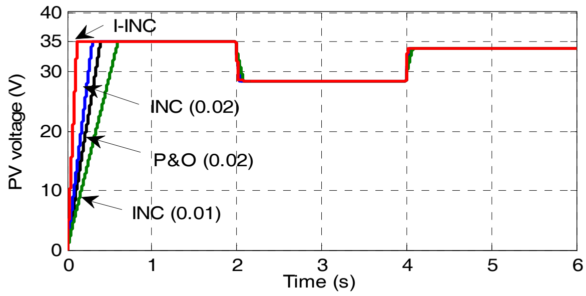


Fig. 10 – PV voltage with improved (I–INC) and conventional method.

Figure 9 exhibit clearly to us the effectiveness tracking of the improved method in comparison to the conventional methods (INC and PO) either on steady state or transient state. Figure 9d (zoom 4) confirms that the oscillation around MPP has been reduced significantly close to zero of the proposed algorithm contrariwise of conventional INC and PO methods although, the step size selected was small. Moreover, the performance of tracking maximum power of improved method is better when irradiation changing occurs. Figure 10 depicts the evolution of the PV voltage.

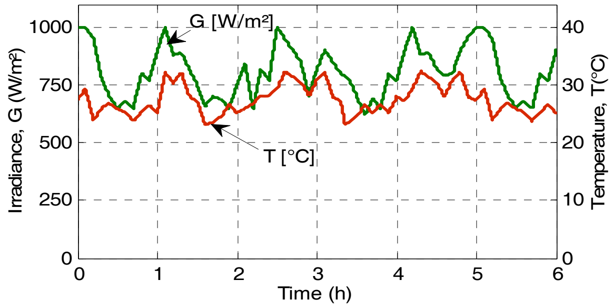


Fig. 11 – Variable profile of irradiance and temperature.

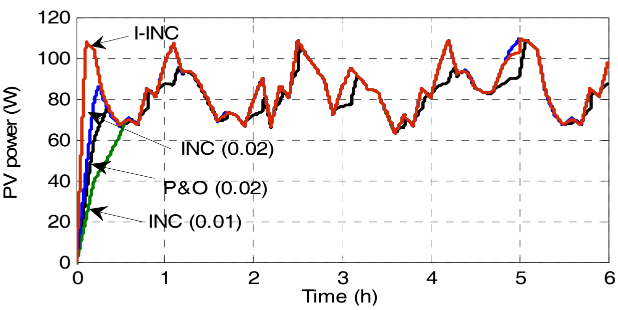


Fig. 12 – PV power for variable climatic conditions with improved and conventional methods.

The solar irradiance and temperature varies continuously over time in reality. Thus, it's important to compare different methods under variable atmospheric conditions, so a variable irradiance and temperature profile is generated to simulate practice data, as shown in Fig. 11. The results demonstrate the effectiveness of the proposed method in comparison, mainly with conventional P & O method that has an important disadvantage, which is the wrong direction when rapid changing carried out. The improved INC shows more stability to settle down at MPP without oscillations Fig. 12. Figures 13 and 14 illustrate the tracking performance of the proposed method when weather condition changes (temperature *T* or irradiation *G*), the proposed method has the ability to keep track the MPP accurately.

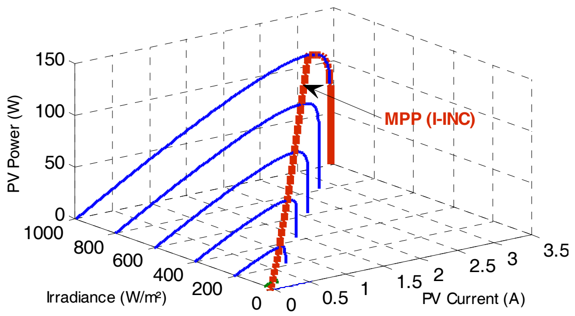


Fig. 13 – *P*pv–*I*pv curves for different insolation and constant temperature (25 °C) with improved (I–INC) MPP method.

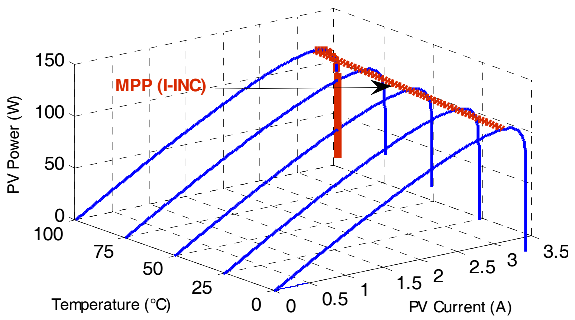


Fig. 14 – *P*pv–*I*pv curves for different temperature and constant insolation (1000 W/m²) with improved (I–INC) MPP method.

5. CONCLUSION

The slowly transit time response and continuous oscillation around the MPP even when the solar irradiation is constant of the conventional MPPT methods (P & O, INC), are strongly mentioned us to overcome these problems.

This study proposed new algorithm combined INC with FLC, which optimize the step size to reach the quick response and stability of the steady state simultaneously. The proposed approach shows better performance, near 0 % error at MPP of energy production in comparison with conventional methods used in the industry (P & O and INC), simulated under different sharp variable conditions operators. This method can be easily implemented in practice, due to the existence of FLC. This study shows the importance of the perturbation rate. When the fixed step of perturbation is too small, the stability and dynamic performance will be harder to achieve.

Nevertheless the proposed method shows more stability under different perturbation rate. It concluded that the I-INC guaranteed to exhibit its effectiveness to eliminate the trade-off between accuracy in the steady state and dynamic response at all these variable conditions. Experimental setup based on digital microcontrollers will be performed for verifying the proposed method in future works.

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