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A SIMULATION OF STAND-ALONE SOLAR ENERGY SYSTEM CONTROLLED BY P&O, IC, AND FUZZY LOGIC USING BIDIRECTIONAL CHARGING OF BATTERY

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ABSTRACT

As is well known, one of the apparent drawbacks of a photovoltaic system is the low power production of solar radiation due to variations in ambient circumstances. Tracking the greatest power point of the solar panel is an economical and effective method of converting solar energy. The study examines approaches for determining the maximum power point based on photovoltaic system disturbance. A comparative study of the methodologies is performed, and their benefits and drawbacks are highlighted. The mathematical model of the system and the methods were examined, with the findings provided. An analog control system for a hysteresis-type DC voltage converter is constructed as an example. The operation of a solar battery under partial shade is considered a challenge in tracking the maximum power point, and solutions to this problem are explored. The study focused on three common techniques in tracking MPPT, Perturb and Observe P& O, Incremental Conductance IC and Fuzzy Logic. For fast charging and increasing the battery life cycle, PI controller was added and connected with the DC-DC converter. This system was studied and developed in MATLAB/Simulink.

KEYWORDS

The photovoltaic system, MPPT methods, DC-DC convertor, Bi-directional battery charge, PI control

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1. INTRODUCTION

Solar energy, photovoltaic cells, or PV panels as known is one of the main sustainable energies although of the high cost of installation but it has many advantages. Globally, some of countries began establishing huge fields of the PV panels systems which can in turn abate the need of a classical energy source that depends on the combustion of oil, coal, and other sources that have a direct impact on global warming and the environment in general, another purpose of using the PV systems is adopting it as an alternative source of the electrical energy to convert the desert areas to agricultural areas, which will be resulted in mitigating the impact of climate change are being taken place at the moment because of the water scarcity, lack of rains and increasing of the dust storms. On the other hand, it reduces the unemployment rate that increased in many countries (Kchaou *et al.*, 2017; Pathak and Yadav, 2019a).

Continued studies have been implemented for the last five decades; an intensified effort began newly about the MPPT. Our study focused on some classical and modern algorithms, Perturbation and Observation (P&O) and Incremental Conductance (IC) methods are classical and easiest in terms of construction and implementation. A fuzzy logic method is a modern and smart technique that simulates a human understanding in terms of approach (Tahiri *et al.*, 2016; Salman, Ai and Wu, 2018; Abo-Sennah, El-Dabah and Mansour, 2021).

All the techniques work to get the best values produced from the solar panel based on tracking the maximum power point which is identified as a joint point between the voltage and current at the maximum value (Vmax and Imax) or a joint point between the power and voltage at the maximum value (Pmax and Vmax), this concept represents or can be called a characteristic of PV panel as shown in Fig. 1 (Koutroulis and Blaabjerg, 2012).

All the proposed systems have been used to feed a certain load based on the capacity of the PV panel, and to charge a battery with a capacity of 12 volt under varying solar irradiance between 500-1000 w/m^2 using a PI controller. The purpose of using the PI controller is for controlling the battery charge and increasing the life cycle of the battery (Pathak and Yadav, 2019b).

A technique of fuzzy logic concept or theory is proposed to improve the efficiency of the photovoltaic system as an alternative to the traditional algorithms. All the study implemented in a simulation environment in MATLAB to see the behavior of system among the proposed and developed techniques based on the new studies and theories (Haji and Genc, 2018).

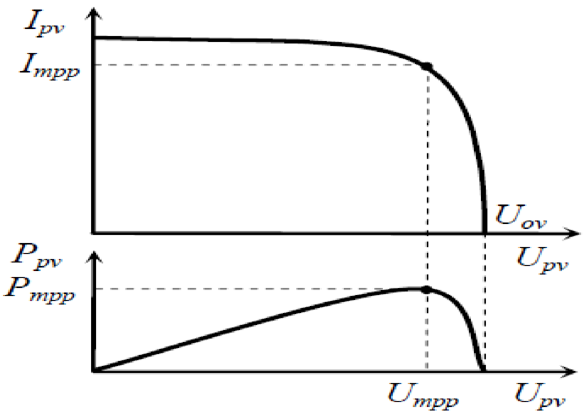
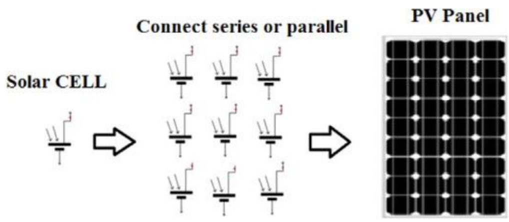


Fig. 1 Solar module static characteristics.

2. RESEARCH METHOD

A PV panel can be unique or as a grid linked with each other in parallel or series or combined from certain numbers in series and others in parallel based on the desired energy (Fig. 2). The main unit of a PV panel is a PV cell and it works on the photovoltaic principle, which means a conversion of light or as mentioned earlier radiation to electrical energy



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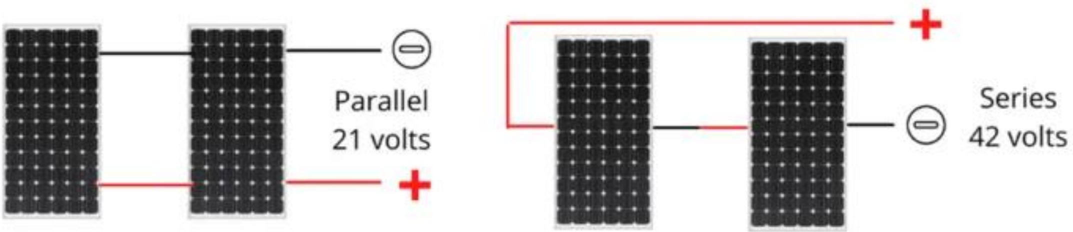

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Fig. 2 PV Panel (a) A unique (b) Connected in series and Parallel

The PV panel can be represented by the equivalent electricity network shown in Fig. 3 (Pathak and Yadav, 2019c).

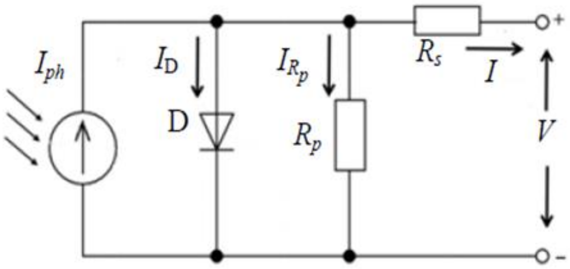

Fig. 3. Solar panel equivalent circuit.

The relationship between the output current and voltage could be represented in equation (1):

$$I = I_{ph} - I_D - I_{R_p} = I_{ph} - I_{sat}\left(\exp\left[\frac{q(V+IR_s)}{AKT}\right] - 1\right) - \frac{(V+IR_s)}{R_p} \quad (1)$$

Where, I_{ph} is the current of photovoltaic array, I_D is the diode current, I_{R_p} is the current flowing through the equivalent parallel resistance, I_{sat} represents the reverse saturated current of the PV array, R_s is the equivalent series resistance, R_p means the equivalent parallel resistance, V is the output voltage, I is the output current, q means the electron charge, A means the P-N junction curve constant of the diode, k is the Boltzmann coefficient ($1.38*10^{-23}$ J/K) and T is the temperature of P-N junction of diode.

A PV cell consists of a semiconductor diode, its equation is given by equation (2):

$$I_D = I_{sat}\left[\exp\frac{q(V+IR_s)}{AKT} - 1\right] \quad (2)$$

Hence the output current and voltage depend on the solar irradiation and temperature. Achieving the maximum power will be at a certain voltage. To get maximum power, it very essential to regulate both output voltage and load resistance. This approach needs to provide a DC-DC converter work to achieve these main points mentioned above (Zhou *et al.*, 2010; Al-Majidi, Abbod and Al-Raweshidy, 2018).

Our PV system consists of a PV panel, DC-DC converter, MPPT controller, load, PI controller in addition to the sub-system of battery charge as shown in Fig. 4 and Fig. 5.

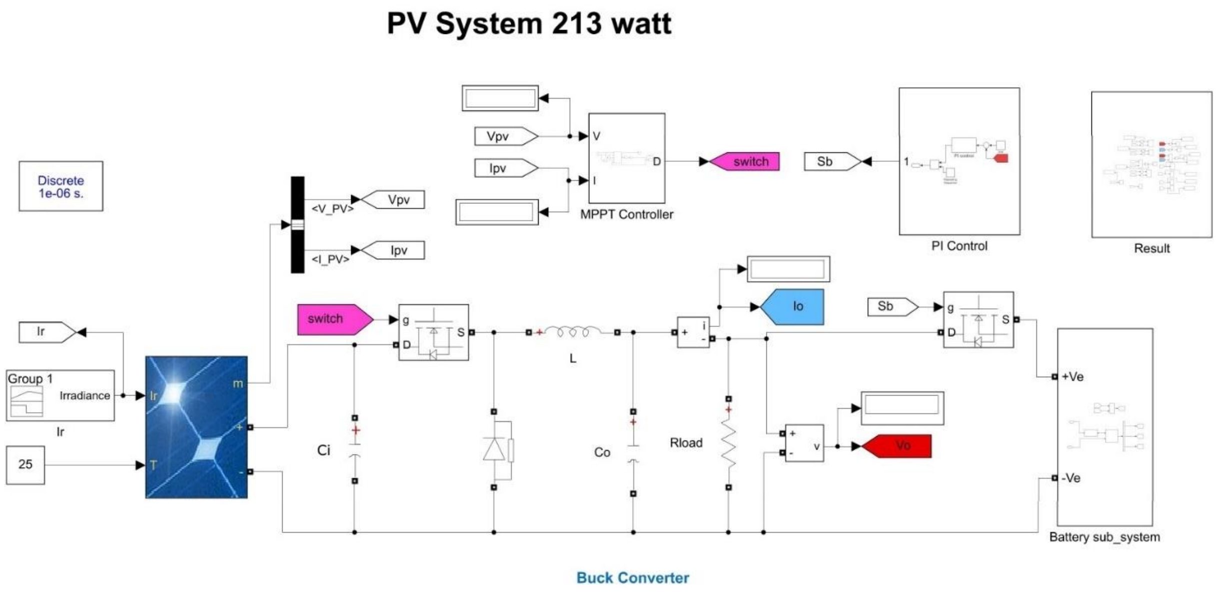

Fig. 4 PV system in Simulation.

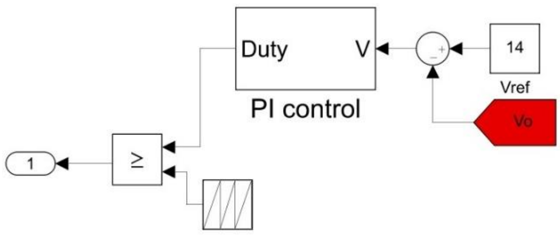

Fig. 5 Bidirectional charge sub-system.

To design a DC-DC buck converter as selected in our study and shown in Fig. 6, it consists of MOSFET, diode, inductor, and capacitor in addition to the load resistance. A DC-DC converter is used to operate the PV panel at MPPT, different MPPT techniques are applied to switch of MOSFET of the converter to adjust the value of the duty cycle of PWM. Thus, a duty ratio, inductance, and capacitance values can be calculated by the following equations:

$$D = \frac{\mathrm{V_o}}{\mathrm{V_{in}}} \tag{3}$$

$$V_L = L\frac{di_L}{dt} = L\frac{\Delta I_L}{(1-D)T}V_o \tag{4}$$

$$L = \frac{V_o(V_{in}-V_o)}{V_{in}f_{sw}\Delta I_L} \tag{5}$$

$$C = \frac{\Delta I_L}{8\, f_{sw}\Delta V_o} \tag{6}$$

Where, D is the duty cycle, V_o is the output voltage of converter, V_{in} means the input voltage of converter, L is the inductance, V_L is the voltage across the inductance, T is a period of converter operation, f_{sw} is the operation frequency of converter, ΔI_L or ΔI_o is the current ripple across the inductor, ΔV_o means the ripple of output voltage. All the parameters are explained more in Table 1.

Changing the duty cycle based on power loss in high-efficiency converters usually does not have much effect on the inductor value and can be ignored when choosing an inductor.

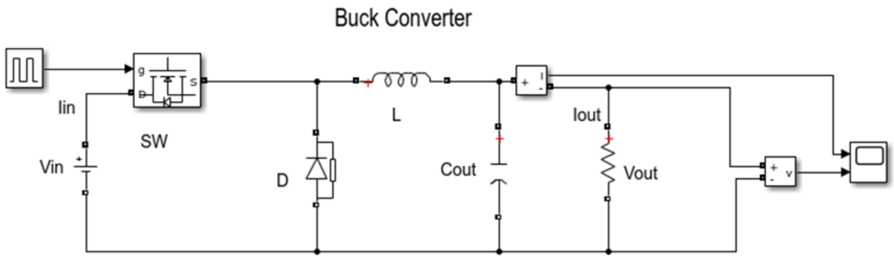

Fig. 6 PV system in Simulation.

2.1. MPPT Methods

2.1.1. Perturb and Observe P&O method

The classical algorithm of Perturb and Observe assumes an increase or decrease in the reference voltage V_{ref} of the photovoltaic system in to disturb the system at regular intervals and further compare the output power of the solar module at k and k-1 stages of operation. If, when the output voltage of the solar module changes on the k-th measurement interval, its power increases (transitions A2 → A1, B2 → B1 in Fig. 7).

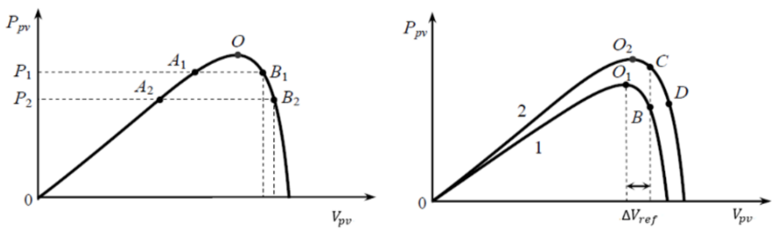

Fig. 7 Movement of the solar module operating point in conditions of (a) constant and (b) variable solar radiation.

Then, the control system continues to move the operating point of the solar module in this direction; otherwise, the sign of the reference voltage increment ΔV_{ref} changes, and the operating point of the solar module moves in the opposite direction. At each subsequent stage of the disturbance, one of the main disadvantages when using this algorithm is the wrong behavior and low efficiency at the low solar irradiation applied to the system, the algorithm presented in Fig. 8 demonstrated a better behavior, the dP-P & O method proposed as a simple and effective solution to the problem of tracking MPPT in the wrong direction. The power measurement is disassembled to discover several reasons for fluctuation in solar module power, such as disturbance or variations in solar radiation. The algorithm solely considers the power changes induced by the MPPT controller's activities as a result of command execution. As illustrated in Fig. 9, the dP-P & O method assumes a different measurement of the solar module's power Px at a position corresponding to the midpoint of the sample period T (Narendiran, 2013; Selvan and Kumar, 2015; Ali et al., 2022).

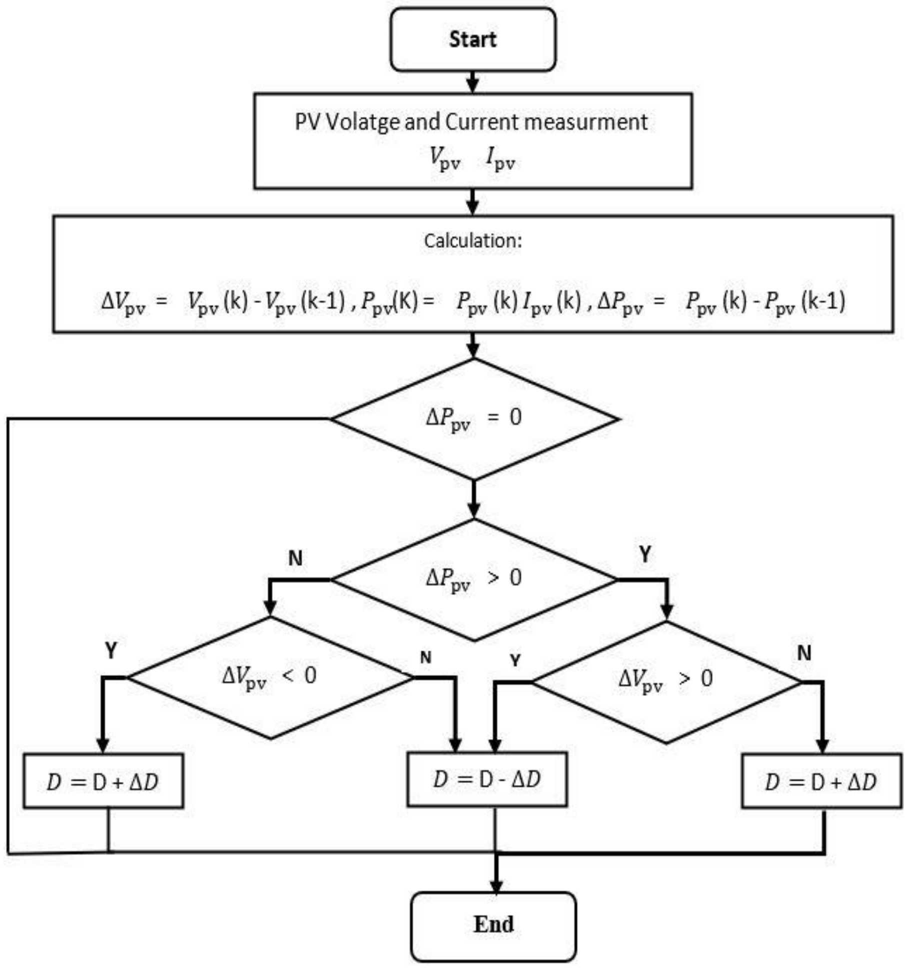

Fig 8. Block diagram of (P & O) algorithm (Abo-Sennah, El-Dabah and Mansour, 2021).

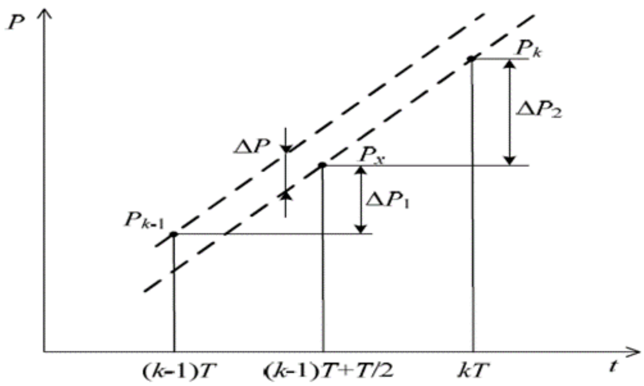

Fig. 9 The power gain of the dP-P & O algorithm (Sera et al., 2006).

2.1.2. Incremental Conductance IC method

It is known that at the point of maximum cardinality the equality as follows:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} = 0 \tag{7}$$

Which can be converted to the form:

$$\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} = 0 \tag{8}$$

where I_{pv} and V_{pv} are the current and voltage of the solar module; $\frac{I_{pv}}{V_{pv}}$ - conductivity of the solar module; $\frac{dI_{pv}}{dV_{pv}}$ - incremental (increasing) conductivity. The fulfillment of condition (2) in the absence of a change in the solar module current ($dI_{pv} = 0$), caused by a change in the intensity of solar radiation, allows the control system to maintain the nominal voltage of the solar module found in this way without additional disturbance. The algorithm on the k-th operating interval begins with measuring the current values of the current $I_{pv}(k)$ and voltage $V_{pv}(k)$of the solar module. Then, using the corresponding values obtained in the k - 1 interval of operation, the increments of current ΔIpv and voltage ΔV_{pv} are calculated. The main one is to check the fulfillment of equality (2), according to the results of which the reference voltage V_{ref}, which sets the voltage at the output terminals of the solar module, will be corrected as in Equation (9) (Bendib, Belmili and Krim, 2015a):

$$\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} < 0 \tag{9}$$

The operating point on the P_{pv} (V_{pv}) plane is to the right of the MPPT, therefore, the reference voltage is corrected downward at Equation (10):

$$\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} > 0 \quad (10)$$

In general, the IC algorithm, when tracking the MPPT, uses a fixed iteration step size ΔV_{ref}, which is determined by the tracking accuracy and speed requirements. A modified IC algorithm with a variable step size was proposed. This approach automatically adjusts the step size when moving towards the solar module's operating point. When the operating point is considered to be far from the MPPT, the modified algorithm increases the step size to quickly approach the operating point to the MPPT, and vice versa, when the operating point is near the MPPT, the step size is reduced. By varying the step size, the accuracy and speed of the algorithm are increased. The small signal model confirms the stability of the system in almost all cases (Fig. 10) (Bendib, Belmili and Krim, 2015; Singh, Shukla and Gaur, 2021) .

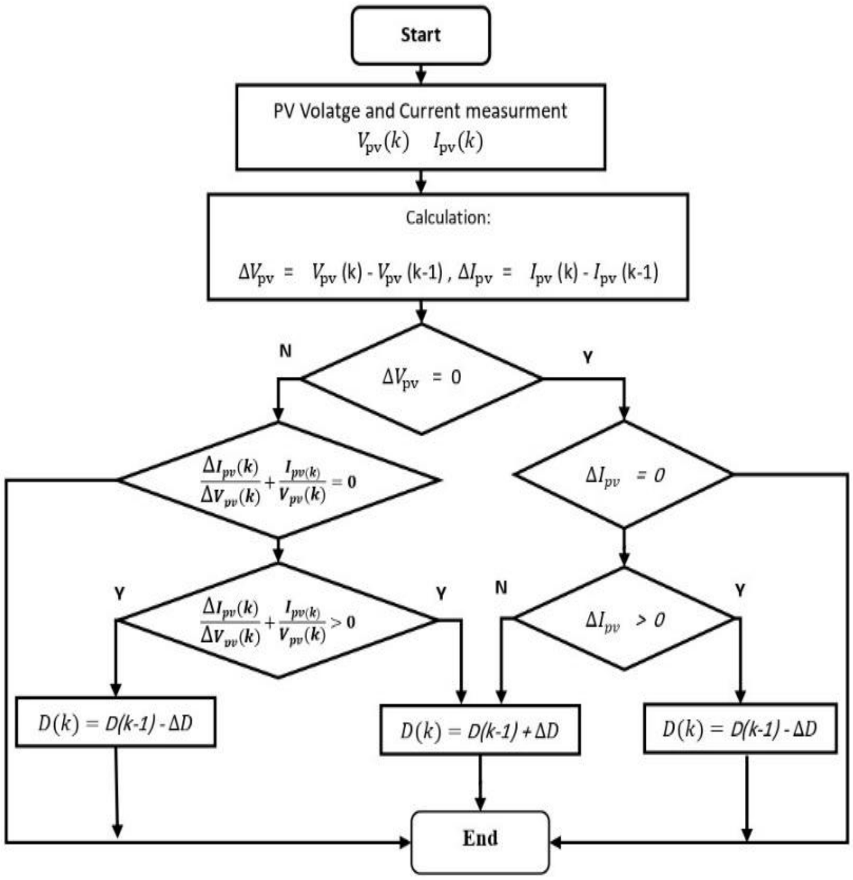

Fig. 10 Flow chart of IC algorithm (Abo-Sennah, El-Dabah and Mansour, 2021).

2.1.3. Fuzzy Logic Controller FLC

FLC can easily deal with the non-linearity conditions to reach maximum power from PV modules (Yilmaz, Kircay and Borekci, 2018). FLC can work in any weather conditions, whether high temperature or low irradiation or light (Sharma and Jain, 2015). The concept of work is attributed to the main equations below:

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad (11)$$

$$\Delta E = E(k) - E(k-1) \quad (12)$$

Where P(k), P(k–1) is the current power of the solar cell and at the previous cycle, respectively, V(k), V(k–1) is the output voltage from the solar cell, current and at the previous cycle, respectively, E(k), E(k–1) – current error and on the previous cycle, respectively. The derivative ΔP/ΔV makes it possible to determine on which side of the MPPT on the characteristic P(V) the system is currently located. Being in MPPT corresponds to ΔP/ΔV = 0. The rate of increase of the error makes it possible to determine in which direction the operating point is shifted along the curve of PV power figure. The output variable is the duty cycle D.

Fuzzy logic in our case study has two inputs E(K) as shown in Fig. 11, E(K-1) as presented in Fig. 12, and output D as in Fig.13.

Fuzzy logic as an internal approach has three stages; fuzzification, fuzzy inference, and defuzzification, there are fuzzy rules which link among these stages as explained in Fig. 14 (Dhanaraju, Srinu and Satyanarayana, 2015; Doubabi *et al.*, 2021).

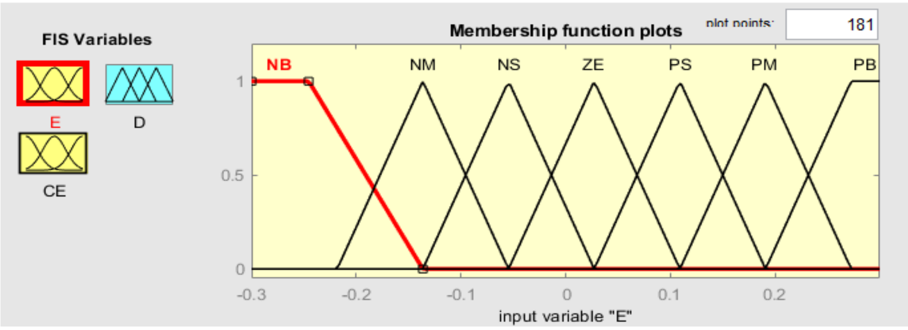

Fig. 11 Input variable “error”.

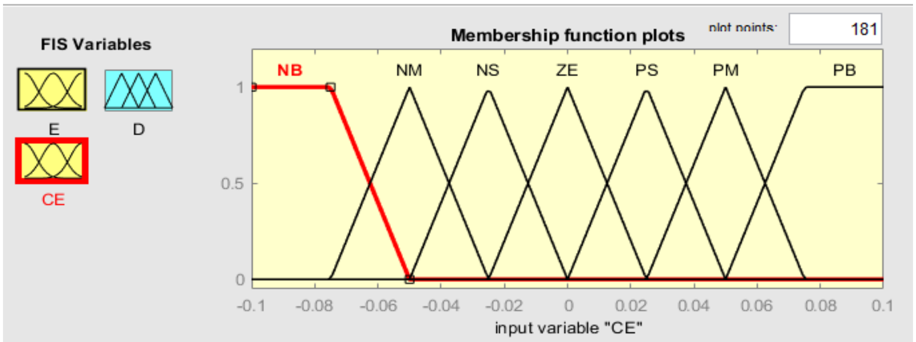

Fig. 12 Input variable "Error slew rate".

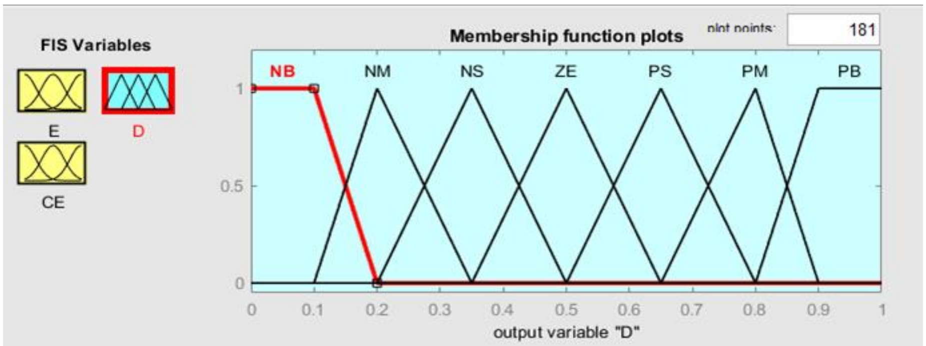

Fig. 13 Duty cycle.

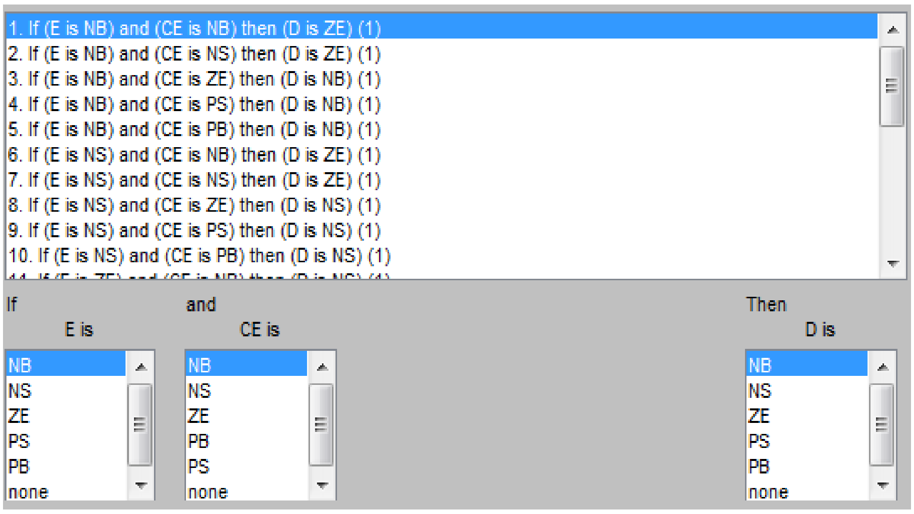

Fig. 14 Fuzzy rules.

3. RESULTS AND DISCUSSION

A PV system has been designed as shown in Fig. 4 in MATLAB/Simulink. The numerical values are given in Table 1, The proposed system consists of a unique PV panel 213 W, model 1Sollech 1STH-215-P, a DC-DC buck converter operates at 10 KHz to charge a battery 12V, and a PI controller is used to control the charge of battery. To operate the system of PV at the maximum power point, three MPPT methods P&O, IC, and FLC are employed. The optimum values of DC-DC parameters have been modified based on the try and error but it strongly depended on the equations 3, 4, 5 and 6.

Table 1. Numerical values used in the simulation design.

System	Parameter	Symbol	Value
SPV	Maximum power	P_m	213W
	Voltage at maximum power	$V_m = V_{in}$	29V
	Current at maximum power	$I_m = I_{in}$	7.35A
	Open circuit voltage	V_{oc}	36.3V
	Short circuit current	I_{sc}	7.84A
	Number of cells per module	N_{cell}	60
	Number of cells in series	N_s	1
	Number of cells in parallel	N_p	1
DC-DC converter	Switching frequency	f_{sw}	10KHz
	Output voltage	V_o	13.5V
	Output current	I_o	14.6A
	Input current ripple	ΔI_{in}	2% of I_{in}
	Input voltage ripple	ΔV_{in}	0.2% of V_{in}
	Output current ripple	ΔI_o	4% of I_o
	Output voltage ripple	ΔV_o	0.2% of V_o
	Input capacitor	C_{in}	750µF
	Output capacitor	C_o	750µF
	Inductor	L	1.2mH
	Load resistance	R_{load}	1.5Ω
Battery	Battery voltage	V_b	12V
	Rated capacity	–	50Ah
	Initial state of charge	SoC	45%
PI controller	Proportional gain	K_p	0.85
	Integral gain	K_i	10

A test signal (Fig. 15) for operating the system represents the irradiation, it has four varying stages where the values of irradiation change from 1000 to 700 w/m^2 at the period t=2 to 3 sec, then to 500 w/m^2 during the period 3-4 sec, and eventually return to 1000 w/m^2 during the period 3-4 sec. The purpose of that is to monitor the performance of the system, particularly during the transition period as well as comparison among the systems that used different three MPPT techniques P&O, IC and FLC. Fig. 16-21 are for the PV signals showing the power, current, and voltage of PV panel. Fig. 22, Fig. 23, and Fig. 24 are for the output signals of systems, while Fig. 25, and Fig. 26 are for the battery current and voltage respectively. Finally, Fig. 27 showed the charging signals for all the used techniques.

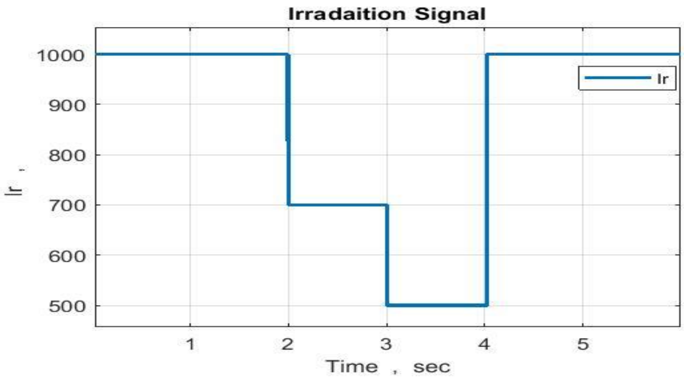

Fig. 15 Irradiation signal.

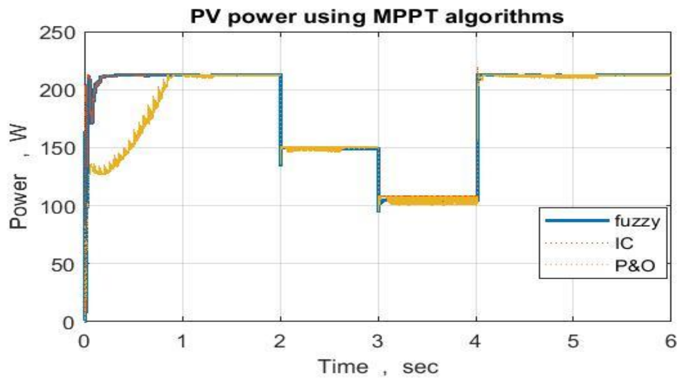

Fig. 16 Power of PV panel.

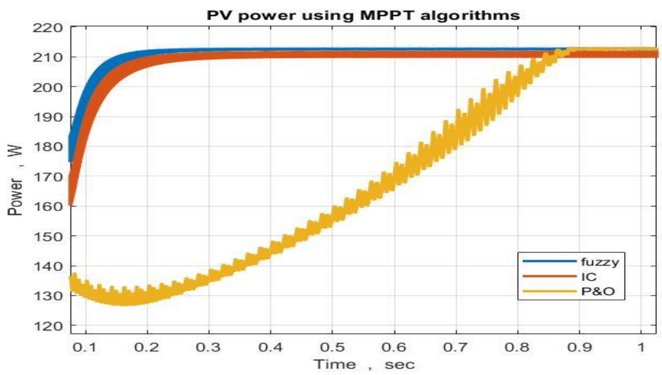

Fig. 17 Power of PV panel at settling time.

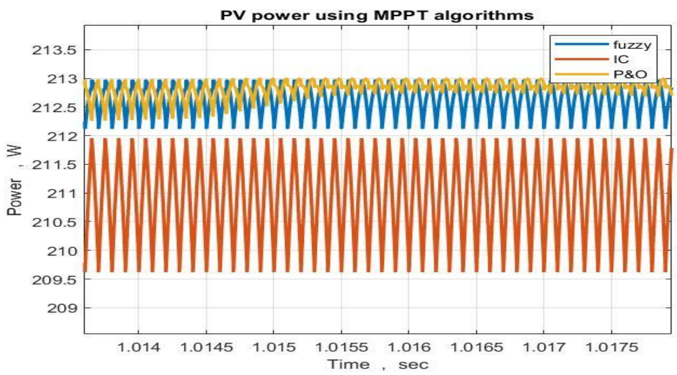

Fig. 18 Power ripple of PV panel.

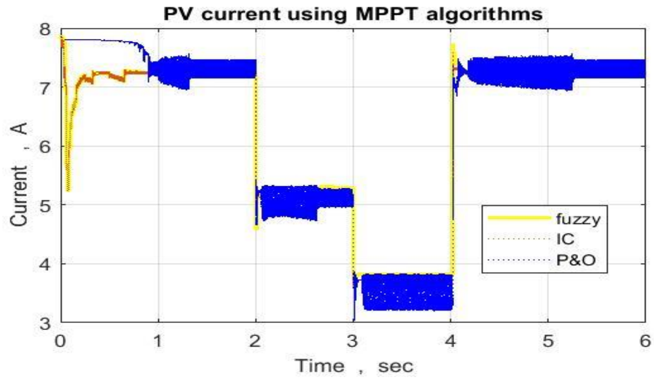

Fig. 19 Current of PV panel.

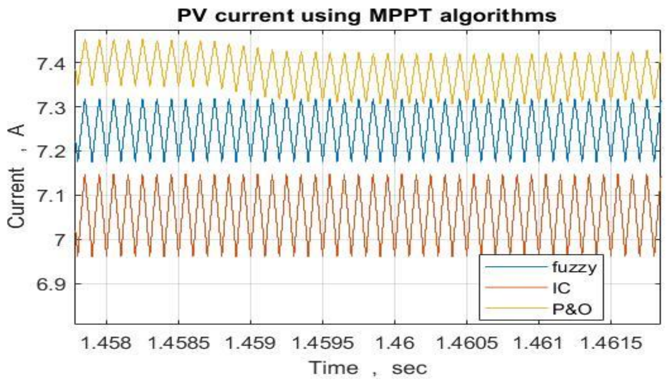

Fig. 20 Current ripple of PV panel.

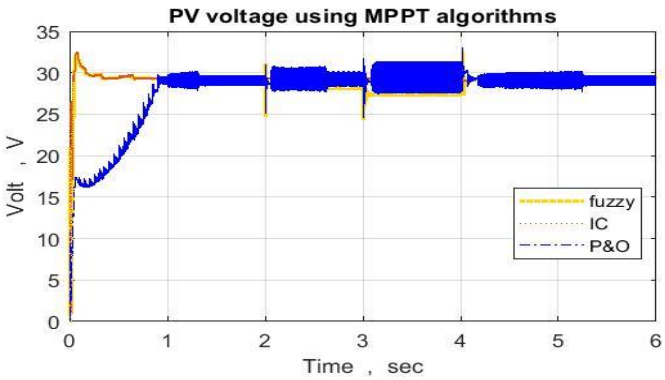

Fig. 21 Voltage of PV panel.

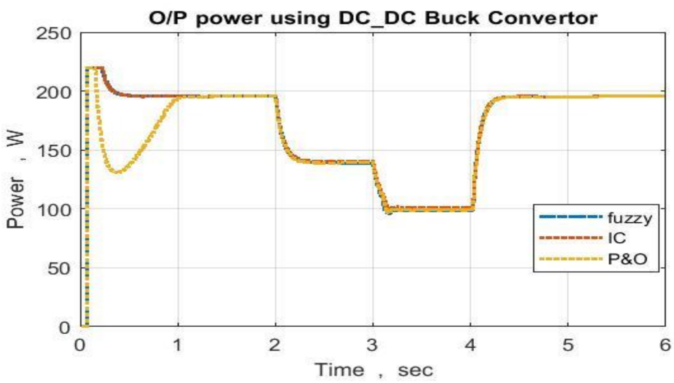

Fig. 22 System output power.

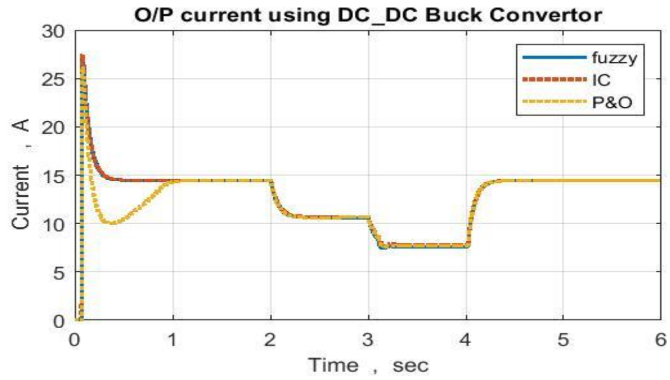

Fig. 23 System output current.

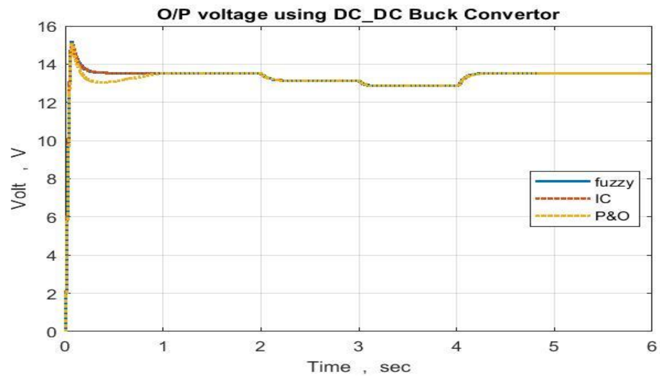

Fig. 24 Output voltage.

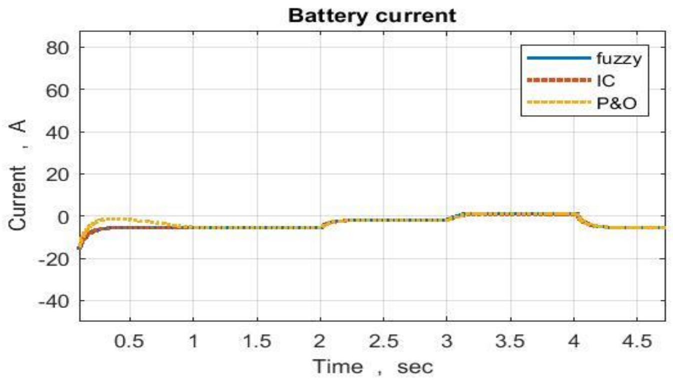

Fig. 25 Battery current.

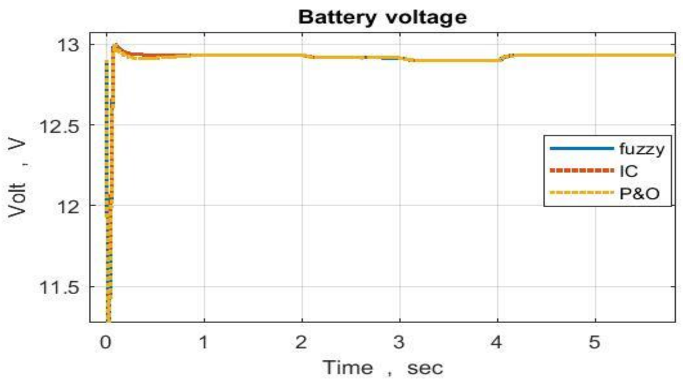

Fig. 26 Battery voltage.

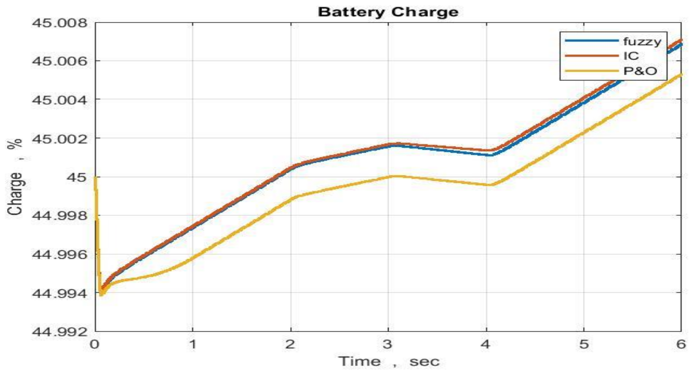

Fig. 27 Battery charge.

Perturb and Observe technique still suffer from the oscillation around the MPPT although some improvement was added to the algorithm particularly at the low irradiation values applied on the system. Fuzzy Logic and Incremental conductance techniques showed better results. The systems showed their performance that reach to 90-92 % for the all used techniques.

4. CONCLUSION

A system of PV 213 watt has been designed based on the new concepts and research, comparing of performance of all the techniques have been observed after applying four varying states of solar insolation. The modified techniques showed better performance than the old references approach. A Perturb and Observe is the simplest technique and does not very work well at low irradiation. The incremental conductance IC method has no complicated technique like P&O but gave a better result, a new algorithm gave a result very close to the behavior of FLC. The FLC showed the best result among all the used techniques but it is complicated. All the designed systems gave a fixed output voltage. A bi-directional battery charge is also designed to increase the life cycle of the battery and charging period, this approach will be helpful to decrease the operating of the battery for a long period but it compensates for the decrease of the required output voltage in the state of a lack of radiation applied on the system. Since there is no standard for designing a DC-DC converter with a unique PV panel or groups of them connected in series, parallel or series and parallel in one design, the equations of conventional DC-DC convertor do not give the optimum values of its parameters, that are attributed to varying of PV power from zero to maximum power of selected PV panel, hence in our study, the supplied power is changing from 0 to 213 watt, also the voltage is changing from 0 to Voc, so it leads to instability in switch gate signal D. Also, it is very clear that when connecting a PV system with the battery which consider an unstable load R, and this will lead to non-ideal results if compared with a fixed load. So, our parameter values for the DC-DC converter have been modified based on try and error. A study will give a good vision for future research.

5. REFERENCES

Abo-Sennah, M.A., El-Dabah, M.A. and Mansour, A.E.B. (2021) "Maximum power point tracking techniques for photovoltaic systems: A comparative study," *International Journal of Electrical and Computer Engineering*, 11(1), pp. 57–73. Available at: https://doi.org/10.11591/ijece.v11i1.pp57-73.

Al-Majidi, S.D., Abbod, M.F. and Al-Raweshidy, H.S. (2018) "A novel maximum power point tracking technique based on fuzzy logic for photovoltaic systems," *International Journal of Hydrogen Energy*, 43(31), pp. 14158–14171. Available at: https://doi.org/10.1016/j.ijhydene.2018.06.002.

Bendib, B., Belmili, H. and Krim, F. (2015a) "A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems," *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 637–648. Available at: https://doi.org/10.1016/j.rser.2015.02.009.

Dhanaraju, K., Srinu, I. and Satyanarayana, K. (2015) *Performance Improvement of Fuzzy PID Controller Based Process Control System, International Journal of Engineering and Advanced Technology (IJEAT)*.

Doubabi, H. *et al.* (2021) "High Performance MPPT based on TS Fuzzy–integral backstepping control for PV system under rapid varying irradiance—Experimental validation," *ISA transactions*, 118, pp. 247–259.

Haji, D. and Genc, N. (2018) "Fuzzy and PO Based MPPT Controllers under Different Conditions," in *7th International IEEE Conference on Renewable Energy Research and Applications, ICRERA 2018*. Institute of Electrical and Electronics Engineers Inc., pp. 649–655. Available at: https://doi.org/10.1109/ICRERA.2018.8566943.

Kchaou, A. *et al.* (2017) "Comparative study of different MPPT techniques for a stand-Alone PV system," in *2016 17th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering, STA 2016 - Proceedings*. Institute of Electrical and Electronics Engineers Inc., pp. 629–634. Available at: https://doi.org/10.1109/STA.2016.7952092.

Koutroulis, E. and Blaabjerg, F. (2012) "A new technique for tracking the global maximum power point of PV arrays operating under partial-shading conditions," *IEEE Journal of Photovoltaics*, 2(2), pp. 184–190. Available at: https://doi.org/10.1109/JPHOTOV.2012.2183578.

Narendiran, S. (2013) "Grid tie inverter and MPPT-A review," in *2013 International Conference on Circuits, Power and Computing Technologies (ICCPCT)*. IEEE, pp. 564–567.

Pathak, P.K. and Yadav, A.K. (2019a) "Design of battery charging circuit through intelligent MPPT using SPV system," *Solar Energy*, 178, pp. 79–89. Available at: https://doi.org/10.1016/j.solener.2018.12.018.

Pathak, P.K. and Yadav, A.K. (2019b) "Design of battery charging circuit through intelligent MPPT using SPV system," *Solar Energy*, 178, pp. 79–89. Available at: https://doi.org/10.1016/j.solener.2018.12.018.

Salman, S., Ai, X. and Wu, Z. (2018) "Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system," *Protection and Control of Modern Power Systems*, 3(1). Available at: https://doi.org/10.1186/s41601-018-0099-8.

Selvan, S. and Kumar, G. (2015) "Comparative study of perturb & observe and fuzzy logic control based MPPT algorithms," *International Journal of Advances in Engineering & Technology*, 7(6), p. 1649.

Sera, D. *et al.* (2006) "Improved MPPT method for rapidly changing environmental conditions," in *IEEE International Symposium on Industrial Electronics*, pp. 1420–1425. Available at: https://doi.org/10.1109/ISIE.2006.295680.

Sharma, C. and Jain, A. (2015) "Performance comparison of PID and fuzzy controllers in distributed MPPT," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 6(3), pp. 625–635.

Tahiri, F.E. *et al.* (2016) "Comparative study between two Maximum Power Point Tracking techniques for photovoltaic system," in *Proceedings of 2016 International Conference on Electrical and Information Technologies, ICEIT 2016*. Institute of Electrical and Electronics Engineers Inc., pp. 107–112. Available at: https://doi.org/10.1109/EITech.2016.7519571.

Yilmaz, U., Kircay, A. and Borekci, S. (2018) "PV system fuzzy logic MPPT method and PI control as a charge controller," *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 994–1001. Available at: https://doi.org/10.1016/j.rser.2017.08.048.

Zhou, S. *et al.* (2010) "A novel maximum power point tracking algorithms for stand-alone photovoltaic system," *International Journal of Control, Automation and Systems*, 8(6), pp. 1364–1371. Available at: https://doi.org/10.1007/s12555-010-0624-7.