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Conventional and Soft-Computing Based MPPT Methods Comparisons in Direct and Indirect Modes for Single Stage PV Systems

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***Abstract*—Improving power efficiency for a Photovoltaic (PV) system becomes important issue for researchers. To achieve maximum power extraction from PV panels, different kinds of Maximum Power Point Tracking (MPPT) methods have been investigating in the literature. In all techniques, direct and indirect mode approaches can be implemented. Based on the physical application of the PV system under different condition, the efficiency and convergence speed become important. In this paper, a grid connected simple single stage PV system by using different MPPT methods in direct and indirect modes has been analysed to find out the best mode and technique for a specific PV system application. Three of the most preferred MPPT algorithms: the perturb & observe (P&O), incremental conductance (Inc. Cond.) and fuzzy logic control (FLC) have been performed in MATLAB Simulink and compared their performance in direct and indirect modes in terms of convergence speed and tracking accuracy by the proposed single stage PV system. The results show that direct mode MPPTs have better tracking accuracy but less convergence speed than indirect MPPTs. Therefore, indirect mode MPPTs present better performance for the rapid atmospheric changing applications. Additionally, FLC based MPPT exhibits almost best tracking performance for direct and indirect modes.**

***Index Terms*—PV system, Maximum power point tracking, Perturb and observe; Incremental conductance; Fuzzy logic control; Single stage.**

I. INTRODUCTION

Concern over the limited stock of conventional energy sources such as coal and other petroleum products has pushed the researches to the development of renewable sources of energy [1]. Among the renewables, the solar Photovoltaic (PV) is expected to be among the most prominent due to its abundance, ease of installation and almost maintenance free [2]. However, the power generated by PV panels depends on a number of parameters, such as solar irradiance, ambient temperature and the electrical load in that it is connected [3]. In uniform environment condition, there is single particular point, called Maximum Power Point (MPP). In this point, the available maximum power is extracted by PV panels for the current situation. The position of this point is not fixed and changes according to the solar irradiance and temperature. To detect actual MPP against the changing of solar irradiance or temperature, Maximum Power Point Tracking (MPPT) algorithms are used. The function of MPPT is to ensure that the operating voltage and current always stay at the MPP on the P-V characteristic curve [2]. In the literature, various MPPT techniques have been presented [4]–[8].

The most popular conventional MPPTs are Perturb & Observe (P&O), hill climbing and Incremental Conductance (Inc. Cond.). These algorithms are widely used in commercial products due to their simplicity and robustness. However, these algorithms suffer from two main drawbacks. First is the continuous oscillation that occurs around the MPP. Secondly, especially P&O is to lose its tracking direction when the solar irradiance and temperature change rapidly [2]. This problem especially becomes very important issue in some applications such as mobile and roof-based PV power generation units due to fast change of environmental conditions. To avoid these drawbacks, soft-computing based MPPT techniques such as Particle Swarm Optimization (PSO) [9], Fuzzy Logic Control (FLC) [10], Artificial Neural Network (ANN) [11], Genetic Algorithm (GA) [12] are widely used for PV systems.

In this paper, P&O, Inc. Cond. and FLC MPPT methods have been investigated in two modes: direct mode and indirect mode in order to increase all over efficiency and/or convergence speed. The direct mode uses the instantaneous values such as PV voltage and PV current and finds MPP by incrementing/decrementing PV voltage in real-time. The indirect mode also uses the instantaneous PV voltage and PV current values but finds MPP by using the equivalent circuit model and its electrical characteristics.

In the literature, transferring the power to the grid is commonly completed in two stages. One of stages is consists of a DC-DC converter including MPPT algorithm. The second stage has a DC-AC inverter. Two stage systems are complicated, costly and additional loss occurs in each

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stage. Because of simplicity and low-cost reasons, single stage PV systems become popular [13]. In this paper, 150W single stage PV system is investigated separately by using P&O, Inc. Cond. and FLC MPPTs in direct and indirect modes in MATLAB Simulink. The comparisons for each MPPT control mode have been investigated in terms of tracking performance and convergence speed in detail. According to the comparisons, direct mode MPPTs have better tracking performance but worse convergence speed than indirect mode MPPTs. Hence, indirect mode MPPTs are more successful for rapid atmospheric changes and they are more convenient for roof installed PV systems, mobile vehicle installed PV applications, i.e. The rest of this paper is organized as follows: Section II discusses modelling of PV cell and PV panel by using equivalent circuit model. Section III presents mechanism for the used MPPT methods (P&O, Inc. Cond and FLC). Section IV explores the proposed single stage inverter which is used to connect the PV panel to the grid and presents operation mechanism with PV panel connection and its corresponding simulations. Section V depicts the proposed MPPT controlled single stage PV system and makes comparisons for each MPPT method in direct and indirect mode. Section VI concludes this study.

II. PV Modelling and Equivalent Circuit Model

PV cells have p-n junction similar to a diode. It generates the electrical current by absorbing photons. It has capacity to absorb the solar irradiance and mobilize the photons to electrons until it converges [14]. In the literature, there are various types of PV cell equivalent circuit representations. Single diode equivalent circuit model is widely used to express typical electrical characteristics [15], [16].

A PV panel is built from connecting several PV cells in series or parallel to achieve the corresponding voltage and current. Figure 1 displays a PV cell equivalent circuit model and a PV panel with 9 PV cells.

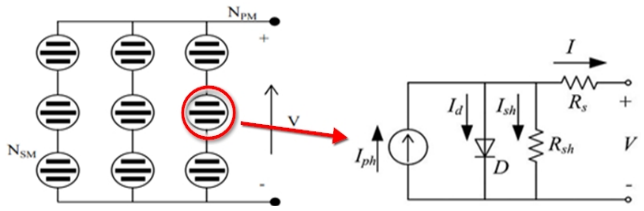


Fig. 1. PV panel and single diode equivalent circuit model of a PV cell [13].

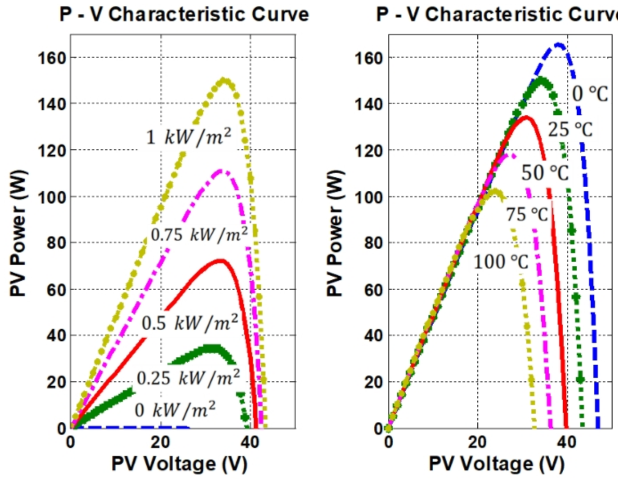
The modelling of the PV cell is defined by voltage-current relationship of PV system as follows

$$I = I_{ph} - I_o\left(\exp\left(q\left(V + R_s I\right)/AKT\right) - 1\right) - \\ -\left(V + R_s I\right)/R_{sh}, \quad (1)$$

where I and V represent PV cell output current and voltage. R_s and R_{sh} the PV cell series and shunt resistance respectively. I_{ph} is PV cell photo current, I_o is diode saturation current, A is the diode quality factor (≈1.2), K is Boltzmann's constant (1.38 × 10^{-23} J/K) and T is PV cell temperature in kelvins.

By using (1), the 150W PV panel system can be modelled in MATLAB Simulink. As known by researches about PV cells and panels, solar irradiance and temperature affect PV panel operating point and electrical characteristics. In this context, the voltage-current and voltage-power characteristic curves are plotted for different solar irradiance and temperature values to show electrical changes [17].

Variation of solar irradiance and/or temperature affects PV panel power value. PV panel power level changes with solar irradiance proportionally but varies in temperature inversely. The relationships between PV panel power-solar irradiance and power-temperature curves are shown in Fig. 2 respectively.



(a) (b)

Fig. 2. Power-voltage PV characteristic curves: (a) under constant temperature (25°C) and different solar irradiance; (b) under constant solar irradiance (1 kW/m^2) and different temperature.

III. Maximum Power Point Tracking Methods

PV cells and panels generate different power depended on different environment condition and electrical load. Thus, generation of maximum power is not guaranteed at all electrical load [13]. MPPT methods aim to ensure that at any environmental condition, i.e. any solar irradiance and temperature, maximum achievable power is extracted from PV system [18]–[20]. A MPPT system directs the operating point of PV system toward maximum power point [21].

To date, numerous MPPT methods are reported in the literature; they are broadly classified into two categories, namely the conventional and soft-computing approach [2]. The ones of the most popular are the P&O and Inc. Cond. [22]. On the other hand, soft computing based MPPT methods such as FLC tend to be more robust, versatile and flexible.

In this study, conventional and soft computing MPPT methods such as P&O, Inc. Cond. and FLC based MPPT have been implemented as MPPT controlling algorithm for the designed PV system. Additionally, these MPPT methods have been compared in detail to clarify their convergence speed and performance enhancement in direct and indirect modes.

A. Perturb and Observe MPPT Method

In this method, a perturbation is applied to the PV voltage and the change in PV output power is observed. If the perturbation causes to increase in the output power, the actual operating point is in the left side of MPP and the voltage is further increased; otherwise the actual point is in the right side of MPP and the voltage is decreased [21], [23]. And this process continues until the change of the output power becomes null. The related equations to describe this relationship are provided in (2), (3) and (4):

$$dP/dV = 0 \Rightarrow at\ \ MPP, \quad (2)$$

$$dP/dV > 0 \Rightarrow Left\ \ Side\ \ of\ \ MPP, \quad (3)$$

$$dP/dV < 0 \Rightarrow Right\ \ Side\ \ of\ \ MPP. \quad (4)$$

The main advantage of this method is that it is simplest method among the conventional MPPTs and exhibits very good convergence [2]. The limitations are oscillation around the MPP in steady state condition and tracking deviation from the maximum operating point under fast changing environment condition. The accurate perturbation value is important to provide good performance in both steady state and dynamic response [2], [14], [21], [22], [24], [25].

B. Incremental Conductance MPPT Method

This method is derived from the same basis as P&O method but it is based on a comparison of PV voltage and current change [25]. Inc. Cond. method tracks the MPP by comparing the sum of incremental conductance of PV panel with zero [26].

In Inc. Cond. method, a perturbation ΔV in PV voltage is applied and the change in current ΔI sensed. Since ΔV and ΔV are small, dI/dV and ΔI/ΔV are assumed the same. Then, if ΔI/ΔV > -I/V, the voltage is increased and if ΔI/ΔV < -I/V, the voltage is decreased [21]. The related equations to describe this relationship are provided in (5)–(8):

$$dP/dV = d(V \times I)/dV = 0 \Rightarrow \Delta I/\Delta V = -(I/V), \quad (5)$$

$$\Delta I/\Delta V = -(I/V) \Rightarrow at\ \ MPP, \quad (6)$$

$$\Delta I/\Delta V > -(I/V) \Rightarrow Left\ \ Side\ \ of\ \ MPP, \quad (7)$$

$$\Delta I/\Delta V < -(I/V) \Rightarrow Right\ \ Side\ \ of\ \ MPP. \quad (8)$$

The main advantage of this method is that it helps to overcome the disadvantage of the P&O method which fails to track the MPP under fast changing environment condition [14]. Additionally, it has improved robustness to measurement noise when compared to the P&O method [27]. But, the main drawback of this algorithm is that, the oscillation problem around MPP is also available in steady state condition and it is more complicated than P&O method to implement.

C. Fuzzy Logic Control Based MPPT Method

Fuzzy logic controllers (FLCs) have been widely used for MPPT application in the literature [28]–[31]. Every FLC consists of three parts; fuzzification, fuzzy rule tables and defuzzification. FLCs gain several advantages of better performance, robust and simple design. In addition, this method does not require the knowledge of exact model of system [32], [33]. In this method, the variables manage some non-numeric and linguistic variables such as high, low medium, etc. in fuzzification process.

In the proposed FLC method, the input of FLC is sum of angle conductance ($\theta_1 = \tan^{-1}(I_{pv}/V_{pv})$) and angle of increment of conductance ($\theta_2 = \tan^{-1}(dI_{pv}/dV_{pv})$). The input variables are described in (9)

$$\theta_1 + \theta_2 = \tan^{-1}\left(I_{pv}/V_{pv}\right) + \tan^{-1}\left(dI_{pv}/dV_{pv}\right) = 0. \quad (9)$$

The sum of angle conductance and angle of increment of conductance ($\theta_1 + \theta_2$) and PV panel power-voltage characteristic curves relations are illustrated in Fig. 3.

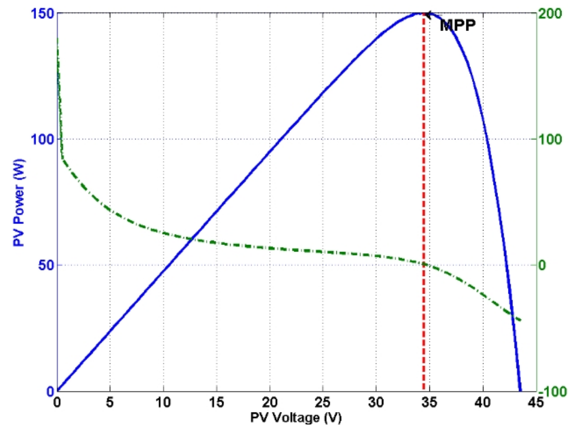


Fig. 3. Power-voltage of PV panel and the corresponding sum of angle conductance and angle of increment of conductance characteristic curves.

As seen in Fig. 3, the sum of the angles of PV panel conductance and increment of conductance equals to zero around MPP point. Therefore, the membership function of the input and the rule base set of the FLC based MPPT must be identified according to that condition for fuzzy inference system. In this context, the input variable of sum the angles ($\theta_1 + \theta_2$) is assigned to several linguistic variables which are denoted by NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big). Hence, the number of corresponding fuzzy rules is decreased to 5. The corresponding fuzzy rule set is shown in Fig. 4.

	Region 1		Region 2	Region 3	
$\theta_1 + \theta_2$	NB	NS	ZE	PS	PB
ΔV_{pv}	NB	NS	ZE	PS	PB

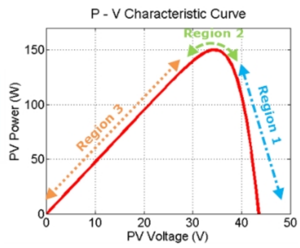


Fig. 4. The fuzzy rule table and power-voltage fuzzy region of the proposed FLC based MPPT system.

The use of this method in designing output domains allows greater step sizes that improve the efficiency of the MPPT process. The other advantage is that this algorithm would not require the system to use a second set of MPPT input variables [34].

IV. CONTROLLED SINGLE PHASE FULL WAVE CONVERTER OPERATING IN INVERTER MODE

The interface between PV modules and the system load (or grid) are generally made by power circuits. In these interfaces, the power circuits make connection between PV modules and the system load (or grid) and perform MPPT process to extract maximum power from PV modules. In the literature, multi-stage PV system topology is widely preferred for energy conversion in PV systems [35]. This study proposes a simple controlled full wave converter instead of using multi converters, which can be used in rectifier or inverter mode for energy conversion as shown in Fig. 5.

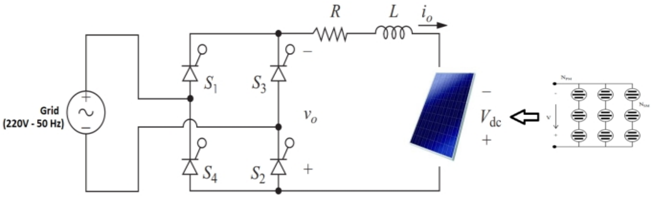


Fig. 5. Controlled full wave converter with RL – source load [13].

In inverter mode, the delay angle of the semi-conductor devices must be higher than 90°. So that, the electrical power flows from PV panel to the grid [36]. In addition to being simple, the does not require any modulation techniques.

In the controlled converter system, the delay angle of the semiconductor switches called (α) must be also

$$\alpha \geq \sin^{-1}\left(V_{dc}/V_m\right), \tag{10}$$

where V_{dc} is dc voltage source and V_m is maximum voltage source of the grid. The output voltage of the converter can be calculated as follows

$$V_o = \int_{\alpha}^{\pi+\alpha} V_m \sin(\omega t)\, d(\omega t) = \left(2V_m/\pi\right)\cos\alpha. \tag{11}$$

The output current of the PV panel is calculated as shown in (12)

$$I_o = \left(V_o + V_{dc}\right)/R. \tag{12}$$

By calculating PV panel output current, voltage and power losses in the converter, the transferred power to the grid is described in (13)

$$P_o = P_{dc} - P_{losses} = I_o V_{dc} - I_o^2 R. \tag{13}$$

To extract maximum power from the PV panel for any environment condition, the switches in the converter must be triggered in a specific delay angle (α) which is calculated by MPPT controller. As changing maximum power level of PV panel for different environment condition such as solar irradiance and temperature, the proper delay angle varies on different value. Thus, the proper delay angle must be calculated for each environment changes to provide maximum energy conversion by the converter.

To emphasize the delay angle importance, the proposed PV system without MPPT controller has been initially analysed in MATLAB Simulink. The proposed PV system without MPPT controller is shown in Fig. 6.

In Fig. 6, the proposed PV system has been simulated for two different environment conditions. The proper delay angle has been entered to the system manually. Firstly, the system has been performed for ideal condition (1 kW/m^2 – 25°C). For the ideal condition, the proper delay angle, which was calculated by MPPT algorithm, must be 97.019° to extract maximum power from the PV panel. If the delay angle is changed to 95°, the output power decreases from 149.987 W to 132.713 W.

If the environment condition changes, the proper delay angle also must be recalculated to extract maximum allowable power from the PV panel for the actual environment condition. For example, the actual environment condition changes to 0.5 kW/m^2 – 30°C, the proper delay angle must be 97.672°. Hence, the corresponding MPP is 70.566 W. The related simulation results are also summarized in Table I and the corresponding output power is shown in Fig. 7.

TABLE I. TEST RESULTS FOR THE PROPOSED 150 W PV SYSTEM IN DIFFERENT ENVIRONMENT CONDITION BY ADJUSTING DELAY ANGLE MANUALLY.

Solar Irradiance (kW/m^2)	**Temperature (°C)**	**Delay Angle (°)**	**PV Power (W)**
1	25	97.019°	149.987
1	25	95°	132.713
0.5	30	97.672°	70.566

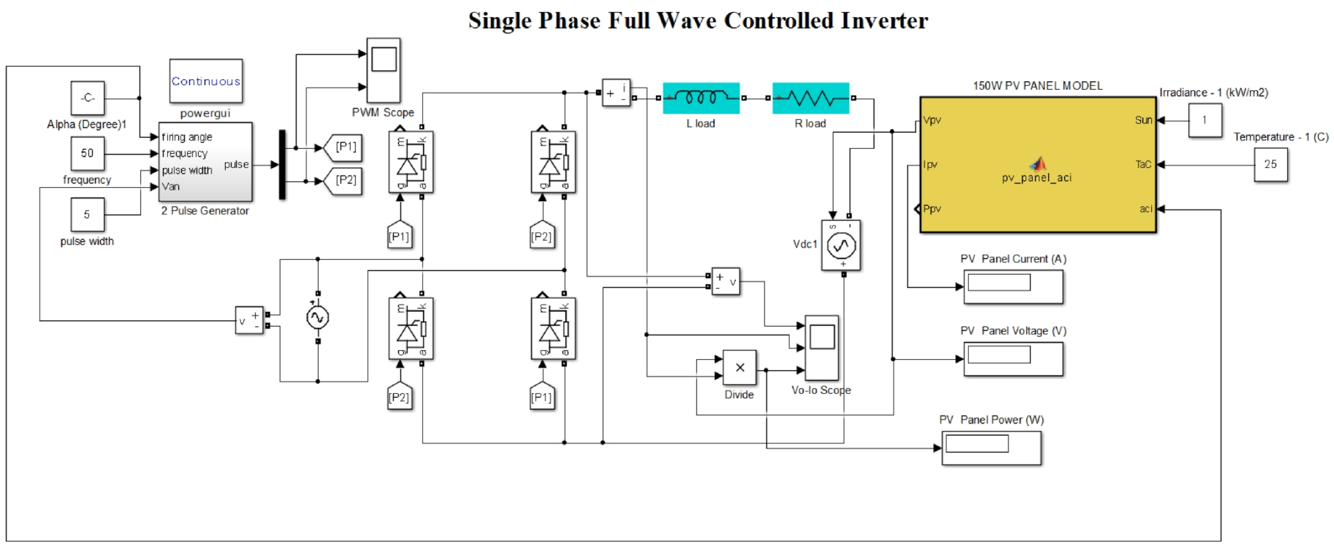


Fig. 6. Connecting 150 W PV panel system to the grid by controlled single phase converter without MPPT controller in MATLAB Simulink.

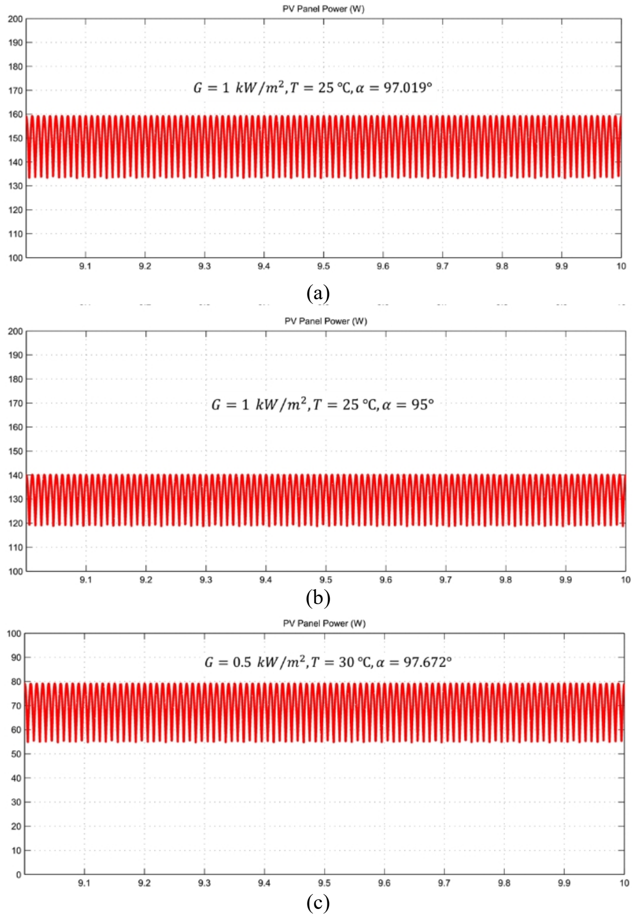


Fig. 7. PV output power for different delay angle values under different environment condition.

V. MPPT Controlled PV System Comparisons and Simulation Results

In the literature, transferring power to the grid is generally achieved by using multi-stage PV system topology which comprises generally two stages for power conversion [37]–[41]. In the first stage, a DC-DC converter is used to extract maximum power from PV panel by being controlled MPPT. In the second stage, a DC-AC inverter is used to transfer the extracted maximum power to the grid. In this study, the proposed PV system does not require additional DC-DC converter to perform MPPT task. The proposed system performs MPPT and also provides directly connection to the grid by its single power circuit. The proposed circuit scheme with MPPT controller is shown in Fig. 8.

Environment conditions are time dependent. Hence, in the proposed PV system, the MPPT controller must continuously calculate the delay angle (α) to extract maximum power from PV panel. The MPPT controller uses PV output voltage, current and ambient temperature as inputs and calculates the delay angle (α) for the actual environment condition by finding available maximum power.

To illustrate the performance of the proposed PV system, the system has been performed under ideal and different environment conditions for each MPPT methods (P&O, Inc. Cond. and FLC). In addition, to observe the performance of MPPT methods, the experiments are tested for direct and indirect modes of MPPT. The direct mode uses the instantaneous values such as PV voltage and PV current and finds MPP by incrementing/decrementing PV voltage in real-time. The indirect mode uses the instantaneous PV voltage and PV current values but finds MPP by making calculation in its controller. For P&O and Inc. Cond. methods, increment/decrement parameter is selected as 0.5 V for all simulations. The convergence speed of the system and tracking performance of each condition and each mode (direct and indirect modes) have been observed and compared in MATLAB Simulink in detail.

The first experiment is conducted in ideal environment condition (1 kW/m^2 – 25 °C) in indirect and also direct modes for P&O, Inc. Cond and FLC MPPT methods. In the first experiment, the convergence speeds of P&O, Inc. Cond. and FLC MPPTs are 2.968 s, 2.694 s and 5.017 s in indirect mode, 7.058 s, 7.058 s and 5.917 s in direct mode respectively. Figure 9 shows output power of PV system in indirect and direct modes respectively for each MPPT method and the simulation results are given in Table II.

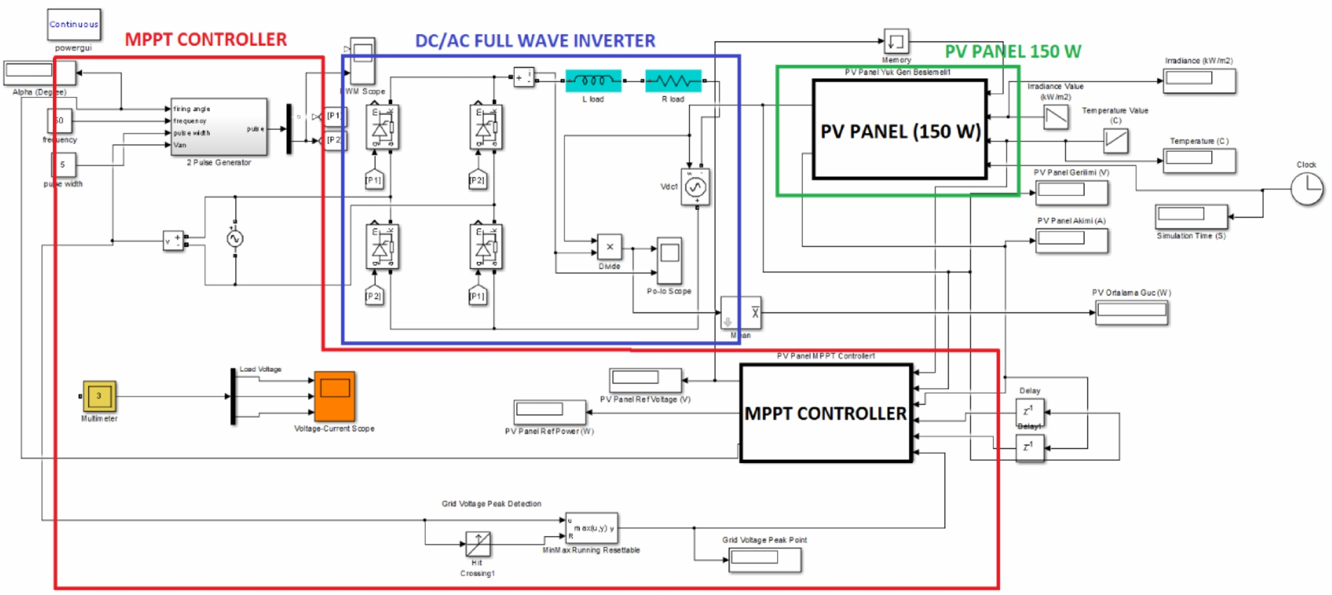
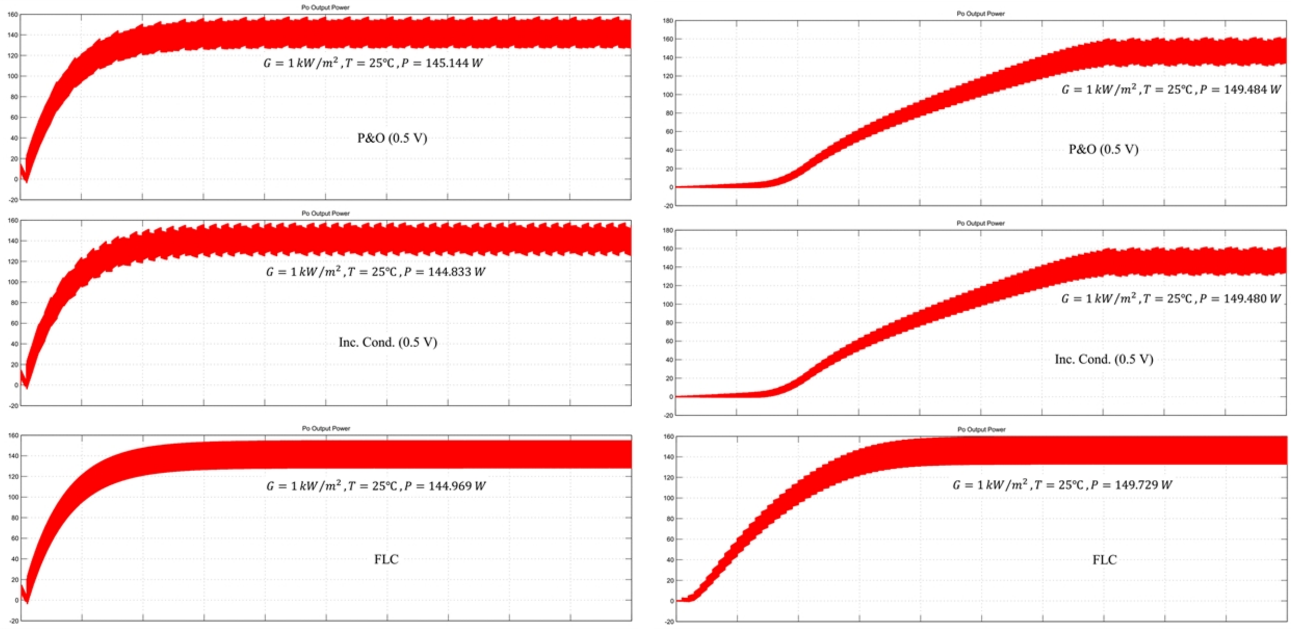


Fig. 8. The proposed PV system with MPPT controller circuit scheme.

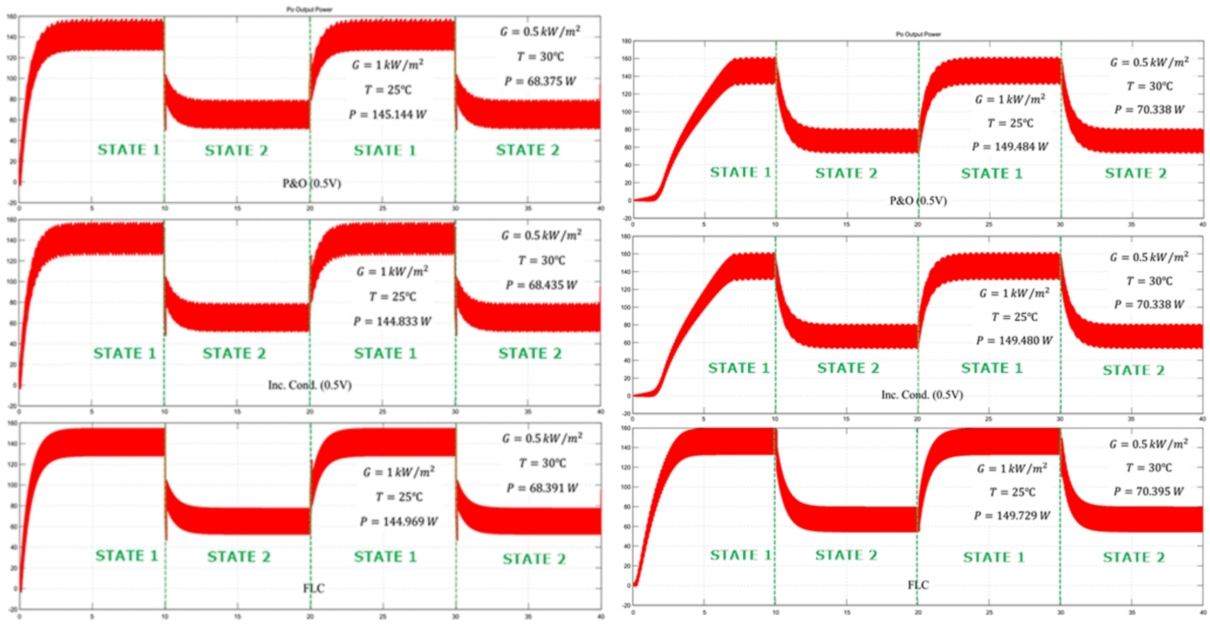


(a).. ..(b)

Fig. 9. PV system power for P&O, Inc. Cond and FLC MPPT methods in ideal environment condition: (a) in indirect mode; (b) in direct mode.

TABLE II. TEST RESULTS FOR THE PROPOSED 150 W PV SYSTEM WITH MPPT CONTROLLER IN IDEAL ENVIRONMENT CONDITION.

MPPT Type	Solar Irradiance (kW/m^2)	Temperature (°C)	Ideal PV Power (W)	Indirect Mode		Direct Mode	
				PV Power (W)	Convergence Speed (s)	PV Power (W)	Convergence Speed (s)
P&O (0.5V)	1	25	150	145.144	2.968	149.484	7.058
Inc. Cond. (0.5V)	1	25	150	144.833	2.694	149.480	7.058
FLC	1	25	150	144.969	5.017	149.729	5.917



(a) (b)

Fig. 10. PV system power for P&O, Inc. Cond and FLC MPPT methods in different environment condition: (a) in indirect mode; (b) in direct mode.

TABLE III. TEST RESULTS FOR THE PROPOSED 150 W PV SYSTEM WITH MPPT CONTROLLER IN DIFFERENT ENVIRONMENT CONDITION.

MPPT Type	Solar Irradiance (kW/m^2)		Temperature (°C)		Ideal PV Power (W)		Indirect Mode				Direct Mode			
							PV Power (W)		Convergence Speed (s)		PV Power (W)		Convergence Speed (s)	
	State 1	State 2	State 1	State 2	State 1	State 2	State 1	State 2	State 1 to 2	State 2 to 1	State 1	State 2	State 1 to 2	State 2 to 1
P&O (0.5V)	1	0.5	25	30	150	70.57	145.144	68.375	2.391	2.187	149.484	70.338	2.788	2.480
Inc. Cond. (0.5V)	1	0.5	25	30	150	70.57	144.833	68.435	2.395	2.091	149.480	70.338	2.788	2.479
FLC	1	0.5	25	30	150	70.57	144.969	68.391	3.694	4.359	149.729	70.395	4.130	5.221

According to the simulation results for the first experiment, the convergence speed to reach MPP is faster in indirect mode than direct mode for ideal environment condition. The convergence speed is 2.38 times faster for P&O, 2.62 times faster for Inc. Cond. and 1.18 times faster for FLC in indirect mode than the direct mode.

But the tracking accuracy and efficiency performance in direct mode is greater than indirect mode. The maximum power increases 2.89 % for P&O, 3.1 % for Inc. Cond. and 3.17 % for FLC in direct mode according to the indirect mode.

The second experiment is conducted in different environment condition (1 kW/m^2 – 25 °C) and (0.5 kW/m^2 – 30 °C) in indirect and also direct modes for P&O, Inc. Cond and FLC MPPT methods. Figure 10 shows output power of PV system in indirect and direct modes respectively for each MPPT method and the simulation results are given in Table III.

According to the simulation results for the second experiment, the convergence speed to reach MPP point is also faster in indirect mode than direct mode when environment condition changes to 0.5 kW/m^2 – 30 °C. The convergence speed is 1.17 times faster for P&O, 1.16 times faster for Inc. Cond. and 1.12 times faster for FLC in indirect mode than the direct mode.

But the tracking accuracy and efficiency performance in direct mode is greater than indirect mode. The maximum power increases 2.78 % for P&O, 2.7 % for Inc. Cond. and 2.84 % for FLC in direct mode according to the indirect mode when environment condition changes to 0.5 kW/m^2 – 30 °C.

Consequently, direct mode based MPPTs have better tracking accuracy but less convergence speed than indirect mode based MPPTs in ideal and different environment conditions. However, it is necessary to emphasize that FLC has almost best tracking accuracy in direct and also indirect mode comparing to the other examined MPPT methods.

Therefore, this research gives important hints in different terms of characteristics of the MPPT methods in each mode. Although, the indirect mode based MPPTs are more appropriate for rapid atmospheric changes, the direct mode based MPPTs provides better efficiency for PV systems.

VI. CONCLUSIONS

This paper compares P&O, Inc. Cond and FLC based MPPT methods for direct and indirect modes by the proposed grid connected single stage PV system. Because of complexity, high losses and additional costs of conventional two stage PV system, grid connected single stage PV system has been investigated in this study. The proposed system performs connection to the grid and MPPT control in a single power circuit. MPPT methods in direct and indirect modes have been performed in MATLAB Simulink by the proposed system in ideal and different environment conditions. The MPPT methods for direct and indirect modes have been compared in terms of tracking efficiency and convergence speed for each environment conditions (ideal and different conditions) in detail. The results have verified that the MPPT methods provide almost 99.7 % high tracking efficiency in direct mode. Comparing with indirect mode MPPTs, direct mode MPPTs improves tracking efficiency by 3 % and 2.8 % under ideal and different environment conditions, respectively.

However, the indirect mode MPPTs present approximately 0.4 s faster response to track MPP quickly under the rapid atmospheric changes. Comparing with direct mode MPPTs, indirect mode MPPTs enhance the convergence speed by 1.12 times faster under the atmospheric changes. Besides, FLC based MPPT exhibits superior tracking performance improving by 0.1 % compared with the other examined MPPT methods in direct mode.

Hence, this study provides an extensive overview about the different kind of quality for P&O, Inc. Cond. and FLC based MPPTs in direct and indirect modes and compares their different characteristics against the environment changes.

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