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Ehsan Mohsin Alhamdawee Nashiren Farzilah Binti Mailah Mohd Amran Mohd Radzi Suhaidi Bin Shafie Shahrooz Hajighorbani Ahmed Qasim Turki

Comparison of developed FLC and P&O MPPT algorithms for improving PV system performance at variable irradiance conditions

Ehsan Mohsin Alhamdawee
Department of Electrical Power Engineering, Southern Technical University of Basra (STU), Basra, Iraq and Center for Advanced Power and Energy Research (CAPER), Department of Electrical and Electronic Engineering, University Putra Malaysia, Malaysia, and

Nashiren Farzilah Binti Mailah, Mohd Amran Mohd Radzi, Suhaidi Bin Shafie, Shahrooz Hajighorbani and Ahmed Qasim Turki
Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Malaysia

Abstract

Purpose – This work aims to overcome the drawbacks of the nonlinear characteristics of the photo-voltaic (PV) system which are affected by the atmospheric variations.

Design/methodology/approach – As a result, the optimum power point on these characteristics accordingly changes and the efficiency of photovoltaic systems reduces. Maximum power point tracking (MPPT) algorithms track this optimum point and enhance the efficiency despite the irradiance and temperature changes.

Findings – The conventional perturbation and observation (P&O) algorithm uses fixed step sizes to increment and decrement the duty ratio that leads to slow response time and continuous oscillation around the MPP at steady state conditions. The paper proposes a fuzzy logic-based controller that overcomes the drawbacks of P&O algorithm in term of response time and the oscillation.

Originality/value – MATLAB/Simulink environment was used to model and simulate the KC200GT PV module, direct current (DC)-DC boost converter and the MPPT algorithms.

Keywords Boost converter, FLC, MPPT, P&O, Photovoltaic system

Paper type Research paper

1. Introduction

Conventional energy resources, such as fossil fuels, have been the main source of consumed energy since the past century, which has imposed high energy costs, caused air pollution and contributed to global warming. In contrast, green energy resources, such as solar cells, have the advantage of being of no cost to the environment, by virtue of their sustainable and pollution-free operation (Sharma *et al.*, 2012). Photo-voltaic (PV) cells operate efficiently at their maximum power only when there are standard weather conditions. As irradiance or the temperature changes, the curves for nonlinear output current-voltage (I-V) and output power-voltage (P-V) also change. Consequently, the MPP on these nonlinear curves changes accordingly and the efficiency reduces (Liu *et al.*, 2014). One vital technique for extracting the maximum power from a PV system in different environmental conditions is known as the maximum power point tracking (MPPT) algorithm. This method modulates the duty ratio variations periodically to drive a direct current (DC)-DC converter, which is located between the PV source and the load.

The DC-DC converter functions as a matching device to step up or step down the input voltage, or to match the impedance between the PV source and the load side. In this case, the PV source can generate its maximum power efficiently (Taghvaee *et al.*, 2013). MPPT algorithms are categorized as conventional or artificial-intelligence-based algorithms. The classic algorithms such as perturbation and observation (P&O) use a fixed step size to modify the duty ratio, which imposes a slow convergence toward the MPP, and continuous oscillation in steady-state conditions (Femia *et al.*, 2005). Moreover, the fixed step sizes cause a tradeoff between the response time and the continuous oscillation around the MPP, which leads to the reduced total efficiency of the PV system. Large step sizes can improve response times, but oscillation will also be increased, whereas small step sizes can reduce the oscillation but lead to slower response times

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(Gao *et al.*, 2013). Many previous works have proposed a P&O algorithm when there is a variable duty ratio step size. Pandey *et al.* (2006) and Xiao *et al.* (2004) proposed a modified P&O algorithm that provides a small step size to improve the steady-state oscillation and a large step size at the transient stage. However, this technique requires manual tuning for various irradiance levels and PV systems. Recently, the artificial fuzzy logic controller (FLC) was used to optimize the step size of duty ratios adaptively for different irradiance levels so that the drawbacks of the P&O algorithm could be eliminated. In Aashoor *et al.* (2012), Al Nabulsi and Dhaouadi (2012) and Zainuri *et al.* (2012), a hybrid FLC-P&O algorithm was proposed to provide a variable duty ratio step size, which reduced the drawbacks of the P&O algorithm in terms of response time, oscillation and stability. This paper proposes an FLC controller that would also eliminate the disadvantages of the conventional P&O algorithm in terms of response time and continuous oscillation at constant and variable irradiance levels.

2. Mathematical modeling of the PV module

The output power and voltage of each solar cell depends on the irradiance that hits the PV cell. The equivalent mathematical modeling circuit of PV cells is shown in Figure 1. The series resistance (Rs) represents the losses of the solar cell, and it connects the solar cells of the PV module in series. It has a major effect on the efficiency of a PV cell, where a small change in its value creates significant changes in the characteristics of voltage and, hence, of power. In contrast, the shunt resistance (Rsh) has no effect on the efficiency of the PV cell and is consequently considered as an open circuit. The equivalent mathematical formula that represents the characteristics curves of PV cells is shown in equation (1):

$$\mathrm{I} = \mathrm{Iph} - \mathrm{Id}\left(exp\left(\frac{q(\mathrm{v} + \mathrm{Rs} \times 1)}{n \times k \times T}\right) - 1\right) \tag{1}$$

Figure 1 Equivalent circuit of the PV cell

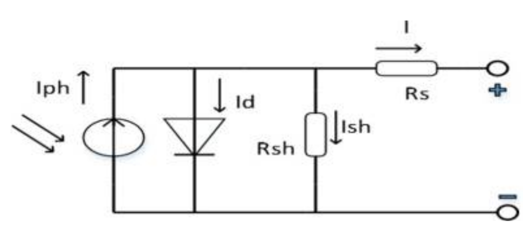

Table I Manufacturer parameters of KC200GT module

Parameters	Values
Maximum power at MPP	200 W
Maximum voltage at MPP (Vmpp)	26.3 V
Maximum current at MPP (Impp)	7.61 A
Open circuit voltage (Voc)	32.9 V
Short circuit current (Isc)	8.2 A
Voc temperature coefficient (Vk)	−0.123 V/K
Isc temperature coefficient (Ik)	0.0032 A/K
Solar cells per module (Ns)	54

This study used a KC200GT PV module as a power source for the PV system whose parameters are shown in Table I below. Based on the manufacturer datasheet, different irradiance levels from 200 to 1,000 W/m^2 and a constant temperature of 250°C are considered appropriate for testing this module (Kyocerasolar, 2016). The simulation of the I-V and P-V curves showed that irradiance has the major effect on the output power of the module. As irradiance increases, the output current and voltage increase. Hence, the output power increases to reach a maximum power of 200 watts at an irradiance level of 1,000 W/m^2 as shown in Figure 2.

3. DC-DC boost converter

A PV module directly connected to a load cannot provide its maximum power efficiently due to the continuous variation of environmental conditions as well as the load fluctuation. As long as the load changes, the load impedance will not match the internal impedance of the PV module. Consequently, the PV module cannot deliver its maximum power (Hajighorbani *et al.*, 2015). One matching converter is located between the source and the load to match the impedance between both sides so that the PV source is able to generate its maximum power (Li *et al.*, 2009). DC-DC boost converters function as step-up choppers of the PV input voltage so that it is always greater on the output side. This matching converter is driven by the MPPT controller, which periodically samples the input data of the PV source and infers appropriate duty ratio to the boost converter. Equation (2) reveals how the boost converter steps up the output voltage to be greater than the input voltage depending on duty ratio variations, where Vi, Vo and D are the input voltage, the output voltage and the duty ratio, respectively. Figure 3 below shows the connection of the boost converter, which stores the energy for the duration of the switching time and then releases it to the load as a bigger value depending on two switching modes of operation. When the switch is on, the input voltage is charging the inductor, and the load is supplied by the capacitor. When the switch is open-circuited, the inductor current is released to the load and the capacitor starts charging:

$$\frac{V_o}{V_i} = \frac{1}{1 - D} \tag{2}$$

4. Maximum power point tracking techniques

4.1 Perturbation and observation algorithm

The conventional P&O technique has commonly been used due to its ease of implementation and flexibility of operation. Figure 4 shows the flowchart of the conventional P&O algorithm, which operates by increasing or decreasing the voltage of the PV source or the duty ratio for one cycle and observing the change in the output power of the next cycle. If both the voltage and the power increase, the next cycle perturbation will be in the same direction. Furthermore, if the voltage decreases while the power increases, the next perturbation cycle will be in the same direction as well. The perturbation cycle will be changed in the reverse direction only if the power decreases. As P&O uses a fixed step size for incrementing or decrementing the voltage or duty ratio, the fast response time and reduced oscillation cannot be achieved simultaneously (Femia *et al.*, 2005). The modified P&O algorithm exploits a variable step size to achieve faster

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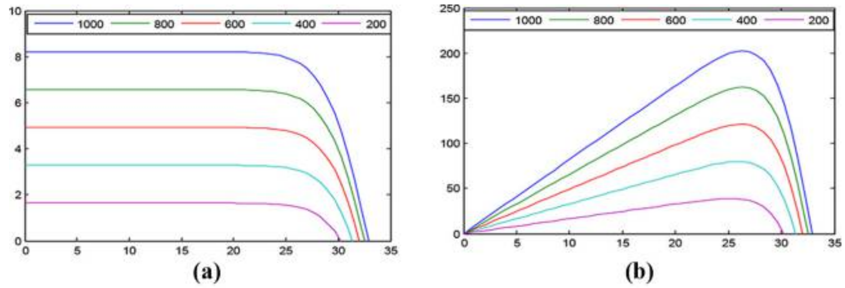
Figure 2 PV module curves at different irradiances



Note: (a) I-V curve and (b) P-V curve

Figure 3 Boost converter configuration

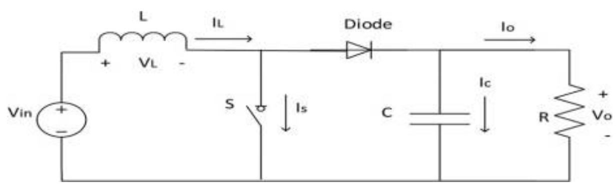
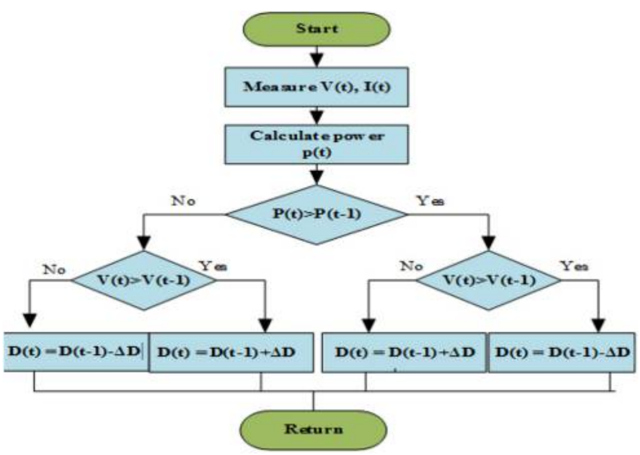


Figure 4 Flowchart of the P&O method



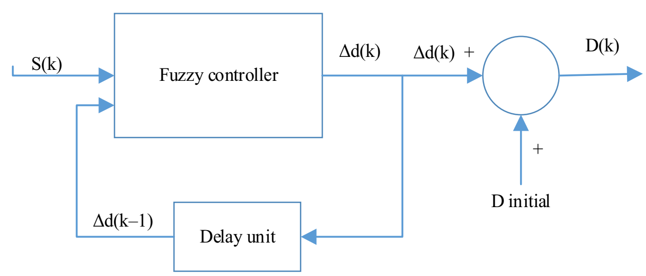
convergence toward the MPP and higher efficiency than a conventional one (Femia *et al.*, 2004). However, the modified type also malfunctions during rapid environmental changes.

4.2 Proposed fuzzy logic controller

FLC is the most widely used MPPT technique because of its faster response time, better accuracy and greater robustness than the conventional and the artificial-intelligence-based techniques, such as the genetic algorithm and the neural network (Salah *et al.*, 2011). The conventional FLC includes the input parameters of the error (E) and the change of error (CE), where E is the change of power divided by the change of voltage or current, and CE is the derivative of E, while the output of the FLC is the change in the duty ratio (Δd) (Hajighorbani *et al.*, 2014).

Figure 5 shows the schematic diagram of the proposed FLC. The first input is the error or the slope tangent of the P-I curve at which the location of the operating point is indicated. The second input is the previous change of duty ratio Δd(k−1) that moves the operating point to reach the MPP, while the output is the new implied change of duty ratio (Δd). After the inputs are calculated and converted to linguistic variables, their universe of discourse is divided into five fuzzy subsets denoted as positive big (PB), positive small (PS), zero (z), negative small (NS) and negative big (NB). This implies that the proposed FLC has 25 rules as depicted in Table II, while Figure 6 below reveals the membership functions for the FLC's input and output, respectively.

Figure 5 Proposed FLC schematic diagram



Equations (3) and (4) demonstrate the calculation process of fuzzy inputs and outputs, where equation (3) calculates the error value S(k) or the location of the operating point on the P-V curve, whereas equation (4) calculates the output change of duty ratio D(k). Large changes of duty ratio are applied when the error value is far away from the MPP on the left or right side of the P-I curve. A small change of duty ratio is needed when the operating point approaches the MPP. Zero change in duty ratio is required only when the error is zero, which indicates that the system is working on the MPP. For example, if S(k) is PB and Δd(k−1) is z, then Δd(k) is PB. This rule implies that if the operating point is located far from the MPP on the left side of the P-I curve and the previous change of duty ratio is zero, the new change of duty ratio is PB to track the MPP faster. As another example, when S(k) is z and Δd(k−1) is PB, then Δd(k) is z. This indicates that the operating point is located on the MPP, and no change of z is needed for tracking the MPP:

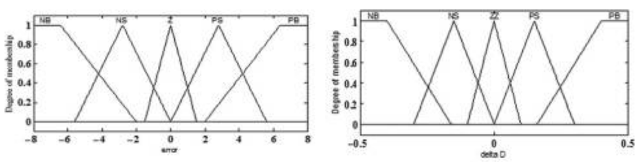
$$S(k) = \frac{p(k) - p(k-1)}{I(k) - I(k-1)} = \frac{\Delta p}{\Delta I} \quad (3)$$

$$D(k) = D_{initial} + \Delta d(k) \quad (4)$$

Table II The proposed FLC rules

			Δd(k−1)		
S(k)	**NB**	**NS**	**Z**	**PS**	**PB**
NB	Z	NS	NB	NB	NB
NS	PS	Z	NS	NS	NS
Z	Z	Z	Z	Z	Z
PS	PS	PS	PS	Z	NS
PB	PB	PB	PB	PS	Z

Figure 6 The membership function of the proposed FLC



Note: (a) input and (b) output

5. Results and discussion

A MATLAB/Simulink environment was used to model and simulate the PV system, as it is shown in Figure 7. A KC200GT PV module was chosen as a power source, which supplied the output power of 200 W at 1,000 W/m^2. The module was mathematically representative according to the manufacturer's datasheet, and it simulated under variable irradiances ranging from 200 to 1,000 W/m^2. The boost converter was the other important part of the PV system for which the input voltage was 26.3 V, and the output voltage was almost 62 V. The parameters of the boost converter included Cin and Cout selected as 470 μF, the inductor was chosen to be 24 0 μH and the load was determined to be 20 Ω.

The last part of the system represented the proposed FLC and the conventional P&O MPPT algorithms that modulate the duty ratio variations for appropriate switching of the metal–oxide–semiconductor field-effect transistor. The proposed FLC and P&O algorithms were designed and developed, and their performance was tested and compared at the same irradiance conditions. The proposed FLC used the triangular and trapezoidal membership functions for the fuzzification process, which included the calculation of inputs, and converted it to linguistic variables. The universe was partitioned into five fuzzy subsets for the inputs and the output. The fuzzy inference system was applied based on the Mamdani method, which is associated with max-min operations. The last part for designing the fuzzy controller was the defuzzification process, which calculated the crisp output based on the center of gravity method.

The system was simulated under two steady-state tests to compare the performance of both MPPT algorithms in terms of response time and continuous oscillation around the MPP. First, both algorithms were tested at a constant irradiance of 1,000 W/m^2. Figure 8 shows the simulation results of the FLC and P&O algorithms, where FLC performed with a faster response time and less oscillation. In terms of response time, both algorithms showed the same rise time toward the MPP, yet a different settling time was noted. FLC required only 0.0068 s to settle at the MPP, while P&O required 0.015 s to achieve stability. The oscillation around the MPP was the second factor that increased the power losses, and therefore the efficiency of the PV system was reduced. FLC performs with less oscillation around the MPP of 0.4 W compared to 5 W for the P&O algorithm.

Another test was conducted under different irradiance levels to verify the improved performance of the FLC over the P&O algorithm. These irradiance variations included the low and high irradiance levels from 200 to 1,000 W/m^2 as shown in Figure 9. Table III below summarizes the response time of the FLC and the P&O algorithm at

Figure 7 The PV system in MATLAB/Simulink

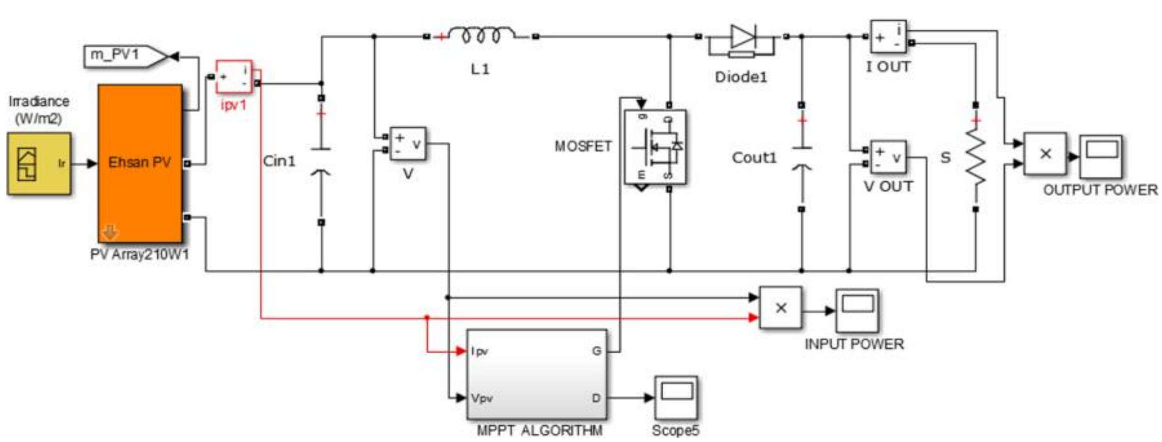


Figure 8 Test at 1,000 W/m^2

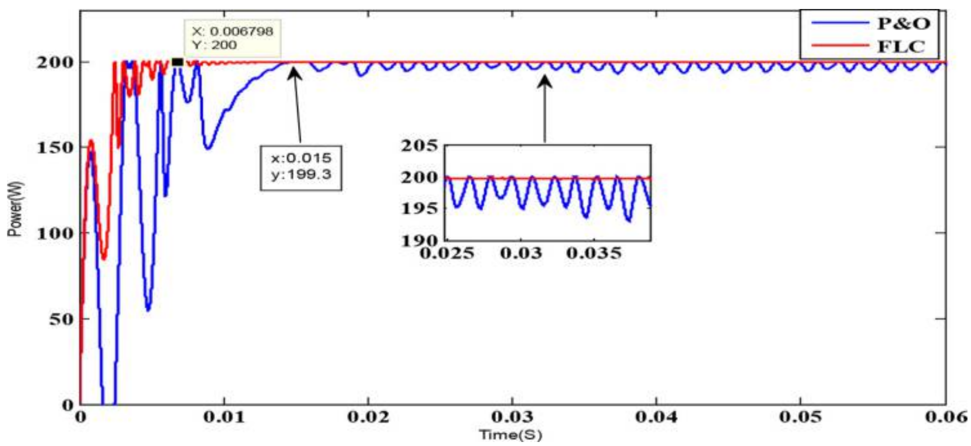


Figure 9 Test at many irradiance levels

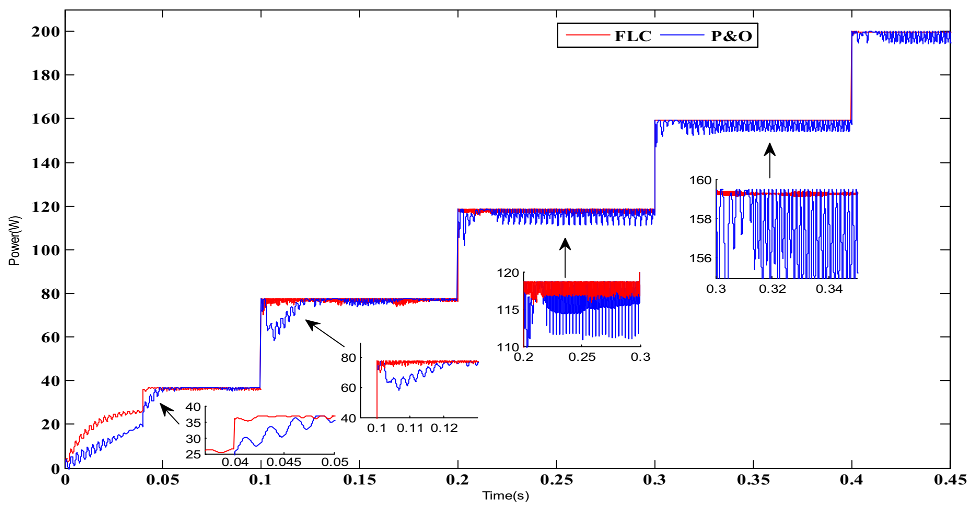


Table III FLC and P&O response times

Irradiance	FLC	P&O
200 W/m^2	0.0428 s	0.049 s
400 W/m^2	0.1 s	0.123 s
600 W/m^2	0.2 s	0.212 s
800 W/m^2	0.3 s	0.311 s
1,000 W/m^2	0.4 s	0.41 s

variable irradiance levels where the FLC performed with a faster time response toward the MPP than P&O at low irradiance levels. Particularly at the irradiance levels of 200 and 400W/m^2, FLC responded to reach the MPP quicker at 0.043 and 0.1 s, respectively, compared with 0.049 and 0.123 s for the P&O algorithm. The disparity of convergence toward MPP between the MPPT algorithms was degrading, as the irradiance increased because both algorithms reached stability in steady-state conditions. However, FLC still responded better in conditions of high irradiances due to its adaptive nature. In terms of oscillation around the MPP, FLC performed at a lower oscillation level than the P&O algorithm in variable irradiance conditions. It can be seen from Figure 9 that FLC had the same oscillation value for all irradiance levels because it modulated the duty ratio adaptively. By contrast, P&O performed with a higher oscillation value at higher irradiance levels from 600 to 1,000 W/m^2 because of its fixed step sizes of tracking the MPP and its continued oscillation around the MPP in steady-state conditions.

6. Conclusion

The nonlinear characteristics of a PV system are affected by irradiance and temperature conditions, which leads to power losses and reduced efficiency. The conventional P&O algorithm performs with slow time responses and continuous oscillation in steady-state conditions, which reduces the total efficiency of the PV system. The proposed FLC has eliminated these drawbacks under different irradiance conditions. The simulation results show that the proposed FLC responded faster to reach MPP, and it performed with low oscillation around the MPP at different irradiance levels. As a result, the efficiency of the PV system was improved.

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Corresponding author

Ehsan Mohsin Alhamdawee can be contacted at: ehsanm360@gmail.com