Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 50 (2014) 383 – 392
Energy Procedia

The International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES14

Advanced Fuzzy MPPT Controller for a stand-alone PV system

B. Bendib[a,b], F. Krim[b], H. Belmili[a], M. F. Almi[a], S. Boulouma[a]*

[a]*Unité de développement des equipements solaires,UDES/Centre de développement des energies renouvelables,CDER,Bou-Ismail,42415,Algeria*
[b]*Département d'électronique ,Facultie de technologie,Université de Sétif, Route de Bejaia, 19000,Setif, Algeria*

Abstract

In this paper an intelligent method of maximum power point tracking (MPPT) using fuzzy logic control for stand-alone photovoltaic (PV) system has been presented. The PV system is composed of PV solar array, buck DC-DC converter, and MPPT controller. Fuzzy logic controller (FLC) is easy to implement, and does not need knowledge of the exact model of the system. Simulation results compared with those obtained by the conventional perturbation and observation (P&O) technique show the effectiveness of the fuzzy logic controller during steady-state and varying weather conditions.

Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
Keywords: Photovoltaic (PV) system; MPPT;fuzzy logic controller (FLC); P&O; DC-DC converter; Matlab/Simulink.

1. Introduction

Renewable energy from solar photovoltaic (PV) is the most ecological type of energy to use. It is based on a clean and efficient modern technology, which offers a glimmer of hope for a future based on sustainable and pollution-free technology. The importance of using renewable energy system, including solar photovoltaic (PV) has been attracted much these days, because the electricity demand is growing rapidly all over the world [1]. The solar energy is directly converted into electrical energy by solar PV module. Each type of PV module has its own specific characteristic corresponding to the surrounding condition such as irradiation, and temperature and this makes the tracking of maximum power point (MPP) a complicated problem. To overcome this problem, many maximum power point tracking (MPPT) control algorithms have been presented [2-7]. Fuzzy Logic

* Corresponding author. Tel.: +213-24-41-02-00; fax: +213-24-41-01-33.
*E-mail address:*bendib.b@udes.dz

Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
doi:10.1016/j.egypro.2014.06.046

(FL) has been used for tracking the MPP of PV modules because it has the advantages of being robust, relatively simple to design and does not require the knowledge of an exact model. In this paper, mathematical models of the PV module, DC-DC converter, are used in the study of FL based MPPT algorithm. The Paper is organized as follows: Section 2 discusses mathematical modeling of PV generator and DC-DC buck converter. Section 3 describes FL based MPPT controller; simulations run with Matlab/Simulink are presented in Section 4. Conclusions are presented in section 5.

2. Photovoltaic system modelling

The system studied in this paper is a stand-alone PV system within backup batteries. As shown in Fig.1, the system consists of a PV generator, battery bank and DC-DC Converter. The Fuzzy logic based MPPT control is performed by adjusting the duty ratio of the DC-DC converter.

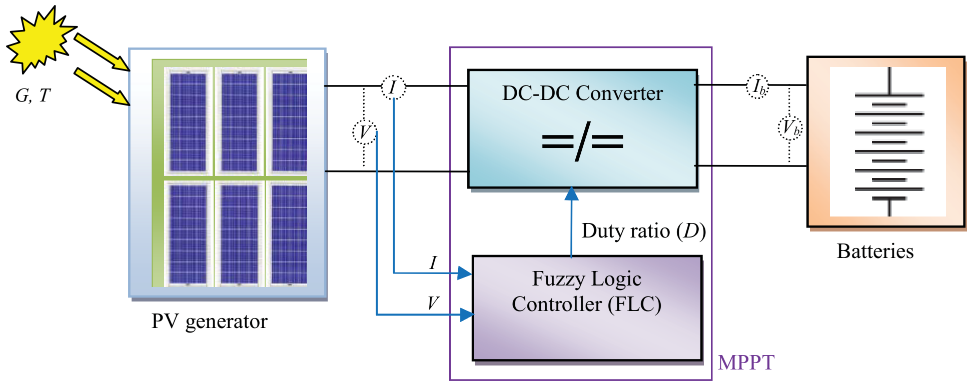


Fig. 1. Block diagram of the stand-alone PV system.

2.1. Photovoltaic generator model

The PV generator is formed by the combination of many PV cells connected in series and parallel fashion to provide desired value of output voltage and current. Solar cell consists of one diode parallel with a photo-current source. To have more accurate model series resistance and parallel resistance added to this combination [7].

Fig.2 (a) displays equivalent circuit of one-diode model of a PV solar cell. Therefore, the *I-V* characteristic equation of a PV array (arranged in N_P parallel and N_S series solar cell) can be described as,

$$I = N_p \cdot I_{ph} - N_p \cdot I_o \left[\exp\left(\frac{V + I \cdot (N_s / N_p) \cdot R_s}{N_s \cdot a \cdot V_T} \right) - 1 \right] - \frac{V + I \cdot (N_s / N_p) \cdot R_s}{(N_s / N_p) \cdot R_s} \tag{1}$$

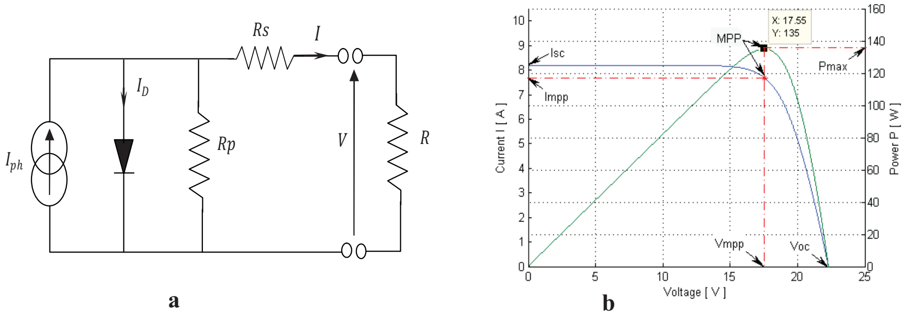
Where: I and V are the output current and output voltage of the PV array, I_o is the diode's reverse saturation current, *a:* is the diode ideality factor, *Rs* and *Rp* is the series and parallel resistance respectively. Other variables are defined as follows: V_T *(=k T/q)* is the thermal voltage of the PV cell, q is the electron charge ($1{,}602 \cdot 10^{-19}$ C), k is the Boltzmann constant ($1{,}380 \cdot 10^{-23}$ *J/K*), and T is the temperature of the p–n junction in Kelvin (*K*). I_{ph} is the generated photo-current, mainly depends on the insolation G and cell's temperature T, which is described as [8],

$$I_{ph} = \left[I_{ph\_STC} + K_i \left(T - T_{STC} \right) \right] \left(G / G_{STC} \right) \tag{2}$$

Where I_{Ph_STC} (in Ampere, A) is the generated photo-current at Standard Test Conditions (STC), T_{STC} (25°C) and G_{STC} (1000 W/m^2) are the temperature and the irradiance at STC. The constant K_i is the short circuit current coefficient, normally provided by the manufacturer. On the other hand, the cell's saturation current I_o varies with the cell temperature, which is described as [8],

$$I_o = \frac{I_{ph\_STC} + K_i\left(T - T_{STC}\right)}{\exp\left(\left(V_{oc\_STC} + K_v\left(T - T_{STC}\right)\right)/a \cdot V_T\right) - 1} \tag{3}$$

Where $V_{oc,STC}$ (in Volt, V) is the open circuit voltage at STC; Kv is the open circuit voltage coefficient, these values are available from the datasheet [9]. In this paper, the Suntech STP135-12/Tb PV module is used for a Matlab simulation model. The module is made of 36 multi-crystalline silicon solar cells in series and provides 135 W of nominal maximum power. The PV module specifications are listed in Table 1 [9].



a b

Fig. 2. (a) Electrical circuit model of PV solar cell; (b) *I–V* and *P–V* Characteristics of a PV module under STC conditions.

Using the PV generator model given by previous equations, and the electrical specification listed in Table 1, current–voltage (*I-V)* and power–voltage (*P-V)* characteristic curves for different temperature and insolation levels can be plotted. Fig.2 (b) shows the *I–V* and *P–V* characteristics of a PV module under STC conditions of 25°C temperature and 1000 W/m^2 of insolation. There is a unique point on the *P–V* curve, known as the maximum power point (MPP), in which at this point the solar module is said to operate at maximum efficiency and produces its maximum output power (*Pmax*) correspondent to a specific current (*Impp*) and voltage (*Vmpp*). This point also changes with environmental conditions of temperature and insolation as shown in fig.3. The PV module output current (*I*) and power (*P*) are greatly influenced by the change in radiation *G*, whereas the output voltage *V* stays approximately constant (fig.3.a). In contrast, for an increasing temperature one can see that the voltage decreases widely while the current remains unchanged (fig.3.b).

Table 1. Electrical characteristics data of PV module.

Electrical characteristics	Values
Open-circuit voltage (Voc)	22.3 V
Short-circuit current (Isc)	8.20 A
Optimum operating voltage (Vmpp)	17.5 V
Optimum operating current (Impp)	7.71 A
Maximum power at STC (Pmax)	135 W
Current temperature coefficient of Isc	(0.055±0.01) %/K
Voltage temperature coefficient of Voc	-(75±10) mV/K

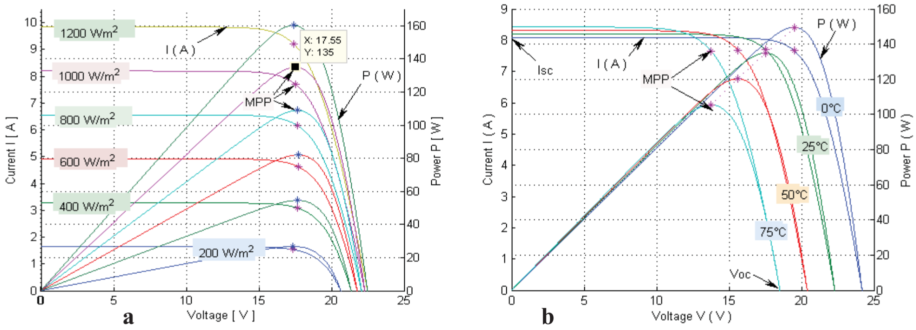


Fig. 3. *I–V* and *P–V* characteristics of a PV module: (a) for various values of irradiance at a temperature of 25 °C, (b) for various values of temperature at irradiance of 1000 W/m^2..

2.2. DC-DC converter

In order to always ensure the operation point on the maximum power point, or close to it, specific circuit, called Maximum Power Point Tracker (MPPT), is employed. Usually, the MPPT is achieved by interposing a power converter (DC-DC converter) between the PV generator and the load (battery), thus, acting on the converter duty cycle (D) it is possible to guarantee the operation point as being the MPP [10]. Fig. 4 shows the circuit of the buck converter, whose output voltage (V_b) is less than or equal to the input voltage V_i (PV generator voltage).

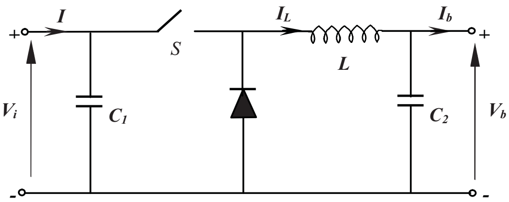


Fig. 4. The buck DC-DC converter circuit.

The switch S operates at a high frequency to produce a chopped output voltage. This converter is suitable for use when the array voltage is high and the battery voltage is low. The power flow is controlled by adjusting the on/off duty cycle of the switching [11]. The average output voltage is given by equation (4), [12].

$$\frac{V_b}{V_i} = D \tag{4}$$

The buck converter can be used to drive a low voltage load from a high voltage PV array, and it can operate efficiently at any insolation level. Therefore, the utilization of the buck converter in PV applications, which contain lower voltage batteries, is highly recommendable [13]. The dynamic model of the used buck converter (fig.4) can be derived as,

$$\frac{d}{dt}\begin{bmatrix} V_i \\ i_L \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ \frac{D}{L} & 0 \end{bmatrix}\begin{bmatrix} V_i \\ i_L \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} & 0 & \frac{-D}{C_2} \\ 0 & \frac{-1}{L} & 0 \end{bmatrix}\begin{bmatrix} I \\ V_b \\ I_b \end{bmatrix} \tag{5}$$

3. Fuzzy logic controller for MPPT

Fuzzy logic or fuzzy set theory is a new method of controlling the MPPT in obtaining the peak power point [14]. Typical fuzzy logic based MPPT controller includes three basic components, fuzzification module, inference engine, and defuzzification module [15]; as shown in fig. 5.

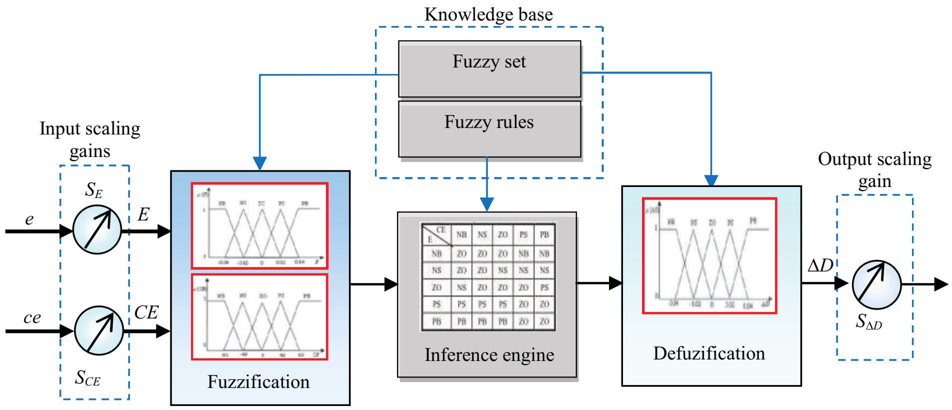


Fig. 5. Structure of fuzzy logic controller.

3.1. Fuzzification

The fuzzification makes it possible to pass from the real variables to fuzzy variables. The actual voltage (V) and current (I) of PV generator can be measured continuously and the power can be calculated ($P = V \times I$). The control is determined on the basis of satisfaction of two criteria relating to two input variables of proposed controller, namely error E (which represents the slope of P-I characteristic) and change of this error (CE), at a sampling instant k [14]. The variable E and CE are expressed as follows,

$$E(k) = \frac{P(k) - P(k-1)}{I(k) - I(k-1)} \tag{6}$$

$$CE(k) = E(k) - E(k-1) \tag{7}$$

Where $P(k)$ and $I(k)$ are the power and current of the PV generator, respectively. Therefore, the input $E(k)$ shows if the operating point at the instant k is located on the left or on the right of the MPP on the P-I characteristic, while the input $CE(k)$ expresses the displacement direction of this point . The change in duty ratio (ΔD) of the DC-DC converter is used as the output of proposed controller. Therefore, the control is done by changing this duty ratio according to the slope $E(k)$ in order to bring back the operation point on the optimal point where the slope is zero.

As shown in fig.5, the input variables of the fuzzy controller (E, CE) are derived from the actual signals (e, ce) by multiplying with the corresponding scale gains (S_E, S_{CE}), and then converted to the linguistic variables such as PB (positive big), PS (positive small), Z0 (zero), NS (negative small), NB (negative big) using basic fuzzy subset. Fig.6 shows the membership grades of five basic fuzzy subsets for input and output variables.

3.2. Inference engine

The inference engine applies the rules to the fuzzy inputs (that were generated from the fuzzification process) to determine the fuzzy outputs. Therefore, before the rules can be evaluated, the crisp input values must be fuzzified to obtain the corresponding linguistic values (that are necessary to determine the active or fired rules) and the degree to which each part of the antecedent has been satisfied for each rule [16]. Table.2 shows the rule table of fuzzy controller, where all the entries of the matrix are fuzzy sets of error (*E*), change of error (*CE*) and change of duty ratio (ΔD) to the converter.

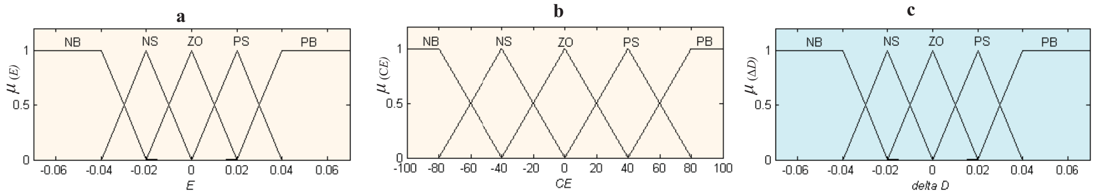


Fig.6. Membership functions for: (a) Input *E*, (b) Input *CE*, (c) Output ΔD (delta *D*).

Table.2. Fuzzy rules

E	*CE*				
	NB	NS	ZO	PS	PB
NB	ZO	ZO	NB	NB	NB
NS	ZO	ZO	NS	NS	NS
ZO	NS	ZO	ZO	ZO	PS
PS	PS	PS	PS	ZO	ZO
PB	PB	PB	PB	ZO	ZO

IF *E* is PB AND *CE* is NB THEN ΔD is PB

The 25 control fuzzy rules included in Table.2 can be presented in *3-dimensions (3-D)* graph as shown in fig.7 (a). These rules are employed for the controlling of the DC-DC buck converter such as the MPP of the PV generator is reached. As shown in the Table 2, the main idea of the rules is to bring operating point to the MPP by increasing or decreasing the duty ratio depending on the position of the operating point from the MPP. If the operating point is distant from the MPP, the duty ratio will be increased or decreased largely. Fig.7(b) demonstrates an example of control rule: IF *E* is PB AND *CE* is NB THEN ΔD is PB. This implies that if operating point is distant from MPP towards left hand side and the change of slope in *P-I* characteristic is big in the opposite direction, then the duty ratio is largely increased.

In general the fuzzy control uses one of the following methods: *Max-Min, Max-Prod*, *Somme-Prod* inference technique. In our case we used the inference method of Mamdani [17], which is the *Max-Min* fuzzy combination.

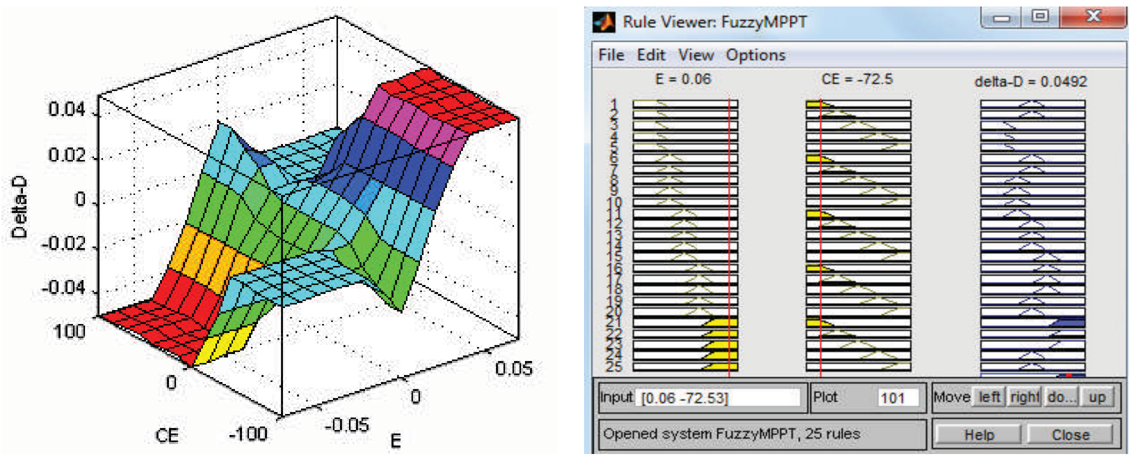


Fig.7.(a): The overview of control rules,(b): Rule viewer in Matlab windows of fuzzy logic controller.

3.3. Defuzzification

It was seen that the inference methods provide a function for the resulting membership variable; it thus acts of fuzzy information. Being given that converter DC-DC requires a precise control signal D at its entry it is necessary to envisage a transformation of this fuzzy information into deterministic information, this transformation is called defuzzification. Defuzzification can be performed normally by two algorithms: Center of Area (COA) and the Max Criterion Method (MCM). The most used defuzzification method is that of the determination of the centre of gravity (COA) of final combined fuzzy set. The final combined fuzzy set is defined by the union of all rule output fuzzy set using the maximum aggregation method [17]. For a sampled data representation, the center of gravity (ΔD) is computed point-wise by,

$$\Delta D = \frac{\sum_{j=1}^{n} \mu\left(\Delta D_j\right) \cdot \Delta D_j}{\sum_{j=1}^{n} \mu\left(\Delta D_j\right)} \tag{8}$$

Once the fuzzy controller output, which is the change of duty ratio ΔD (k), is defuzzified by (8) and scaled by the gain $S_{\Delta D}$, it is converted to the actual duty ratio D (k) by:

$$D(k) = D(k-1) + S_{\Delta D} \cdot \Delta D(k) \tag{9}$$

4. Simulation results

Fig. 8 shows the developed PV model system consisting of PV array, DC-DC buck converter with an MPPT controller connected to a load, as implemented in Matlab/simulink environment. The PV module considered in the simulation is the Suntech STP135-12/Tb in which the data of the PV module is shown in Table 1 [9]. The PV array with a capacity of 810 W consists of 6 PV modules connected in series. A buck DC-DC converter is used to convert the high DC input voltage (105-V) to the 48-V battery [18] voltage level. Fuzzy logic toolbox of Simulink is used to achieve the FLC [19]. Then, the fuzzy logic (FL) based MPPT controller is simulated and compared with the conventional perturbation and observation (P&O) based MPPT controller.

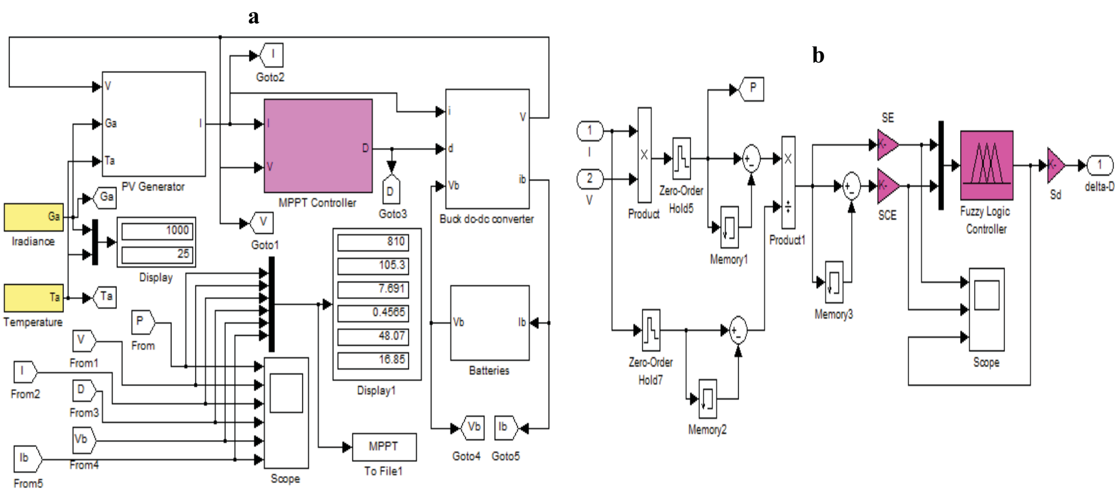
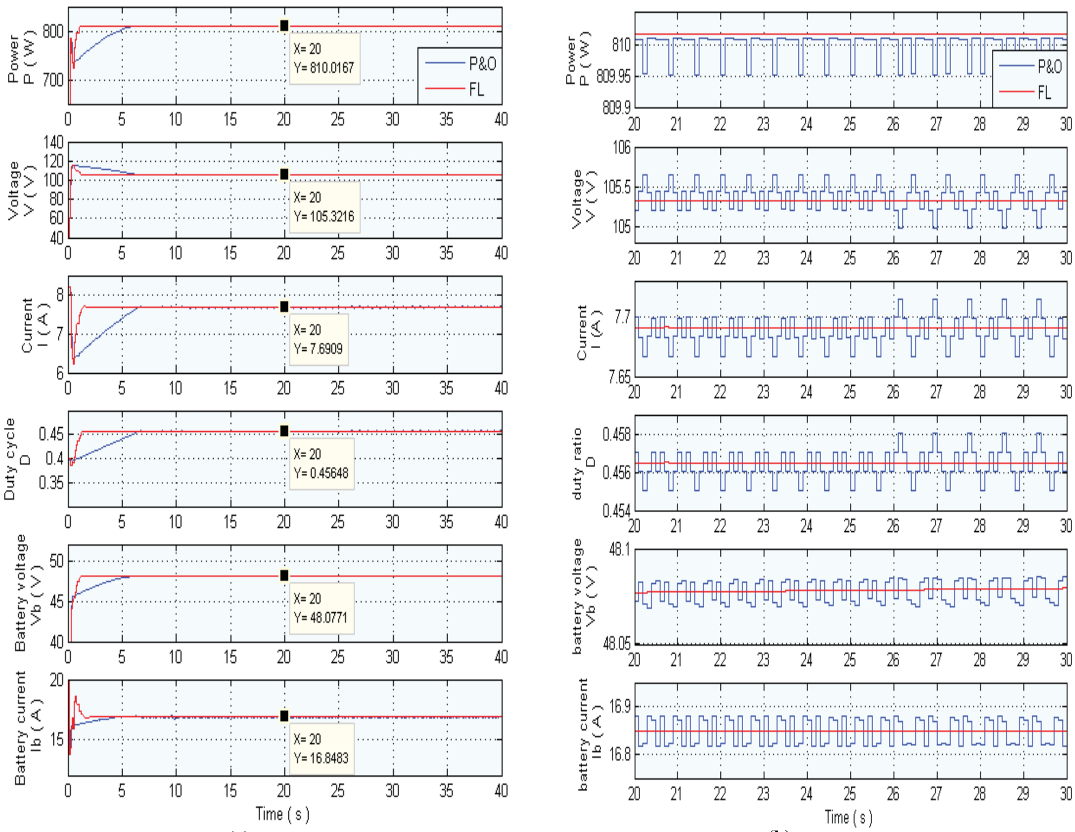


Fig.8.(a) : Simulink® implementation of the stand-alone PV system,(b): Block diagram of fuzzy MPPT algorithm.

Fig.9 shows, by way of comparison, the simulation results of the PV generator output power ,operating voltage, operating current, and the duty ratio *D* using a buck converter under standard test conditions (STC) between FL based MPPT and conventional P&O MPPT. It has seen clearly how FL based MPPT controller reduced the response time of photovoltaic system. It has observed obviously that the system with P&O MPPT has a loss of energy. Fig.9 (b) has detailed results of fig.9 (a). It has been seen clearly continues oscillation of operation point for the P&O conventional technique. It is a result of the continuous perturbation of the operating voltage in order to reach the MPP. Whereas this phenomenon of oscillation it doesn't observed in FL based MPPT technique, where signals of power, voltage, current, and duty ratio remain almost constant. This has as result a power losses reduction.

A rapid increase in irradiance from 1000W/m^2 to 1200W/m^2 within a time period of 2 seconds was simulated (Fig.10). The cell temperature was kept at a constant value of 25°C. Under these operating conditions the FL based MPPT method is more significant. Fig.10 shows how the power output of the FL based MPPT increases linearly, whereas the conventional P&O MPPT technique experiences a vast deviation from the MPP.

A rapid increase in cell temperature from 25°C to 50°C within a time period of 2 seconds was simulated (Fig.11). The irradiation was kept at a constant value of 1000W/m^2. Fig.11 shows how the power output of the tow MPPT (FL and P&O) decrease linearly, but the conventional P&O MPPT technique experiences a low deviation from the MPP.



(a) (b)

Fig.9. (a) Comparison of two MPPT (FL and P&O) signals ;(b) Comparison of detailed signals MPPT at a frequency of 10 Hz (STC).

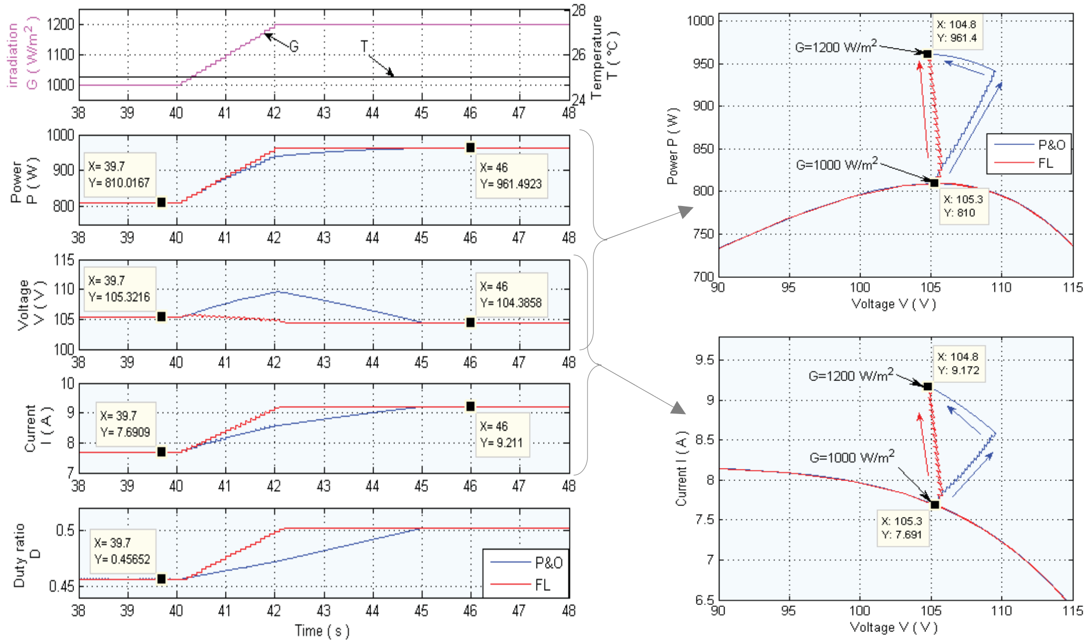


Fig.10 .Signals of the tow MPPT (FL and P&O) techniques under rapidly increasing irradiation.

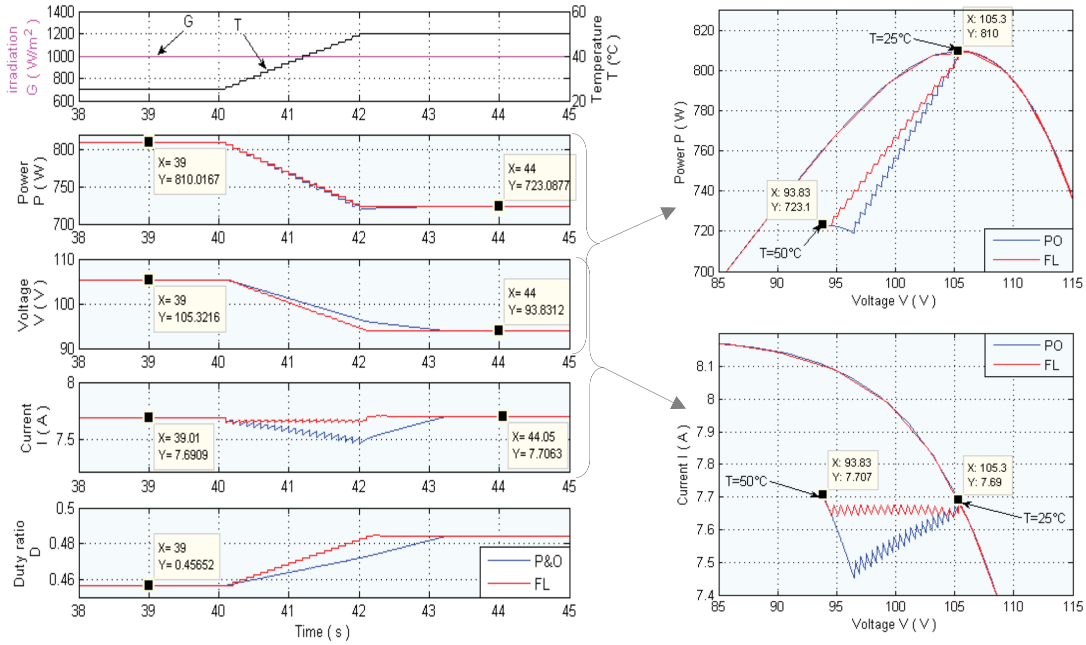


Fig.11 Signals of the tow MPPT (FL and P&O) techniques under rapidly increasing temperature.

5. Conclusion

The PV array has a maximum power point (MPP) which varies with the change of solar irradiation and cell temperature. In this paper, Fuzzy logic (FL) based maximum power point tracking (MPPT) controller is developed to identify the MPP, subsequently regulate the PV array to operate at that particular operating voltage. The FL controller presented and implemented in Matlab-Simulink environment, provides a better response than a conventional P&O controller in terms of the maximum power tracking performance.

References

[1] Seddik M , Zouggar S, Ouchbel T, Oukili M, Rabhi A, Aziz A, Elhafyani ML. A stand-alone system energy hybrid combining wind and photovoltaic with voltage ontrol (feedback loop voltage). *International Renewable Energy Congress*, Tunisia, 2010; pp: 227-232 .

[2] Salas V, Olias E, Barrado A, Lazaro A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Sol Energ Mat Sol C*, 2006 ; 90(11):1555-78.

[3] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE T Energy Conver*, 2007; 22 (2):439-49.

[4] Zegaoui A, Aillerie M, Petit P, Sawicki JP, Jaafar A, Salame C, Charles JP. Comparison of two common maximum power point trackers by simulating of PV generators. *Energy Procedia*, 2011;6:678-87.

[5] Bhatnagar P, Nema RK. Maximum power point tracking control techniques: State-of-the-art in photovoltaic applications. *Renew Sust Energ Rev*, 2013; 23:224-41.

[6] Rekioua D, Achour AY, Rekioua T. Tracking power photovoltaic system with sliding mode control strategy. *Energy Procedia*, 2013; 36:219-30.

[7] Mirbagheri SZ, Mekhilef S, Mirhassani SM. MPPT with Inc.Cond method using conventional interleaved boost converter. *Energy Procedia*, 2013 ; 42 :24-32 .

[8] Villalva MG, Gazoli JR. Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE T Power Electr*, 2009; 24 (5):1198-1208.

[9] Suntech STP135-12/Tb –135W. Multi-crystalline photovoltaic module datasheet. 2001.

[10] Coelho RF, Concer FM, Martins D. A simplified analysis of DC-DC converters applied as maximum power point tracker in photovoltaic systems. *2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems*, 2010; pp.29-34.

[11] Hua C, Shen C. Control of DC/DC converters for solar energy system with maximum power tracking. *23rd Int Conference on Industrial Electronics, Control and Instrumentation (IECON 97)*, 9-14 Nov 1997; pp.827-32.

[12] Erickson RW, Maksimovic D. Fundamentals of power electronics. 2nd edition, New York: Kluwer Academic Publishers; 2001.

[13] Abd El-Shafy AN. An effective and safe charging algorithm for lead-acid batteries in PV systems. *Int J Energy Res*, 2011; 35:733-40.

[14] Won CY, Kim DH, Kim SC, Kim WS, Kim HS. A New maximum power point tracker of photovoltaic arrays using fuzzy controller. *Proceedings of the IEEE Power Elec. Specialists Conference, red Stick*, the USA, 1994, p.396-403.

[15] Subiyanto S, Mohamed A, Hannan MA. Intelligent maximum power point tracking for PV system using Hopfield neural network optimized fuzzy logic controller . *Energy and Buildings*, 2012; 51: 29-38.

[16] Abd El-Shafy AN, Fahmy FH, Abou El-Zahab EM. Maximum-power operation of a stand-alone PV system using fuzzy logic control . *Int J Numer Model*, 2002;15:385-98.

[17] Mamdani EH, Assilian S. An experiment in linguistic synthesis with a fuzzy logic controller. *Int.J Man-Machine Studies*,1975; 7(1):1-13.

[18] Salameh ZM, Casacca MA, Lynch WA. A mathematical model for lead-acid batteries. *IEEE T Energy Conver*, 1992;7(1):93-98.

[19] http:/ /www.mathworks.com.