# EVALUATION OF PV SYSTEM PERFORMANCE WITH FUZZY-PI AND P&O ALGORITHMS AND IN PRESENCE OF SEPIC CONVERTER IN NORMAL AND PARTIAL SHADING CONDITIONS

Ahmad AZADIAN[1]

*The presence of a Maximum power point tracking (MPPT) controller in the photovoltaic system approaches the system to the maximum achievable efficiency. Many algorithms have been proposed for tracking the MPP. Due to these different MPPT algorithms and various categories, a comparison of methods in a particular situation can help to choose the appropriate algorithm in a PV system. In this paper, for MPPT algorithms, perturb and observation and Fuzzy-PI methods are used and the system under study is simulated. The control signal generated by the proposed controllers is applied to a SEPIC converter, and then the results are compared. The systems' performance has been investigated under normal conditions and partial shading. Under normal conditions, different amounts of radiation have been used to evaluate the performance of the algorithms. Rapid response and dynamics of the control system are the items that have been studied. System analysis is done by MATLAB/Simulink. More oscillation of P&O in normal conditions and the inability to track the correct point in partial shading conditions are taken from this study and comparison. This paper is also a seal of approval in the higher convergence rate of fuzzy-PI.*

**Keywords**: PV, MPPT, Fuzzy-PI, SEPIC, Partial shading

## 1. Introduction

Generally, a photovoltaic system contains several main components; Solar cells, control algorithms for MPPT, the existence of a DC-DC converter to effectiveness the controller and increase the voltage level and load. Since the radiation and temperature level have a direct effect on the output, the existence of a control system is necessary to receive the highest power. The curves for the characteristics of a PV cell and the effects of changes in radiation and temperature are shown in Fig. 1, as clearly it can get the most output at a point called the MPP. This point is constantly changing. Because of these nonlinear features, the presence of the MPPT controller is essential for better system performance. This controller keeps the operating point of the system at the peak of the P-V curve (MPP) [1-2].

[1] PhD student, Electrical Engineering Department, Imam Khomeini International University, Qazvin, Iran, e-mail: ahmadazadian@edu.ikiu.ac.ir

Due to the importance of the MPPT control system, many algorithms have been proposed to improve the controller performance, which is known as maximum power tracking algorithms. In addition to introducing new algorithms, methods have been proposed that improve on previous algorithms. Most traditional algorithms have simple circuits and are easy to implement [3]. However, these traditional algorithms cannot find GMPP properly among LMPPs in partial shading conditions, which have also used new intelligent methods and a combination of algorithms to solve this problem [4-5].

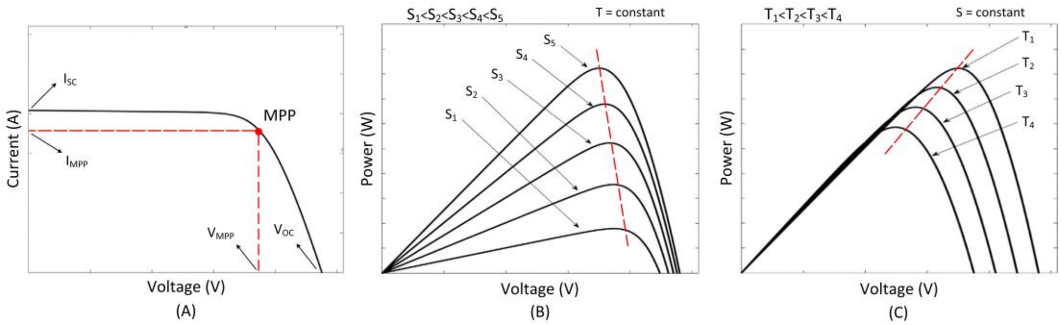


Fig. 1. PV cell characteristics; (A) I-V curve; (B) P-V curve (constant temperature); (C) P-V curve (constant radiation)

In PV systems with the presence of an MPPT control system, the P&O is one of the most widely used and acceptable methods. The advantages of this method include adaptability to modules, no need for information for the configuration of modules, easy implementation, and low costs [10]. Due to the perturbation step size, low accuracy and tracking speed of the P&O are the two main problems of this method. One of the proposed methods for solving this problem is to use a variable perturbation step size, which in turn leads to increased workload and cost [6-9]. The typical operation of a fuzzy system depends on its rules and membership functions; optimization of these cases can lead to improved performance of this algorithm. Optimizing the fuzzy algorithm and combining it with other methods are the trends that lead to improving the performance of the control system's performance; furthermore, in variable climate conditions, hybrid algorithms have provided excellent results [11-14].

The output control signals from the MPPT system in combination with the modulation unit are used in the DC-DC converter as a regulator. This control signal is input to the control pin of the switches used in the converter [15-17]. However, with the advancement of power electronics and the introduction of new high-gain converters, these converters have also been used in photovoltaic systems to increase output power [18].

This paper presents a controlled PV system by using two tracking algorithms P&O and Fuzzy-PI for the MPPT control system. Moreover, in the applying part of the control signal, i.e. the DC-DC converter, a comparison is made between the SEPIC converters despite two stated algorithms. This system is to be studied in normal and partial shading conditions. This paper will examine a traditional algorithm (P&O) and a smart algorithm (Fuzzy) in the presence of SEPIC converter. Since the P&O and Fuzzy are the common algorithms used by researchers, the evaluation of these two in different conditions and in the presence of SEPIC converter can compare the performance of traditional and combined algorithms. Combining the fuzzy with the PI and creating a hybrid algorithm is for better performance in partial shading conditions. The variable step size is also used for the P&O method. By using fuzzy-PI and P&O algorithms and SEPIC converters, the power level changes of this system in normal and partial shading conditions will be analyzed. Also, the ability to track the MPP accurately is checked. After the introduction, the steps of this article will be as follows; review of previous papers, the presentation of a PV cell model in the third section, maximum power tracking algorithms in the fourth section, introducing of the converters and obtaining its elements in the fifth section, and then simulation and results will be presented.

## 2. PV cell

Fig. 2 shows a model of a PV cell with a single diode. If the cell is considered ideal, the elements of the circuit will be the source and the diode. For practical modeling, resistors will be added to the ideal model. In addition to this model, a double diode model is also provided for solar cells. The two-diode model is also used to increase the accuracy of the circuit model when the solar irradiance levels are low. The diode is added to the circuit due to modeling the recombination losses [19].

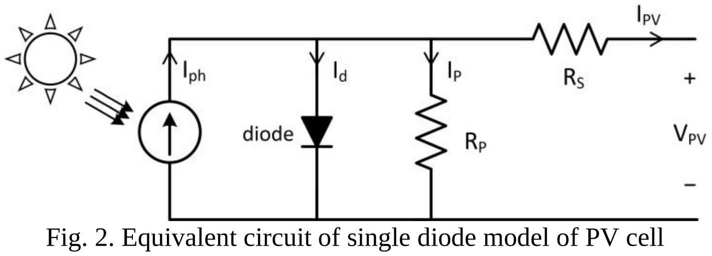


Fig. 2. Equivalent circuit of single diode model of PV cell

According to the circuit model, the output of PV cells can also be modeled by an Equation. The output of the cell is indicated by the photovoltaics' voltage ($V_{PV}$) and current ($I_{PV}$). The parameters and their equations are presented in Table 1.

*Table 1*

**PV cell's parameters and equations**

| Equation | Parameters | Description |
|---|---|---|
| $I_{PV} = I_{ph} - I_d - I_P$ | $I_{PV}$ | PV output current |
| | $I_{ph}$ | Photon current |
| | $I_d$ | Diode current |
| | $I_P$ | Shunt resistor current |
| $I_d = I_o\left[e^{\frac{V_{PV}+I_{PV}R_S}{\alpha}} - 1\right]$ | $I_O$ | Saturation current of diode |
| | $V_{PV}$ | PV output voltage |
| | $R_S$ | Series resistance |
| | $\alpha$ | Modified factor |
| $\alpha = \frac{N_S AKT}{q}$ | $N_S$ | Number of cells in series connection |
| | $A$ | Ideality factor |
| | $K$ | Constant of Boltzmann |
| | $T$ | Cell temperature |
| | $q$ | Electron charge |
| $I_P = \frac{V_{PV} + I_{PV}R_S}{R_P}$ | $R_P$ | Shunt resistance |
| $I_{PV} = I_L - I_o\left[e^{\frac{(V_{PV}+I_{PV}R_S)q}{N_S AKT}} - 1\right] - \frac{V_{PV} + I_{PV}R_S}{R_P}$ | | |

Another issue that is very important about solar cells is the partial shading condition. This phenomenon occurs when there is a barrier between the sunlight and the surface of solar cells. This reduces the power output of the cells. In this case, due to the decreasing amount of radiation, the output current also decreases. Oscillation in this condition leads to the creation of several peaks in the characteristic curve of the cells. Among these points, one point is the global maximum power point (GMPP), and the others are the local maximum power point (LMPP) [20-22]. The purpose of the MPPT control system in partial shading conditions is to find the GMPP between the LMPPs. Also, due to the dependence of voltage on temperature, voltage is also affected by creating shadows and decreasing temperature. The current and power of cells are also directly related to irradiance. Because these parameters change frequently, the MPP also varies, and the control system has a complex task to track [23-24].

## 3. MPPT algorithms

According to the definition and characteristics curve of the solar cell, if the slope of the tangent line on the P-V curve reaches zero or the power derivative of voltage ratio reaches zero, the MPP has been traced. Before the MPP this value is greater than zero and after the MPP this value is less than zero. Since this point depends on environmental conditions (irradiance, temperature, etc.), it is not possible to imagine a precise and permanent place for it. In partial shading conditions, considering the number of peaks at this point, tracking the exact MPP adds to the complexity of the system. If the MPPT control system is applied, the operating point of the system will be continuously at MPP. The generated control signal is transmitted to the DC-DC converter switches by the modulation unit and completes the control system. The control system aims are to track the MPP in the shortest time, reduce steady-state oscillations, stability, robustness, and reduce system losses. In this section, the P&O and Fuzzy-PI will be examined in detail and employed.

### 3.1. P&O

Perturbation and observation is one of the simplest and widespread methods that researchers have used extensively in their papers, and it is also easy to implement [10-12]. This algorithm is based on measurements. By measuring the voltage and perturbed a little value to it, the MPP is found by trial and error. In general, the P&O compares the powers of the operating point and the predetermined value, to get closer to the desired point by changing the amount of voltage. First, the voltage value is measured. Then it becomes somewhat perturbed to change the amount of power. According to the figure, examining the sign of the difference between two powers can indicate an increase or decrease in the amount of voltage perturbation. The constant used to increase or decrease the reference voltage used in the P&O algorithm is assumed to be 0.0003. Since this perturbation is occurring constantly, oscillation around the MPP in a steady-state is an important problem of this algorithm. Changing the amount of perturbation can solve this problem to some extent. This topic is known as modified P&O [13-16]. In this method, if the operating point passes the MPP, the amount of perturbing is reduced. Step size optimization of traditional P&O can also lead to accurate tracking of GMMP in partial shading conditions [25].

### 3.2. Fuzzy-PI

In nonlinear control systems, the PI controller is less compatible, which can be optimized by an intelligent method. On the other hand, the fuzzy controller suffers from steady-state oscillation because it does not have an integral element. The presence of a traditional PI controller can be used to increase accuracy and reduce errors in this hybrid control system. In general, it can be noted that the fuzzy is used to regulate the fast and accuracy when the difference is big, while PI regulates when the difference is small. The block diagram of the fuzzy-PI algorithm is as follows; In the first level of control, there is a PI controller that performs its usual operation of stability and eliminates the steady-state error. At the second level is a fuzzy controller that monitors the first controller and makes possible corrections.

The output power derivative relative to the voltage ($dP/dV$) as the first input and the second power derivative to the voltage ($\Delta dP/dV$) as the second input are applied to the fuzzy controller. The derivations *dP/dV* and *ΔdP/dV* are denoted as e and de. Fuzzy block inputs are *E* and *ΔE* and its outputs are FL($K_P$) and FL($K_I$). Fuzzy rules are also classified into negative big (*NB*), negative medium (*NM*), negative small (*NS*), zero (*Z*), positive small (*PS*), positive medium (*PM*), positive big (*PB*), small (*S*), and big (*B*). First, the numerical values of the E and ΔE are calculated and converted into intelligible variables for the membership functions. Then, using the relations of the Ziegler-Nichols method, the control coefficients of PI are determined. This controller sets the error to zero by using the error value and tuning the coefficients by the fuzzy block.

The Ziegler – Nichols method is an experimental method for obtaining PI parameters. The Z-N method was used for the calculations related to the PI controller. The Z-N equations are used to determine the initial values of the coefficients. The Z-N coefficient determination methods are divided into two categories: determination by the open-loop system and by the closed-loop system. In this paper, the closed-loop system method is used to obtain PI coefficients. In the first step, the derivative and integral blocks must be separated from the circuit. In the second stage, a step input is applied and starts with small values of $K_c$ until the output oscillates. Then the oscillator gain ($K_{cu}$) is obtained. Afterward, using the table of N-Z method, the optimal coefficients of PI are obtained. The initial values of $K_{cr}$ and $T_{cr}$ are considered to be 0.02 and 0.004 respectively. The equations used for the fuzzy-PI controller are presented in Table 2.

*Table 2*

**Fuzzy-PI algorithm equations**

| Equation | Parameter | Description |
|---|---|---|
| $E(n) = \frac{P_i - P_{i-1}}{V_i - V_{i-1}}$ | $E$ | Error |
| | $P_i$ | ($i$)th power |
| | $P_{i-1}$ | ($i$-$1$)th power |
| | $V_i$ | ($i$)th voltage |
| | $V_{i-1}$ | ($i$-$1$)th voltage |
| $\Delta E = E_i - E_{i-1}$ | $\Delta E$ | Change of error |
| | $E_i$ | ($i$)th error |
| | $E_{i-1}$ | ($i$-$1$)th error |
| $G_c(s) = K_P + \frac{K_I}{s}$ | $G_C$ | Transfer function of PI |
| | $K_P$ | Proportional gain |
| | $K_I$ | Integral gain |
| $G(s) = K_P + \frac{K_P}{T_I s}$ | $G(s)$ | Continuous-time equivalent |
| | $T_I = K_P/K_I$ | Integral time constant |
| $K'_P = \frac{K_P - K_{P.min}}{K_{P.max} - K_{P.min}}$ | $K_{p.min} = 0.32K_u$, $K_{p.max} = 0.6K_u$ | Minimum and Maximum range of $K_P$ |
| | $K_u$ | Gain of oscillation |
| | $K'_P$ | Normalize of $K_P$ between 0 to 1 |
| $K_P = (K_{P.max} - K_{P.min})K'_P + K_{P.min}$ | | |

## 4. DC-DC Converter

A switching capability converter is required in a photovoltaic system. Increasing and adjusting the system output voltage and applying the control system to the system are the tasks of these converters. The most common of these are DC-DC converters (choppers). In the PV system, where there is also an MPPT control system, the presence of DC-DC converters is to apply a control signal to the system is necessary. According to the process and operation of the converters, turning the switches on and off is the main reason for the operation of the converters. Therefore, the control and the modulation unit produce this appropriate signal. In this paper, after applying the MPPT control system, the SEPIC converter has been used as a DC-DC converter. The results received in the output are checked and compared.

The SEPIC stands for single-ended primary inductance converter. This converter is one of the step-up converters and increases the input voltage level at the output. This converter consists of one switch, one diode, two inductors, and two capacitors. The circuit of the converter is shown in Fig. 3. Like other dc-dc converters, the SEPIC converts the voltage level using energy storage in the inductor and capacitor. Controls the amount of this energy by a switch. In the steady state, the amount of voltage reached to the capacitor will be equal to the voltage of the input source. When the switch is off, according to the diodes' bias, the diode is activated. The first inductor uses the source energy and delivers the energy to the second inductor and the second capacitor. During these conditions, no energy is supplied to the load. When the switch is turned on, the diode is deactivated. In this case, the first inductor receives energy from the source and the second inductor, and second capacitor deliver their stored energy to the load.

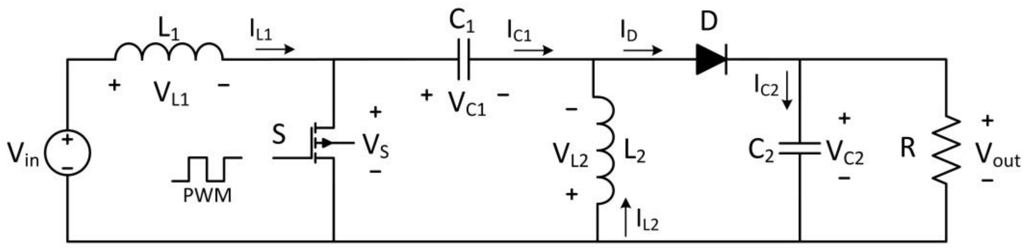


Fig. 3. SEPIC converter circuit and operation modes

## 5. PV system Simulation and Results

In this part, the proposed simulated system is presented, which is shown in Fig. 4. The proposed system is a standalone photovoltaic system that supplies a resistance load. System implementation and analysis of the results have been done in MATLAB/Simulink. Solar cells with electrical parameters in Table 3 were used to simulate the input of the system. To analyze the transient state of the system and the oscillations around MPP, the input of the module (radiation) at different time intervals is considered variable. The numerical values of the applied irradiance in normal conditions are 800, 400, and 1000 ($W/m^2$) respectively. According to the I-V and P-V diagram in Fig. 5, the partial shading condition is applied to the PV array. This array is consisting of four modules with different irradiances. The numerical values of the applied irradiance in partial shading condition are 250, 500, 700, 900 ($W/m^2$) respectively. Due to the presence of four peaks in the curve, tracking the MPP has become more difficult than normal conditions. Also, the MATLAB/Simulink model in the article is presented in Fig. 6.

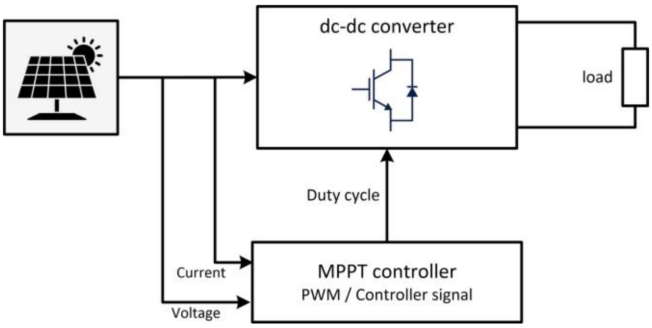


Fig. 4. System under review

*Table 3*

**PV cell parameters used for simulation**

| Parameter | Description | Value |
|---|---|---|
| $P_{MAX}$ | Maximum Power | 130 (W) |
| $V_{OC}$ | Open Circuit Voltage | 36.3 (V) |
| $I_{SC}$ | Short Circuit Current | 4.82 (A) |
| $V_{MPP}$ | Voltage at Maximum Power Point | 29.2 (V) |
| $I_{MPP}$ | Current at Maximum Power Point | 4.45 (A) |
| $N_S$ | Series Connected Modules Per String | 1 |
| $N_P$ | Parallel Strings | 1 |
| $R_S$ | Series Resistance | 1.0362 (Ω) |
| $n_{IscT}$ | Temperature Coefficient of $V_{OC}$ | -0.35 (%/deg.C) |
| $n_{VocT}$ | Temperature Coefficient of $I_{SC}$ | 0.06 (%/deg.C) |

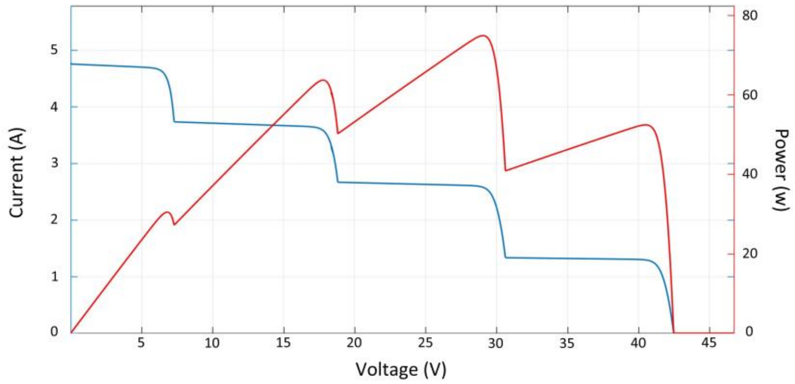


Fig. 5. Partial shading I-V and P-V curves applied for simulation

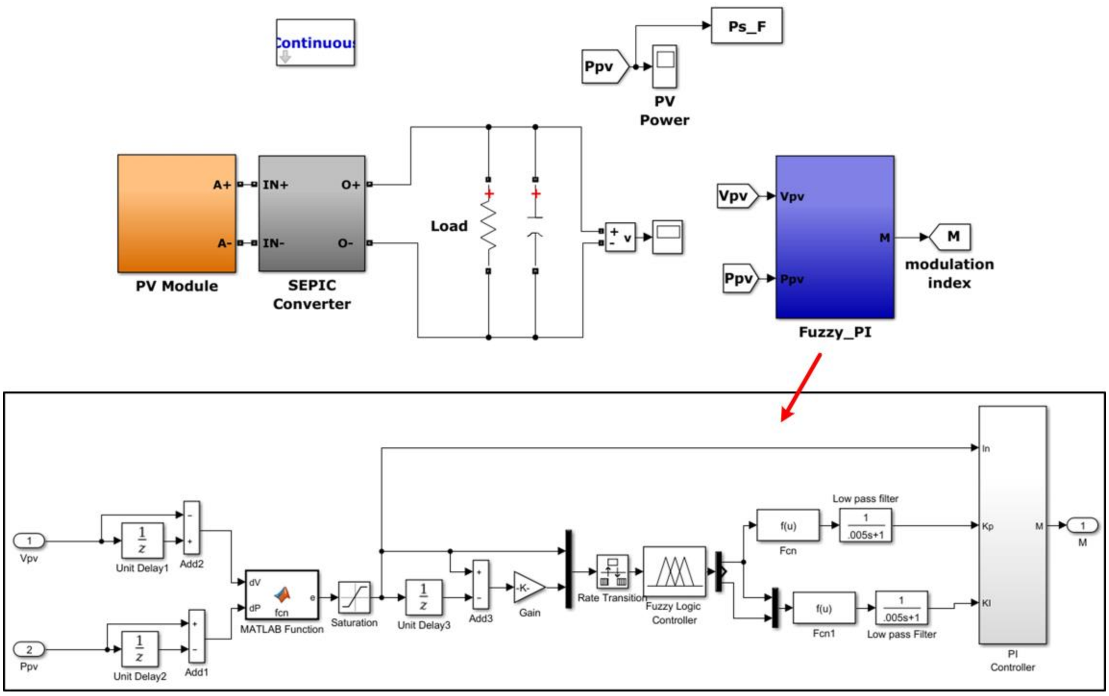


Fig. 6. Presented simulation model

Two methods perturb and observe (P&O) and Fuzzy-proportional integral (Fuzzy-PI) are proposed for simulation in the control system. Thus, P&O is selected from methods based on measurement and Fuzzy-PI from methods based on composition. The control signals generated by the two methods in the MPPT control unit reach the DC-DC converters, where the results will be compared by using SEPIC converter. These are also repeated in partial shading conditions. The results presented in Fig. 7 and 8 are a comparison of the output power of the proposed system, by examining the behavior of P&O and Fuzzy-PI after changing the input under the SEPIC converter. In Fig. 7 the setting time of two algorithms and in Fig. 8 oscillations in steady-state are compared. As shown in the results, the time of reaching the steady-state (setting time) of Fuzzy-PI and its steady-state oscillation is relatively less than other methods. The oscillation of P&O is more than fuzzy-PI, which is due to steady-state energy loss and local maximum power point tracking. One way to improve the performance of the traditional P&O is to optimize the size of the perturbation step according to the weather condition. This significantly reduces the oscillations around the MPP. PI Controller alone and with fixed gain cannot track the operating point correctly. For this, by adding the fuzzy method to PI and determining the coefficients in different operating conditions, the controller has been optimized and has behaved properly. Less oscillation, tracking accuracy, and high speed can be considered the superiority of the Fuzzy-PI method over the P&O.

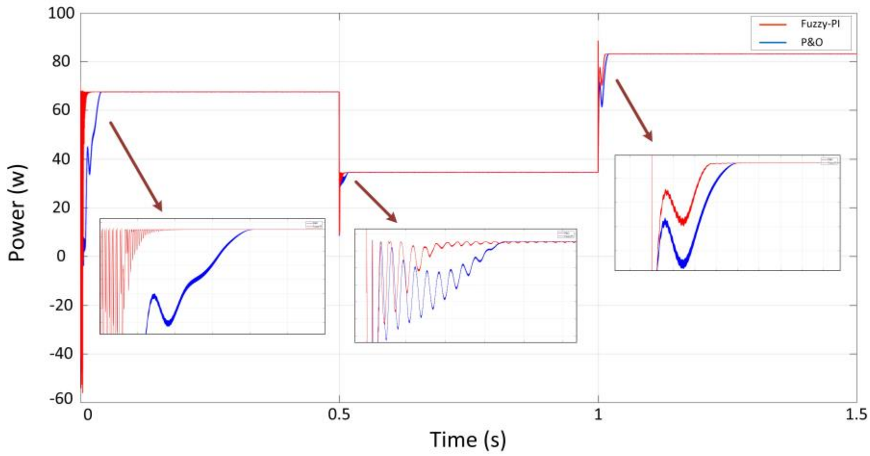

Fig. 7. Comparison of system output powers of two algorithms in normal condition (setting time)

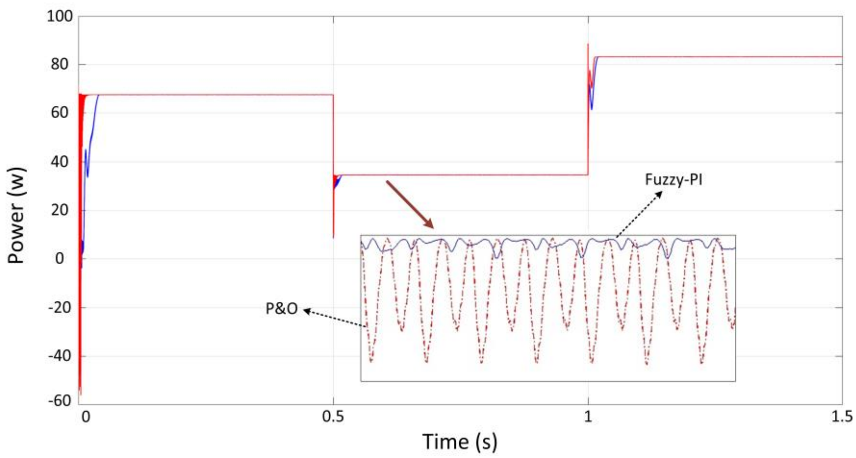

Fig. 8. Comparison of system output powers of two algorithms in normal condition (oscillation)

A comparison of algorithms in partial shading conditions is shown in Fig. 9. According to the power level obtained from the result, it is clear that P&O is stuck in the LMMPs and has not been able to find the GMPP, instead, the Fuzzy-PI has correctly obtained the GMPP in partial shading conditions.

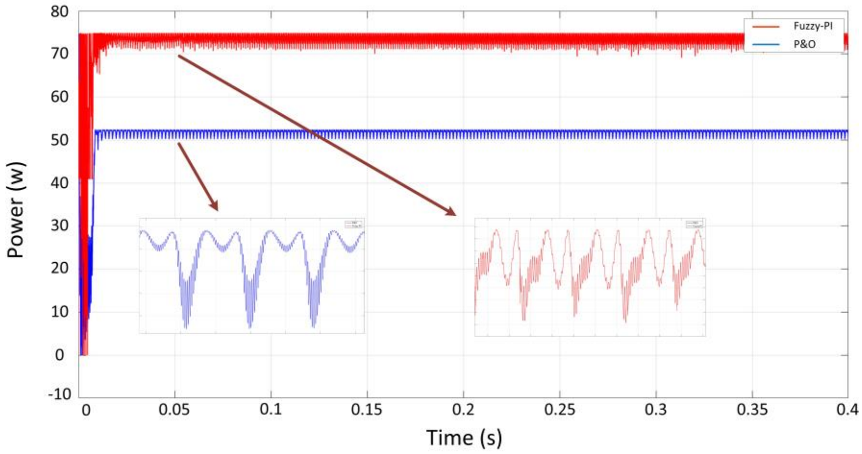

Fig. 9. Comparison of system output powers of two algorithms in partial shading condition

## 6. Conclusions

A standalone photovoltaic system with a controller for tracking the maximum power point is presented in this paper. In the controller, P&O and Fuzzy-PI are used to track the MPP and the SEPIC converter is used to increase the voltage level and perform the control commands to the system. These two methods are compared under normal operating conditions and partial shading conditions. Since the PI controller alone is not able to track the MPP and has a fixed gain in different weather conditions, and due to the fuzzy method integral equation errors, a fuzzy controller has been added to the PI to optimize the coefficients to determine coefficients correctly. In fact, this metaheuristic algorithm can cover the weaknesses of each method. Thus, the cumulative error of fuzzy and the low adaption of PI are eliminated by combining these two methods, and the controller has had acceptable performance. To compare with the Fuzzy-PI, the P&O also has been used as a conventional method. According to observations, both algorithms have quick tracking under variable environmental conditions. The two major drawbacks of the P&O are quite evident in the results. Small oscillations around the operating point (signal ripple) that increase losses and decrease efficiency, and the inability to track the global maximum power point in partial shading conditions. In some cases, LMMPs are received instead of GMPPs. Due to the results from the Fuzzy-PI method, it is obtained that the transient response is faster under normal conditions, and track of GMMPs under partial shading conditions is performed correctly. Oscillations around the operating point and the time to reach the steady-state status are reduced in this method. According to studies in this field and a review of the number of articles, it has been observed that research in the field of MPPT control systems is attractive, and many articles have been published. In recent years, intelligent methods have grown significantly and their application in MPPT control systems has been studied; But despite the high efficiency, they have a high cost and are less used. Introducing new smart methods that can be used in the MPPT control system and optimizing existing methods are the cases that researchers can address. The combination of smart and conventional methods to increase efficiency and better performance in partial shading conditions can also be considered very practical. DC-DC converters are also used to apply the control signal. Advances in this area have led to the emergence of new high-gain DC-DC converters, which can also be used in MPPT control systems to increase system efficiency.

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