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Article

Photovoltaic system with quantitative comparative between an improved MPPT and existing INC and P&O methods under fast varying of solar irradiation

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Research paper

Photovoltaic system with quantitative comparative between an improved MPPT and existing INC and P&O methods under fast varying of solar irradiation

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ABSTRACT

This work aims firstly to extract parameters lacked in the manufacturers' datasheet by using a simple tool provided by PSIM and then model the PV panel. This model is validated using experimental data. In addition, this work presents the effect of solar irradiation and temperature on the performance of the PV panel. Next, this work will demonstrate that existing algorithms such as perturb and observe and incremental conductance respond inaccurately when solar irradiation is increased. For that a modified incremental conductance algorithm is presented, the latter can respond accurately when solar irradiation is increased and reduce the steady-state oscillations. Finally, 'software-in-the-loop' simulation for the conventional and the modified algorithms is made. Thus a quantitative analysis on the amount of energy loss for rapid change of environmental conditions in the modified method with existing INC and P&O methods is done. The results show that the modified algorithm makes an accurate response once the solar irradiation is increased with fast response and high efficiency. Hence, the loss of energy is minimized.

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1. Introduction

The PV panel output power depends on solar irradiation and temperature (Patel and Agarwal, 2008; El Hammoumi et al., 2018). Thus, the load imposes its own characteristic on the power supplied by the PV panel (Motahhir et al., 2015). Therefore, to predict and analyze the impact of these parameters on PV power, firstly a PV panel model must be studied in accordance with the behavior of the PV panel (Wu et al., 2017b, 2016, 2017a). Therefore, various models were suggested in the literature, in Rauschenbach (1980) a single diode model is used, in Barth et al. (2016) a two diodes model is proposed to describe the impact of the recombination of carriers, and in Nishioka et al. (2007) a model of three diodes is used to present the effects which are neglected by the two diodes model. However, the single-diode model is the most widely used photovoltaic model in view of its good simplicity and accuracy (Yildiran and Tacer, 2016). Moreover, manufacturers offer only some characteristics of PV panel. Thus, others characteristics required to model PV panel are lacked in the manufacturers' datasheet, as the light-generated current, the diode saturation current, the diode ideality factor and the series and shunt resistors (Ishaque et al., 2012). Hence, different methods have been proposed by researchers in Yildiran and Tacer (2016), Ishaque et al. (2012), Ishaque and Salam

(2011) and AlHajri et al. (2012) to extract the lacked characteristics based on the datasheet values, but these methods require an implementation and this can increase the time taken in the development of a PV system. Therefore, this work aims firstly to extract parameters lacked in the manufacturers' datasheet by using a simple tool provided by PSIM (PSIM Tutorial, 2014) and then model the PV panel. For simplicity, the single diode model is used in this work. The latter gives a high compromise between accuracy and simplicity (Carrero et al., 2007) and several researchers have used it in their works (Radjai et al., 2014; Ahmed and Salam, 2016). In addition, this work presents the effect of solar irradiation and temperature on the performance of the PV panel.

On the other hand, the maximization of the PV power always remains a major challenge in the literature. Researchers have proposed different MPPT algorithms to maximize PV power, namely Fractional Short-Circuit Current (FSCC), Fractional Open-Circuit Voltage (FOCV), Fuzzy Logic, Neural Network, Perturb and Observe (P&O), and Incremental Conductance (INC) (Amir et al., 2016; El-Khozondar et al., 2016). FSCC and FOCV are the simplest MPPT techniques, which are based on the linearity of short-circuit current or open-circuit voltage to the maximum power point current or voltage. However, these techniques isolate the PV panel to measure the short-circuit current or open-circuit voltage. Therefore, the loss of power is increased due to the periodic isolation of the PV panel (Verma et al., 2016). On the other side, Fuzzy Logic and Artificial Neural Network are knowledge-based controllers

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Nomenclature

a	: Diode's ideality factor
I	: Panel output current [A]
I_s	: Diode saturation current [A]
I_{ph}	: Panel photocurrent [A]
G	: Solar irradiation [W/m^2]
K	: Boltzmann constant [$J K^{-1}$]
K_v	: Temperature coefficient of open circuit voltage [$V/^\circ C$]
K_i	: Temperature coefficient of short circuit current [$A/^\circ C$]
N_s	: Number of cells connected in series
P_{max}	: Maximum power of the panel [W]
q	: Electron charge [C]
R_s	: Series resistance [Ω]
R_{sh}	: Shunt resistance [Ω]
T	: Junction temperature [K]
V	: Panel output voltage [V]
Offset	: Step size

Greek Letters

α	: Duty cycle
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Abbreviations

P & O	: Perturb and observe
INC	: Incremental Conductance
MPP	: Maximum Power Point
MPPT	: Maximum Power Point Tracking
PV	: Photovoltaic
STC	: Standard Test Conditions

where they require a detailed knowledge while implementing them. Fuzzy Logic and ANN are effective in tracking MPP and they obtain a consistent MPPT algorithm due to their ability to treat the nonlinearity of the PV Panel. But they require large memory for rules implementation or training respectively. In particular, the fuzzy logic method requires the designer to have some prior knowledge of how the output responds qualitatively to the inputs, and it suffers from a severe drawback that the rules cannot be changed, once it is defined. ANN presents many disadvantages like the fact that the data needed for the training process has to be specifically acquired for every PV panel and location, also the PV characteristics change with time, so the neural network has to be periodically trained. Hence, since the amount of training involved is quite high for this algorithm, this makes its implementation even more complex (Ram et al., 2017). P&O and INC are mostly used due to their medium complexity. These methods use the (P - V) characteristic of the PV panel. For P&O, steady-state oscillations occur after the MPP is reached due to the perturbation made by this technique to maintain the MPP, which in turn this increases the loss of power (Motahhir et al., 2016). For INC, it is founded in point of fact that slope of the power curve is zero at the MPP, and theoretically, there is no perturbation after the MPP is reached (Sekhar and Mishra, 2014; Jatly and Arora, 2017; Motahhir et al., 2017). Therefore, steady-state oscillations are minimized. However, during implementation, the zero value is rarely found on the slope of the P - V characteristic because real values cannot be precisely represented using binary floating-point numbers (Motahhir et al., 2018). Moreover, P&O and INC methods can make an inaccurate response, when solar irradiation is suddenly increased (Motahhir et al., 2018; Tey and Mekhilef, 2014). Therefore, this work aims

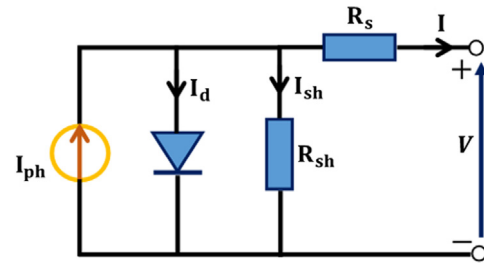


Fig. 1. Single diode model of PV panel.

also to present and implement a modified INC algorithm, which can overcome the wrong response made by the conventional algorithms (P&O and INC) when the irradiance is suddenly increased. The modified algorithm uses the variations in voltage (ΔV) and current (ΔI) of the PV panel to identify the increase in solar irradiation instead of the slope ($\Delta P/\Delta V$) of the P - V characteristic, and then it can make a correct response in duty cycle. Besides, a mini error is accepted to assert that the slope is near to zero and minimize the steady state oscillations.

This paper is organized as follows. Following the introduction, section two presents the modeling of PV panel and investigates the effect of solar irradiation and temperature. Section three illustrates conventional and modified algorithms. 'software-in-the-loop' simulation and quantitative analysis on the amount of energy loss for rapid change of environmental conditions in the modified method with existing INC and P&O methods are elaborated.

2. Modeling of photovoltaic panel and array

2.1. Model of photovoltaic panel

Solar cells are semiconductor with a P-N junction made of a thin plate or a semiconductor layer. When exposed to light a photocurrent proportional to the solar irradiation is generated, if the photon energy is greater than the bandgap. I - V output characteristic of a solar cell has an exponential characteristic similar to that of a diode (Villalva et al., 2009). Not that a PV panel is a set of PV cells, the electric model of literature Kaiser and Reise (Liu and Dougal, 2002) is used in this work, which consists of a source photon current, connected with bypass diode and two resistors bound in series and in parallel. Fig. 1 shows the electrical model of the PV panel, and its characteristic is presented in Eqs. (1)–(3).

$$I = I_{ph} - I_s \left(\exp \frac{q(V + R_s I)}{aKT N_s} - 1 \right) - \frac{(V + IR_s)}{R_{sh}} \quad (1)$$

where:

$$I_{ph} = (I_{sc} + K_i(T - 298.15)) \frac{G}{1000} \quad (2)$$

$$I_s = \frac{I_{sc} + K_i(T - 298.15)}{\exp \left(\frac{q(V_{oc} + K_v(T - 298.15))}{aKT N_s} \right) - 1} \quad (3)$$

2.2. Parameters identification of MSX-60 PV panel

As shown in Fig. 2, some parameters required to model a PV panel are missed in the datasheet. Therefore, these parameters should be determined in advance to simulate a given PV panel. To do that, a utility provided by PSIM is used in this paper due to its simplicity (PSIM Tutorial, 2014); the latter is presented in Fig. 3 and is called 'solar module utility' and it must be used as follows.

This utility extracts initial values of model parameters from the three kinds of user input data groups: One is the datasheet

Typical Electrical Characteristics¹

	MSX-64	MSX-60
Maximum power (P _{max})	64W	60W
Voltage @ P _{max} (V _{mp})	17.5V	17.1V
Current @ P _{max} (I _{mp})	3.66A	3.5A
Guaranteed minimum P _{max}	62W	58W
Short-circuit current (I _{sc})	4.0A	3.8A
Open-circuit voltage (V _{oc})	21.3V	21.1V
Temperature coefficient of open-circuit voltage	... -(80±10)mV/°C ...	
Temperature coefficient of short-circuit current	... (0.065±0.015)%/°C ...	
Temperature coefficient of power	... -(0.5±0.05)%/°C ...	
NOCT ²	... 47±2°C ...	

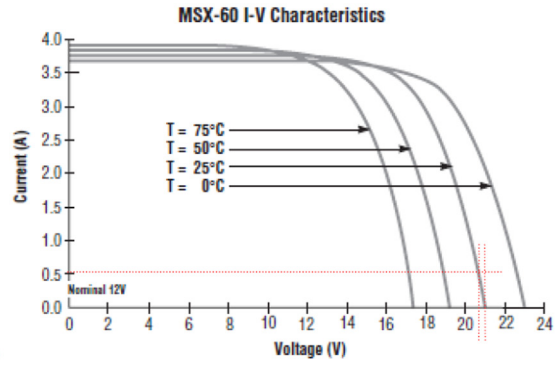


Fig. 2. Datasheet of MSX-60 PV panel at STC.

Fig. 3. Solar module utility.

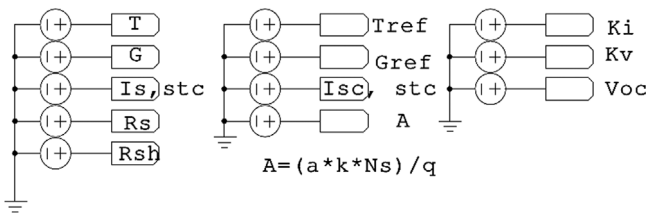


Fig. 4. PV panel parameters.

values such as P_{max} , V_{oc} , I_{sc} , I_{mp} , V_{mp} , K_v , K_i and N_s . The second is the manually calculated data which is the slope evaluated at V_{oc} in the I - V characteristics of datasheet (Fig. 2) by reading the values from the graph (marked in red dotted lines), this data is calculated as shown in Eq. (4) (PSIM Tutorial, 2014). The third is R_{sh} and the ideality factor (a) that usually determined by trial and error or by heuristic methods. They are packed into the user input fields in Fig. 3. Eqs. (5)–(8) are used for the calculation of the parameters $I_{ph,STC}$, $I_{s,STC}$, and R_s from the user-intentioned assumptions in the ideality factor and R_{sh} (Park and Choi, 2017), these parameters are found by clicking in the bottom “Calculate Parameters” and the

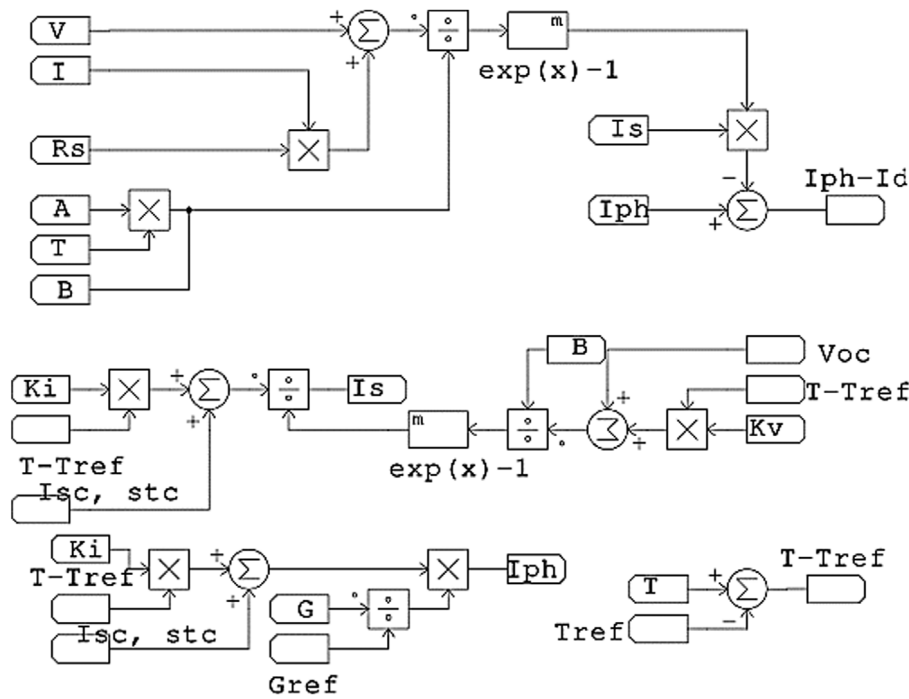


Fig. 5. Eqs. (1)–(3) model.

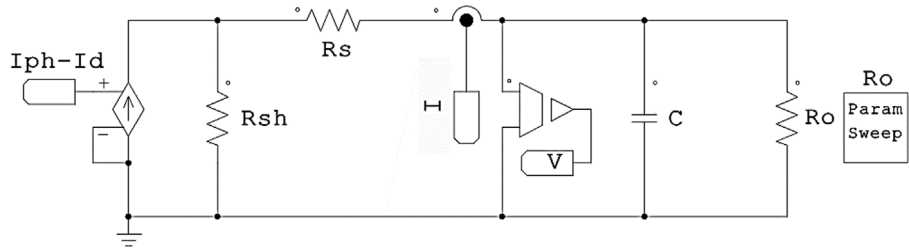


Fig. 6. Circuit based on the electric model of the PV panel.

results are shown in section four of the utility as presented in Fig. 3.

$$\frac{dV}{dI_{Voc}} = \frac{\Delta V}{\Delta I_{Voc}} = \frac{-0.34}{0.5} = -0.68 \tag{4}$$

$$I_{ph,STC} = I_{sc} \tag{5}$$

$$I_{s,STC} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{aKT_N S}\right) - 1} \tag{6}$$

$$R_s = -\frac{dV}{dI_{Voc}} - \frac{1}{X_V} \tag{7}$$

$$X_V = \frac{qI_{s,STC}}{aKT_N S} \exp\left(\frac{qV_{oc}}{aKT_N S}\right) + \frac{1}{R_{sh}} \tag{8}$$

Those equations are derived from Eq. (1) and Fig. 1. At $I = I_{sc}$, $V = 0$, I_{ph} can be approximated by I_{sc} as in Eq. (5) because the current flowing down the diode and the shunt resistance becomes very small. Eq. (6) assumes that the current flows mainly through the diode at $V = V_{oc}$ and $I = 0$. To yield Eq. (7), Eq. (1) has been differentiated and evaluated at $V = V_{oc}$ and $I = 0$ and rearranged in terms of R_s . Therefore, R_s can be estimated from the slope in the I - V curve at V_{oc} . In this method, the approximation of a parameter depends on the already approximate values of the other parameters (Park and Choi, 2017).

2.3. Modeling of PV Panel with tags in PSIM

A PSIM model of PV panel with tags is made, this model uses the parameters extracted in the previous section and it is based on the mathematical Eqs. (1)–(3) and includes the fundamental components of the PV panel (source photon current, connected with bypass diode and two resistors bound in series and in parallel). This model is made by following the steps below.

Step 1

As shown in Fig. 4, this step consists on providing the parameters of the PV panel by tags, and then these tags are used in the model.

Step 2

As shown in Fig. 5, this step consists of modeling Eqs. (1)–(3) by using the tags made in step 1. It should be mentioned that tags make the model easily understandable for readers.

Step 3

In this step, the output of in the previous step which is I_{ph-Id} , it is injected in the circuit shown in Fig. 6, this circuit is based on the PV panel electric model. In addition, a variable resistance is used to simulate the PV panel.

Fig. 7 shows the I - V and P - V characteristics of experimental and our PSIM model data under STC. The experimental (P , V) and (I , V) data are obtained from the datasheet (Solarex MSX60 and MSX64 photovoltaic panel, 1998). Thus as shown, the model accurately is in accordance with the experimental data both in the current and power characteristics.

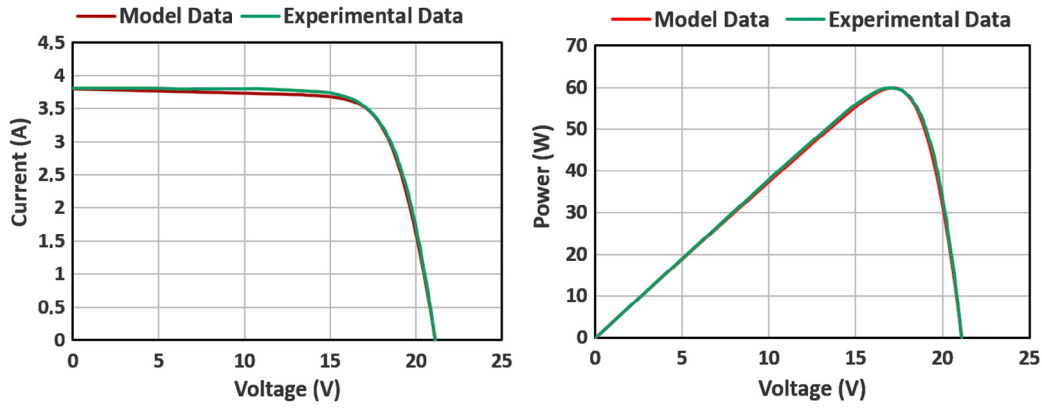


Fig. 7. *I*–*V* and *P*–*V* curves of model data and experimental data.

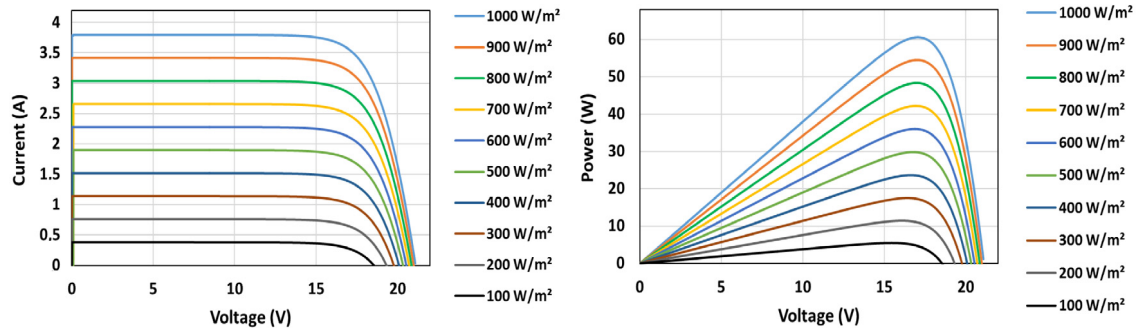


Fig. 8. *I*–*V* and *P*–*V* characteristics for different values of solar irradiation.

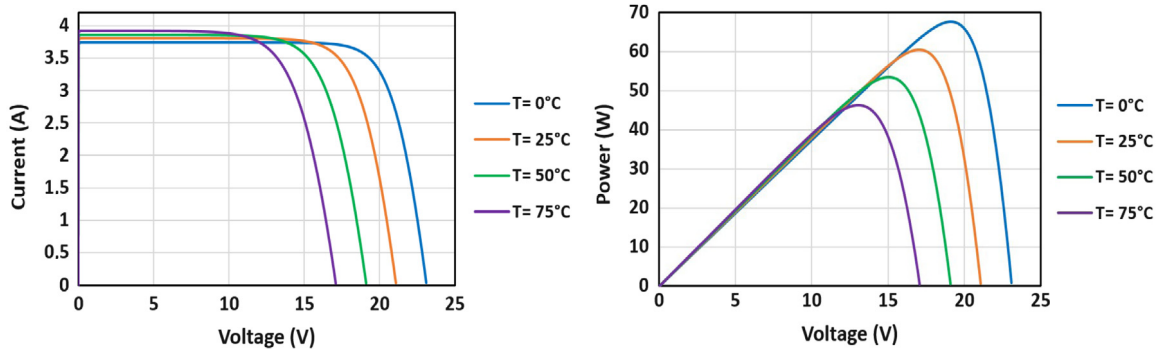


Fig. 9. *I*–*V* and *P*–*V* characteristics for different values of temperature.

2.4. Effect of solar irradiation variation

In order to present the effect of irradiation variation, the PV panel model is simulated for different irradiation values at $T = 25\text{ }^\circ\text{C}$ and the *I*–*V* and *P*–*V* characteristics obtained are shown in Fig. 8.

As shown in Fig. 8, a strong dependence links the PV panel current to the irradiation. Nevertheless, the voltage increases with a little value when the irradiation is increased from 100 W/m^2 to 1000 W/m^2 .

2.5. Effect of the temperature variation

In order to present the effect of temperature variation, the PV panel model is simulated for different values of temperature at $G = 1000\text{ W/m}^2$ and the *I*–*V* and *P*–*V* characteristics obtained are shown in Fig. 9.

As shown in Fig. 9, as the operating temperature increases, the short-circuit current increases slightly, while the open circuit voltage decreases dramatically. Therefore, the change of temperature highly affects the PV voltage. Moreover, based on these results and the manufacturer *P*–*V* curves presented in Fig. 2, the model proves that it is in accordance with the behavior of the PV panel.

3. MPPT under fast varying of solar irradiation

3.1. Problem with conventional INC and P&O algorithms

The working principle of P&O algorithm is presented in Fig. 10, the latter perturbs the duty cycle in order to change the operating voltage, and then the change in the operating power is observed. The next perturbation is made according to the observed value. This process leads the PV system to work near to MPP. However, steady-state oscillations occur after the MPP is reached due to the

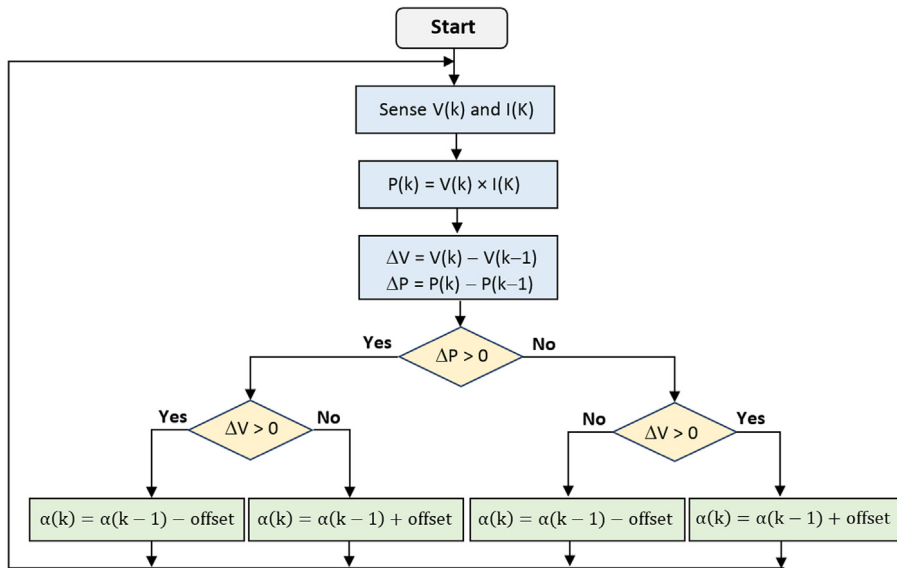


Fig. 10. Flowchart of P&O algorithm.

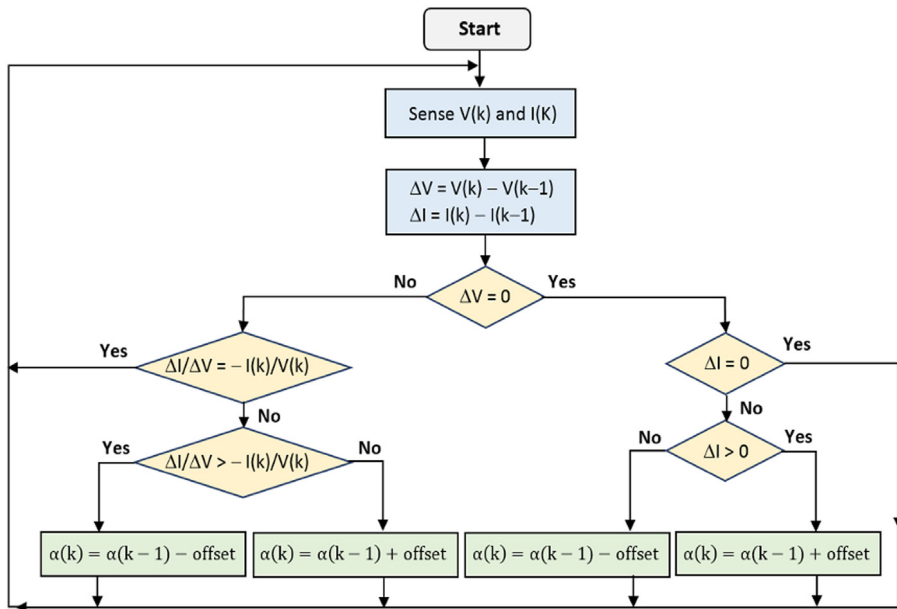


Fig. 11. Flowchart of INC algorithm.

continual perturbation made by this technique to maintain the MPP (Femia et al., 2005).

As shown in Fig. 11, the idea behind INC algorithm is the use of the incremental conductance of the PV panel to determine the slope of the power curve, and theoretically if the slope is equal to zero, the MPP is reached and no more perturbation in duty cycle (Safari and Mekhilef, 2011).

However, the conventional algorithms (P&O and INC) fail to make a good decision when the solar irradiation is suddenly increased (Motahhir et al., 2018; Tey and Mekhilef, 2014). As presented in Fig. 12, when the irradiation is at 500 W/m² and the PV system actuates at load 2, conventional algorithms control the PV system to reach the MPP which is the point B. Once, the solar irradiation is increased to 1000 W/m², Load 2 will force the PV system to operate at point G in I–V curve, which matches to point C in P–V curve. Conventional algorithms compute the slope between point C and point B which is positive. Therefore, the conventional

algorithms will decrease the duty cycle and consequently, the PV panel voltage will be increased. But as the MPP is at point A, the PV panel voltage should be decreased to reach this point when the slope is negative between point A and C, instead of increase voltage and recede from point A as done by the conventional algorithms. In addition, as presented in Fig. 8, the MPP is generally moving to the right as solar irradiation increases and accordingly, the same problem will happen.

Contrariwise, this feebleness does not occur when the solar irradiation decreases since the slope between point A and D is positive, as is the case between point B and D, as shown in Fig. 12. Therefore in this case, conventional algorithms take a correct decision.

3.2. Modified incremental conductance algorithm

It is noted from the previous analysis that when the solar irradiation is increased, both the voltage and the current are increased.

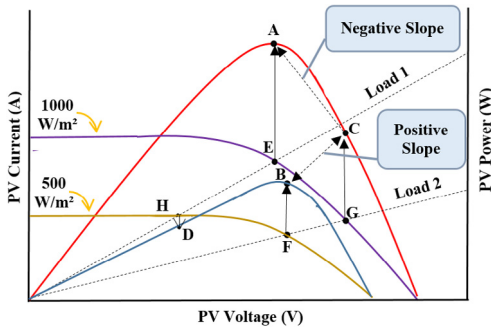


Fig. 12. P–V and I–V characteristics for solar irradiation 500 W/m² and 1000 W/m².

Therefore, the sudden increase of solar irradiation can be detected by checking whether the MPP was reached and the increase in both voltage and current (Motahhir et al., 2018; Tey and Mekhilef, 2014). Subsequently, a permitted error is accepted Eq. (9) to stabilize our system around MPP and detect that the MPP is reached.

$$\left| \frac{dI}{dV} + \frac{I}{V} \right| < 0.08. \quad (9)$$

The modified algorithm is presented in Fig. 13. Note that ‘Var’ is used to memorize that MPP is reached. As shown, the modification is as follows: firstly, initialize ‘Var’ by zero. Then check if the MPP was reached and set ‘Var’ to one when Eq. (9) is met, then execute the algorithm. Next, when Eq. (9) is not met and ‘Var’ is equal to one, that means that an environmental change is happen and the new MPP should be tracked, thus set ‘Var’ to zero. Therefore, the modified algorithm checks if both voltage and current are increased, if yes, that means that a sudden increase of solar irradiance is happen. Hence in this case, the duty cycle is increased instead of decreased as made by conventional algorithms (Motahhir et al., 2018; Tey and Mekhilef, 2014). Consequently, the INC algorithm is

modified to overcome the incorrect decision made by conventional algorithms when the irradiance is increased.

The three algorithms are simulated by using the PV panel modeled in PSIM, note that these algorithms are implemented using C code through the C block provided by PSIM (Motahhir et al., 2015; PSIM User’s Guide, 2016). For instance, Fig. 14 shows the implementation of the modified INC algorithm, as shown the boost converter controlled by C block of the modified algorithm is put between the panel and the load. This kind of simulation is called ‘software-in-the-loop’ test, it is used to test the software of the algorithm (C code in our case) within a modeling environment (PV panel and Boost converter in our case) that can help prove or test the software of the controller (MPPT algorithm in our case). SIL testing and simulation can thus be a useful technique for software proving at earlier stages of the design.

3.3. Results and discussions

The dynamic and steady-state performances of conventional algorithms (P&O and INC) and the modified algorithm are examined through the irradiation changes covering different cases, which includes irradiation changes of 500 to 1000 W/m², 1000 to 800 W/m², 800 to 900 W/m², 900 to 600 W/m² and 600 to 200 W/m². Fig. 15 presents the test result of the conventional P&O algorithm, Fig. 16 presents the test result of the conventional INC algorithm and Fig. 17 presents the test result of the modified algorithm. Therefore, as shown in these figures, the steady-state oscillations are minimized by using the modified algorithm and admit an error equal to 0.08. Contrary to conventional algorithms, which present a high level of oscillations, as a result generate a loss of the PV energy. It is true that theoretically INC algorithm check if the slope of the power curve is equal to zero (at MPP), then there is no perturbation after the MPP is reached. However, during implementation, the zero value is rarely found on the slope of the P–V characteristic because real values cannot be precisely represented using binary floating-point numbers. Therefore, it is required to admit an error as done in the modified algorithm. Moreover as presented in these

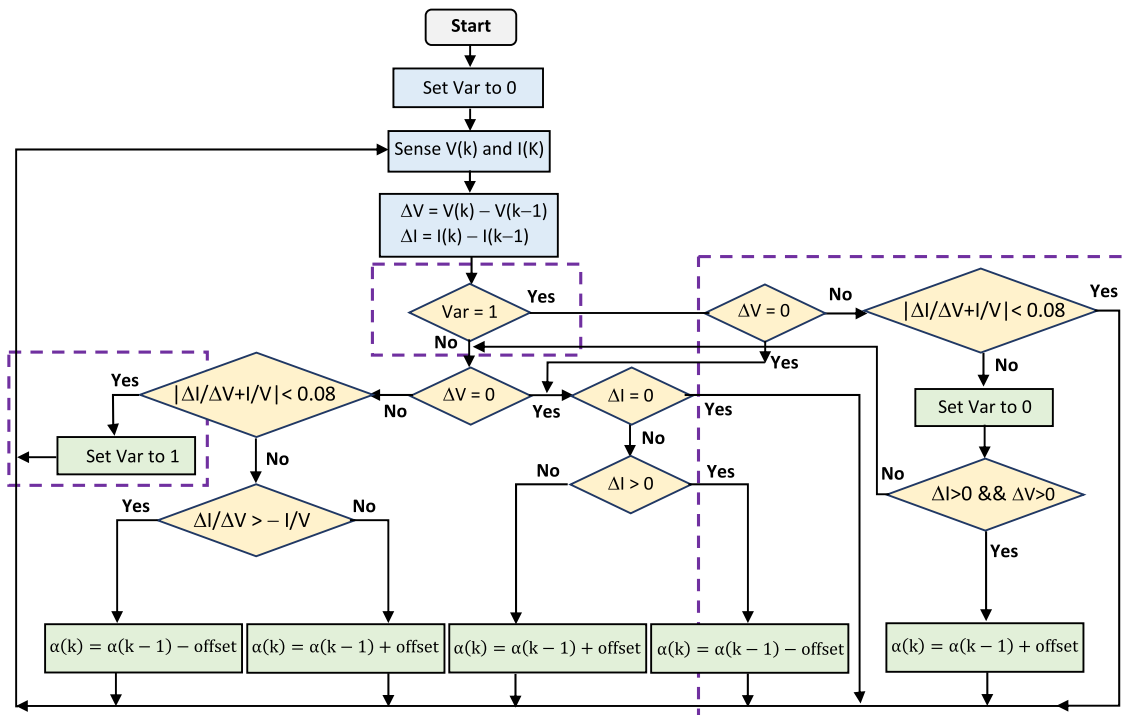


Fig. 13. Flowchart of the modified INC algorithm.

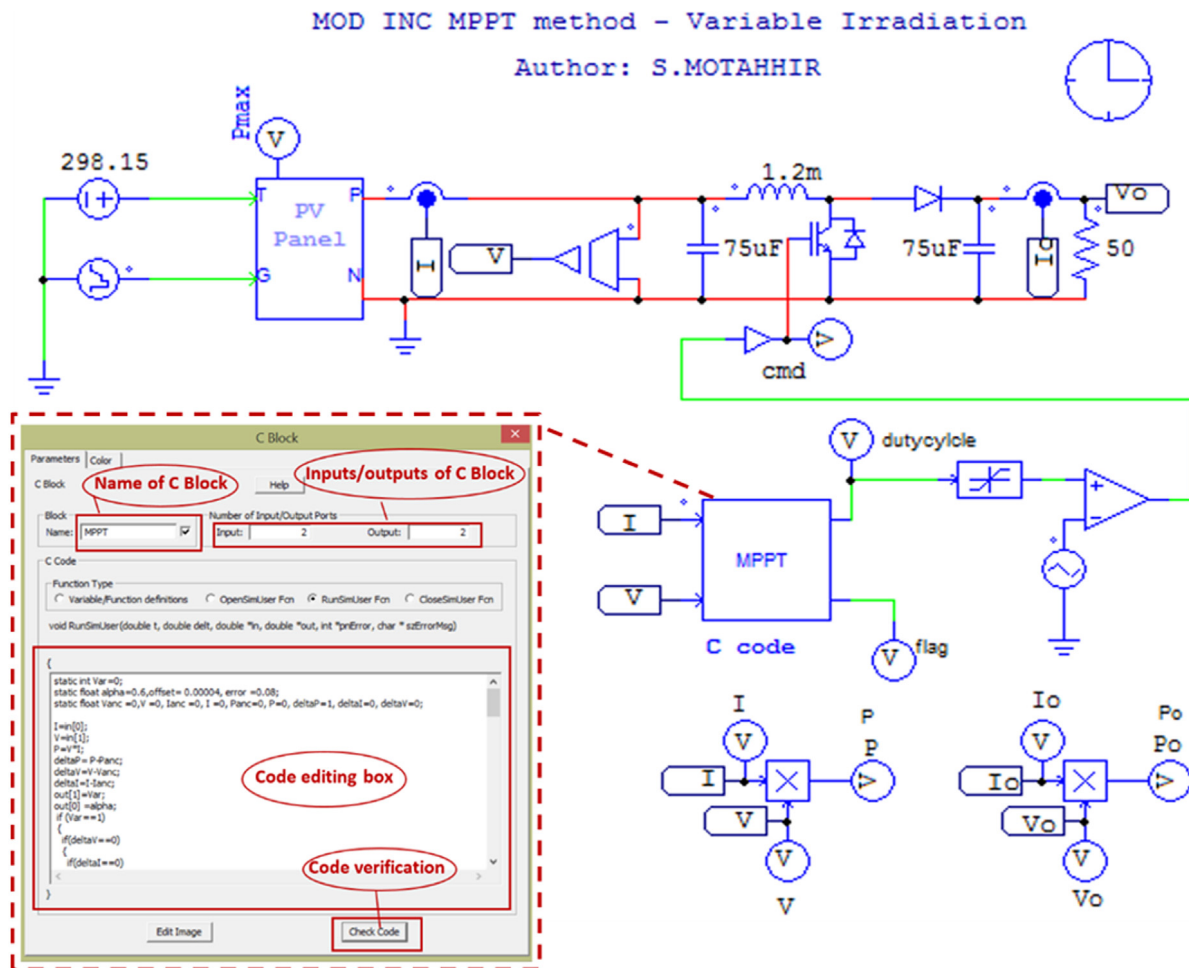


Fig. 14. Software-in-the-loop test for the Mod INC in PSIM.

figures, when solar irradiation is suddenly increased, conventional algorithms lead the power to diverge far from the new MPP. Correspondingly, the system requires a long time to reach the new MPP due to the wrong decision made by conventional algorithms. In addition, steady-state oscillations occur after the MPP is reached. On the other hand, as presented in Fig. 17, the modified algorithm detects the fast increase of irradiation and performs a correct decision in duty cycle. Thus, the power converges to the new MPP from the first step and it is maintained at it. As a result, by using the modified INC, the power is converging faster compared with the response done by conventional algorithms. Table 1 recaps the comparison between the three algorithms in term of oscillations and which is the algorithm that makes the correct decision under sudden increase of irradiation.

Table 2 presents the percentage of power that is left untapped when the modified method is compared with existing INC and P&O methods. As shown for the different irradiation levels, the modified algorithm presents the low percentage of the power loss compared with P&O and INC methods. Moreover, Table 2 shows the duration for which the portion of the power is left untapped so that it results in significant energy loss for the three methods. As shown for the different irradiation levels, the modified algorithm presents the low duration compared with conventional algorithms.

4. Conclusion

In this paper, the PV panel’s parameters are extracted using a utility provided by PSIM tool, thus by using these parameters

a PV panel is modeled also in this tool. The simulation results shows that the obtained data of PV panel model under PSIM is in conformity with experimental data of used panel (MSX-60). Moreover, this paper describes a modified INC algorithm which can detect the confusion faced by conventional algorithms (P&O and INC). As a result, simulation shows that the modified algorithm makes a correct decision when it detects the fast increase of irradiation, contrary to conventional algorithms. In addition by using the admitted error, oscillations are almost neglected and the system converges quickly to the new MPP. Consequently based on the quantitative comparative done in this study, the loss of energy is minimized with an efficiency of 98.84% instead of 97.62% and 97.69% obtained respectively by P&O and INC algorithms.

As a perspective, the modified INC algorithm can be more improved then implemented by a low cost microcontroller as Atmega 328 to propose a low-cost PV system.

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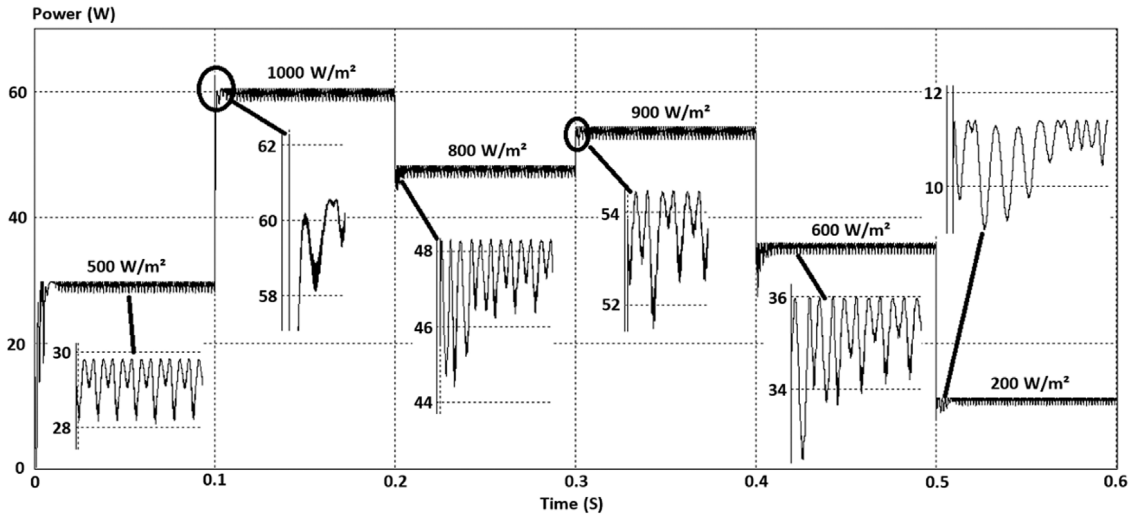


Fig. 15. Simulation result of the P&O algorithm.

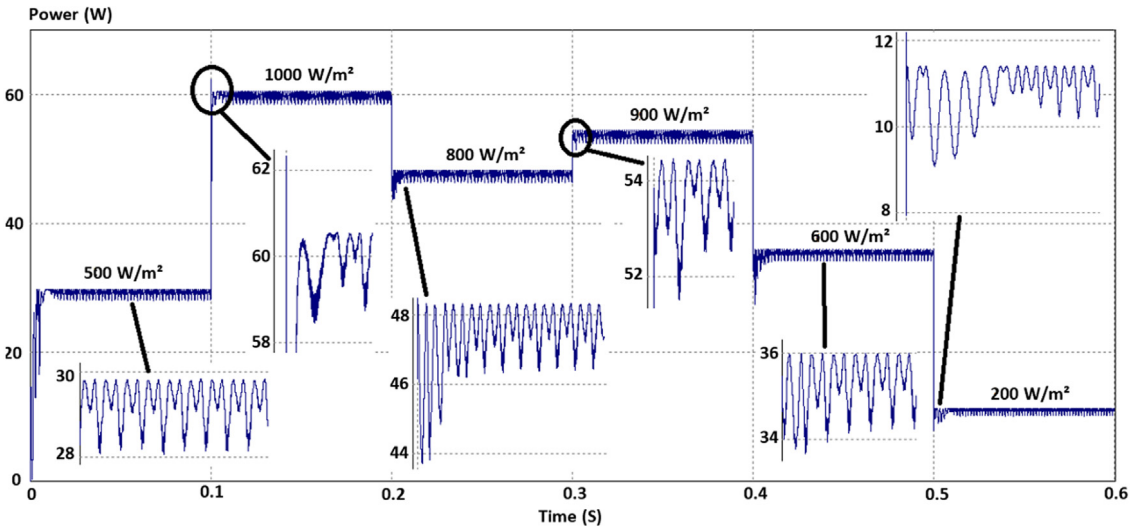


Fig. 16. Simulation result of the INC algorithm.

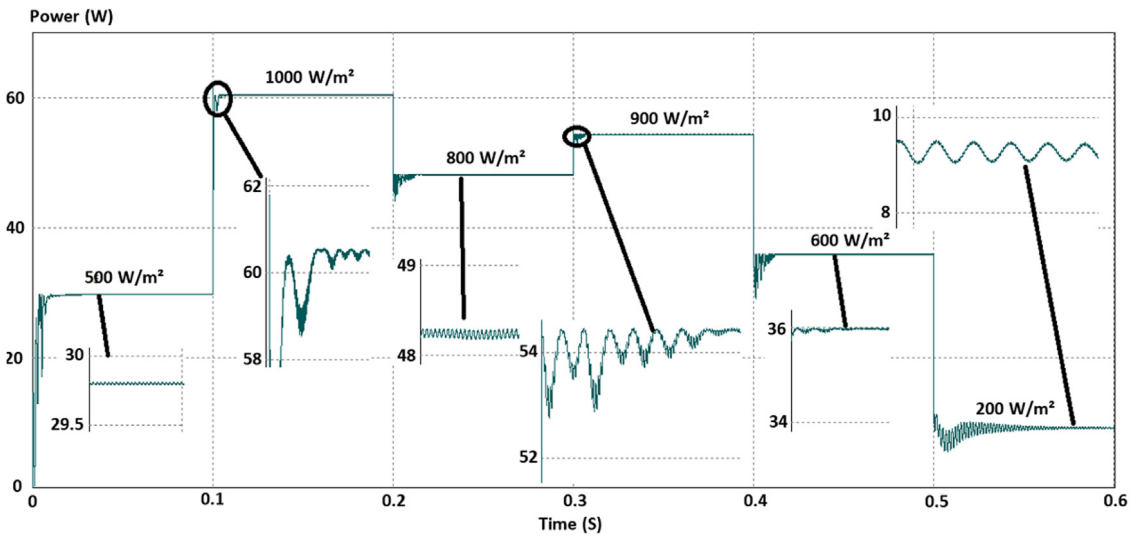


Fig. 17. Simulation result of the modified INC algorithm.

Table 1
Comparison between the modified INC and existing methods (P&O and INC).

Criteria	P&O	INC	Modified INC
Oscillations	High	High	Neglected
Incorrect decision under sudden increase of irradiation	Yes	Yes	No

Table 2
Quantitative comparative table indicating efficiency, power loss and response time for different irradiance levels.

Irradiation (W/m ²)	P&O			INC			Modified INC		
	Efficiency (%)	Power loss (%)	Response time (s)	Efficiency (%)	Power loss (%)	Response time (s)	Efficiency (%)	Power loss (%)	Response time (s)
500	96.05	3.95	0.012	96.05	3.95	0.011	97.53	2.47	0.007
1000	98.6	1.4	0.012	98.64	1.36	0.01	99.67	0.33	0.003
800	98.5	1.5	0.01	98.5	1.5	0.011	99.64	0.36	0.004
900	98.5	1.5	0.015	98.6	1.4	0.013	99.78	0.22	0.002
600	98	2	0.01	98.09	1.91	0.011	99.46	0.54	0.004
200	96.1	3.8	0.1	96.3	3.7	0.009	97	3	0.009

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