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Maximum Power Point Tracker using Fuzzy Control for Photovoltaic System

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Abstract— **Maximum power point tracker (MPPT) is used in photovoltaic (PV) systems to maximize the output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. We have developed a new MPPT system consisting of a boost DC/DC converter, which is controlled by a PI fuzzy controller by action on duty cycle. The knowledge-base of this PI controller is exposed. Computed values of the maximum power point (MPP) and Simulation results are provided under the same atmospheric condition. Simulation show that the operating point of PV panel corresponds to the optimum computed according theory. Thus, the system gives good results, and the PI regulator operates correctly on a large field.**

Keywords— **Photovoltaic (PV) Systems, Maximum Power Point (MPP), DC/DC converter, Fuzzy Logic Control (FLC).**

I. INTRODUCTION

Photovoltaic (PV) energy has increased interest in electrical power applications. It is crucial to operate the PV energy conversion systems near the maximum power point to increase the efficiency.
However, the nonlinear nature of PV system is apparent from Figures 1 and 2 (figures plotted by Matlab Software). The power of the PV array depends on the operating voltage. In addition, the maximum power operating point varies with irradiation level and temperature. Therefore, tracking the maximum power point is a complicated problem. To overcome these problems, many tracking control strategies have been proposed such as regulation by PI regulator using a small sine signal [1], perturb and observe [2]-[3], incremental conductance [4], parasitic capacitance [5], constant voltage [6], neural network [7]-[9]. These strategies have some disadvantages such as high cost and complexity. On the other hand, fuzzy logic or fuzzy set theory has received attention of a number of researchers in the area of power electronics. The fuzzy logic control (FLC) is somewhat easy to implement because it does not need the mathematical model of a system. Many MPPT use the fuzzy controllers for maximizing the output power of PV system such as those described in [10] and [11]. Nevertheless, the use of computer in its circuit controller, for calculation, makes the PV system very expensive.

In this paper, a new method using PI fuzzy controller has been applied to step-up maximum power point tracker for PV arrays. This method requires only the linguistic control rules for reaching the maximum power point; the mathematical model is not required. Therefore, the implementation of this control method is so easy. However, these fuzzy rules were constructed based on the characteristics of steady state conditions. The solar irradiation and the cells temperature vary with time so that the fuzzy control rules should take account of these situations. So, our proposed system is shown in figure 3. A boost DC/DC converter is used to interface the PV output to the resistive load and to track the maximum power point of the PV array. The control circuit must keep ($\partial P/\partial V$) equal zero. That is possible with action on the duty cycle α (0≤α≤1) according the solar irradiation λ and the temperature *T*. Duty cycle is a signal produced by a PI fuzzy controller. The input variables of PI fuzzy controller are error (e) and change of error (de). An analogue controllers proposed in [12]-[14] have used a PI regulator in controller circuit. In these methods a small signal modelling is used for synthesizing the PI regulator. This regulator must keep $(\partial P/\partial V)$ equals zero.

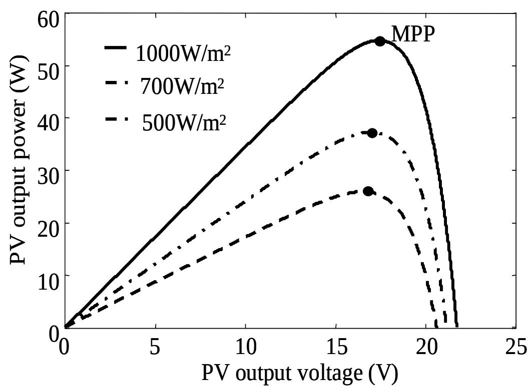


Fig. 1. Photovoltaic characteristics for three irradiations level

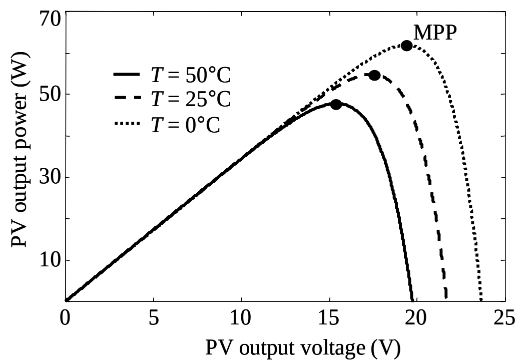


Fig. 2. P-V characteristics for three temperatures level

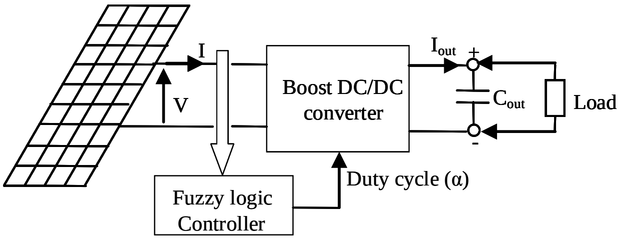


Fig. 3. Block scheme of the proposed photovoltaic system

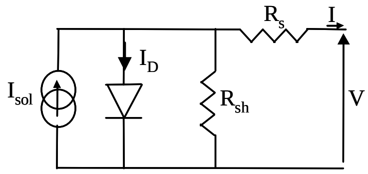


Fig. 4. Equivalent circuit of a PV array module

The organization of this paper is described as follows: the theoretical study is presented in section II. The PV module characteristics and the simulation procedure are presented in sections II and IV respectively. The theoretical and simulated results are given in section V. Finally, the conclusion is presented in section VI.

II. THEORETICAL STUDY

A. Optimal operating

The solar array characteristics significantly influence the design of the converter and the control system, so the PV characteristics will be briefly reviewed here. The solar array is a nonlinear device and can be represented as a current source model, as shown in figure 4.

The traditional I-V characteristics of a solar array are given by the following equation:

$$I = I_{sol} - I_{os}\left\{\exp\left[\frac{q}{\gamma kT}\left(V + R_s I\right)\right] - 1\right\} - \frac{V + R_s I}{R_{sh}} \quad (1)$$

Where I and V are the output current and voltage of the solar array; I_{sol} is the generated current under a given irradiation; I_{sat} is the reverse saturation current; q is the electron charge; k is the Boltzmann constant; γ is the ideality factor for a P-N junction; T is the array temperature; R_s and R_{sh} are the intrinsic series and shunt resistances of the solar array.

The saturation current of the solar array varies with temperature according to the following equations:

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{GO}}{\beta k}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (2)$$

$$I_{sol} = \left[I_{SC} + K_I\left(T - 298.18\right)\right]\frac{\lambda}{1000} \quad (3)$$

where T_r is the reference temperature; I_{or} is the saturation current at T_r; E_{GO} is the band-gap energy of the semiconductor used in the solar array; β is also an ideality factor; I_{sc} is the short circuit current at 25 °C; K_I is the short-circuit current temperature coefficient and λ is the irradiation in W/m^2.

The output power of PV panel is P = VI, at optimal point, we have:

$$\frac{\partial P}{\partial V} = I + V\frac{\partial I}{\partial V} = 0 \Rightarrow \frac{\partial I}{\partial V} = -\frac{I}{V} \quad (4)$$

Hence:

$$I = \left(V - R_s I\right)\left\{I_{sat} A \exp\left[A\left(V + R_s I\right)\right] + \frac{1}{R_{sh}}\right\} \quad (5)$$

Where $A = \frac{q}{\gamma k T N_{cell}}$ and N_{cell} is the number of series cells in the module.

All of the constants in these equations can be determined by using the manufacturer ratings under standard operating conditions (irradiance λ = 1000W/m^2, AM1.5, solar spectrum and cell temperature T = 25 °C) of the PV array.

B. Boost converter study

1) *Inductance and capacitors values*: Value L of the inductor required to ensure the converter operating in the continuous conduction mode is L = 1 mH, and, the input and the output capacitor value are respectively 4.7 µF and 47 µF [15]-[16].

2) *Boost converter model:* If the chopping frequency is sufficiently higher than the system characteristic frequencies, we can replace the converter with an equivalent continuous model as shown in figures 6 and 7. We will consider, for that, the mean values, over the chopping period, of the electric quantities. The transistor had been replaced by a voltage source whose value equals its mean voltage. At the same, the diode hade been replaced by a current source. Thus:

$$V_T = (1-\alpha)V_{out} \tag{6}$$

$$I_D = (1-\alpha)I_L \tag{7}$$

Where I_L is the mean value of inductance current and V_{out} is the output voltage of photovoltaic system.
We deduce from the continuous model equations:

$$C_{in}\frac{dV}{dt} = I - I_L \tag{8}$$

$$L\frac{dI_L}{dt} = V - V_T \tag{9}$$

$$C_{out}\frac{dV_{out}}{dt} = I_D - I_{out} \tag{10}$$

$$V_{out} = R_{Load}I_{out} \tag{11}$$

At optimal operating point, we have:

$$\begin{cases} I_m = I_{Lm} \\ V_m = (1-\alpha_m)V_{outm} \\ I_{outm} = (1-\alpha_m)I_{Lm} \\ \alpha_m = 1-\sqrt{\dfrac{R_m}{R_{Load}}} \end{cases} \tag{12}$$

Where I_m, I_{Lm}, I_{outm}, V_m, α_m are respectively the optimal values of I, I_L, I_{out}, V and α, and $R_m = V_m/I_m$.
The expression of the optimum value α_m of duty cycle (α<1) show that the optimum value R_m of the output resistance of PV panel must be inferior, at time, that the resistance load R_{Load}, so:

$$R_{Load} \rangle R_m$$

(13)

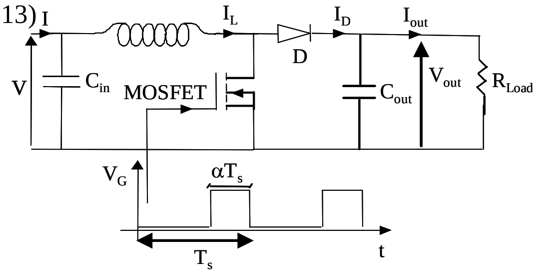


Fig. 6. Boost DC/DC converter

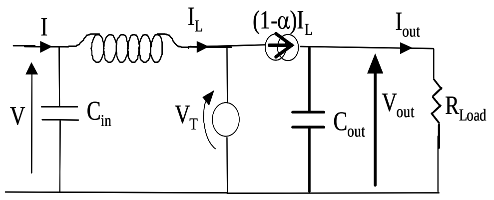


Fig. 7. Boost converter "mean" equivalent circuit.

C. Fuzzy knowledge – base controller

The fuzzy knowledge-base controller is one part of Fuzzy Logic Control (FLC) which is composed of three main parts as shown in figure 8: fuzzification, inference engine and defuzzification.

1) *Fuzzification:* Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big). The partition of fuzzy subsets and the shape of membership function, which can adapt shape up to appropriate system, are shown in figure. 9. The value of input error (e) and change of error (de) are normalized by an input scaling factor. In this system the input scaling factor has been designed such that input values are between -1 and 1. The triangular shape of the membership function of this arrangement presumes that for any particular input there is only one dominant fuzzy subset. The input error (e) for the PI fuzzy logic controller can be calculated from the maximum power point as follows:

$$E(k) = \frac{\Delta I}{\Delta V} + \frac{I}{V} = \frac{1}{V}\frac{\Delta P}{\Delta V}$$

(14)

Where I is the output current from PV array, ΔI is the change of output current, I(k) – I(k-1), V is output voltage from PV array and ΔV is change of output voltage, V(k) – V(k-1).

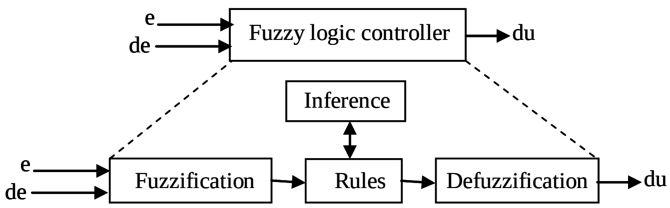


Fig. 8. Internal structure of fuzzy logic controller.

2) Inference method

The composition operation is the method by which a control output is generated. Several composition methods such as Max-Min and Max-Dot have been proposed in the literature. The commonly used method, Max-Min, is used in this paper. The output membership function of each rule is given by the Min (minimum) operator and Max (maximum) operator. Table I shows rule base of the FLC.

3) Defuzzifcation

As a plant usually requires a non fuzzy value of control, a defuzzification stage is needed. Defuzification of this system is the height method which is both simple and fast, and is in a system of m rules given by:

$$du = \left(\frac{\sum_{k=1}^{m} c(k) * w_k}{\sum_{k=1}^{m} w_k} \right)$$

(15)

Where "du" is the change of control output, c(k) is the peak value of each output and w_k is height of rule k.

TABLE I
RULE BASE OF FUZZY LOGIC CONTROLLER

Error (e)	Change or error (de)						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

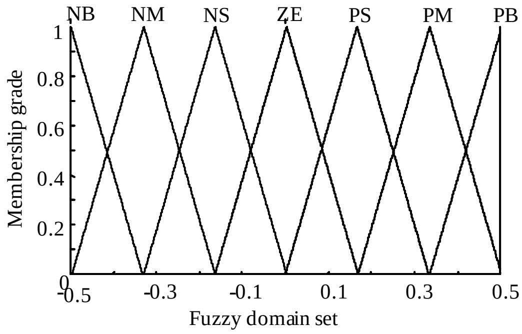


Fig .9. Fuzzy logic control membership function for input and output

III. PV ARRAY CHARACTERISTICS

The PV array considered in this paper is the SM55. It has 36 series connected mono-crystalline cells. The array's electrical characteristics are: open-circuit voltage V_{oc} = 21.7V, short-circuit current I_{sc} = 3.45A, maximum power current I_m=3.15A, maximum power voltage V_m = 17.4V and maximum power P_m = 55W; these are the manufacturer rated values under Standard Test Conditions (irradiation λ = 1kW/m^2, A.M. = 1.5 solar spectrum and cell temperature T=25°C).

Refer to [17]; the measurement of shunt resistance R_{sh} of PV module gives R_{sh}=6500Ω., and, using the electrical characteristics of PV panel, the constants $I_{or,}$ $\gamma(=\beta)$ and R_s in equations (1) and (2), obtained by programming on Matlab Software are 4.842µA, 1.740 and 0.1124 Ω respectively.

IV. SIMULATION PROCEDURE

We have built our model by using Simulink Matlab. The block used for simulations is given by figure 11. In PV module block, equations (1) to (3) are used; and in block (converter + resistive load), equations (8) to (11) are used.

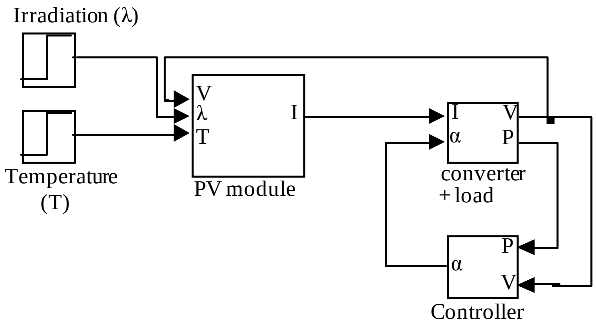


Fig. 11. Bloc diagram for system

The proposed controller circuit that forces the system to operate at its optimal operating point under variable temperature and irradiation conditions is shown in figure 12. Thus, for any temperature and solar irradiation level, the proposed controller circuit is obtained as follows:

- On one hand, we multiply the PV output signal current I by the PV output signal voltage V. We obtain the PV output signal power P which is derived in order to obtain the (dP/dt) signal.
- On the other hand, we derive the signal voltage V, which is inverted. Thus, the signal $1/(dV/dt)$ is obtained.

The product of $1/(dV/dt)$ by (dP/dt) signals, gives the (dP/dV) Signal, which is compared to zero. The resulting difference signal (error signal) is used as an input signal of the PI regulator. This PI regulator is used to deliver a duty cycle signal to the DC/DC converter corresponding to the condition: $\frac{dP}{dV} = 0$.

The product of $1/(dV/dt)$ by (dP/dt)signals, gives the (dP/dV) signal, which is compared to zero.
The resulting difference signal (error signal) is used as an input signal of the PI fuzzy logic controller. This controller is used to deliver a duty cycle signal to the DC/DC converter corresponding to the condition: $\frac{dP}{dV} = 0$.

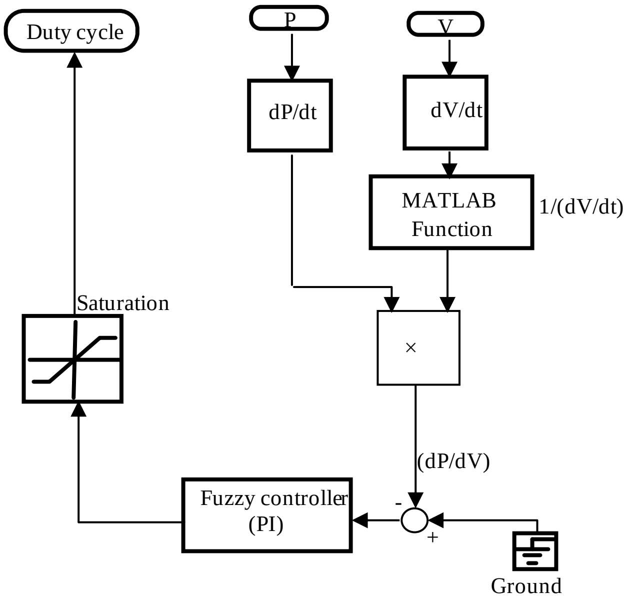


Fig. 12. Controller circuit

A. *PI Fuzzy logic controller*

The PI fuzzy logic controller used to generate the duty cycle of the converter receive as input the error and the error variation of the quantity $\left(\partial P/\partial V\right)$ regarding to zero (Fig. 13). As output, it delivers the normalized variation of duty cycle calculated recording the three fuzzy steps.

Bay varying gains $K_{d\alpha}$, K_e and K_{de}, one can have mentioned stability, and static and dynamic performance desired. For our case $K_{d\alpha} = 5500$, $K_e = 8.31*10^{-3}$ and $K_{de} = 10^{-10}$.

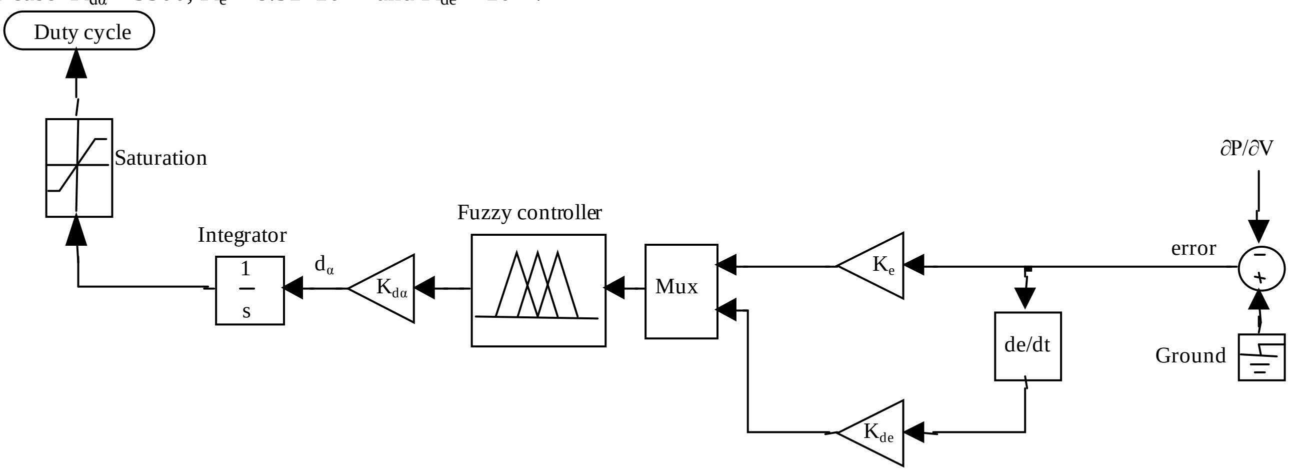


Fig. 13. PI Fuzzy logic controller

V. RESULTS

A. *Theoretical results*

For different values of irradiance λ and temperature *T*, the computation of the theoretical optimum quantities α_m, V_m and P_m are assembled in table II.

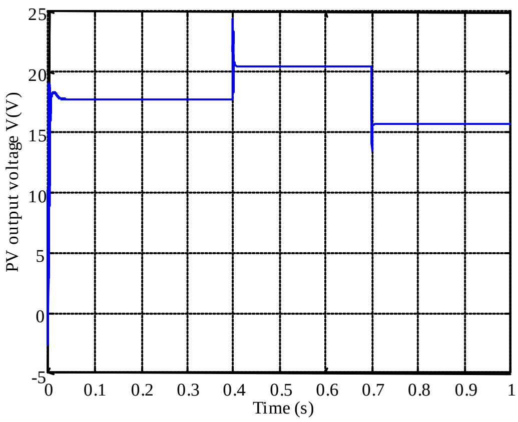
TABLE II

Quantities V_m, P_m and α_m for different values of λ and T

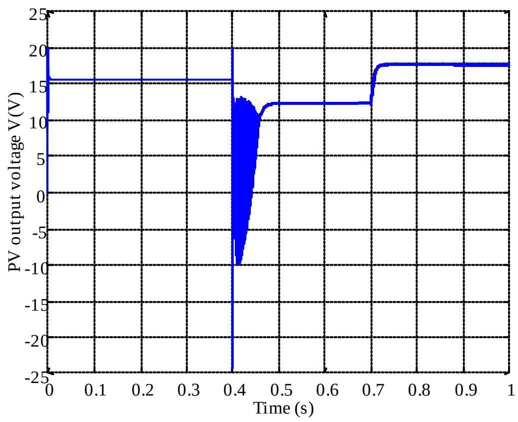
Values of λ (W/m^2) and T (K)	**V_m (V)**	**P_m (W)**	**α_m**
λ = 100 and T = 270. 18	17.69	05.27	0.0306
λ = 1000 and T = 270. 18	20.45	65.73	0.6811
λ = 1000 and T = 320. 18	15.67	49.61	0.71

B. *Simulation results*

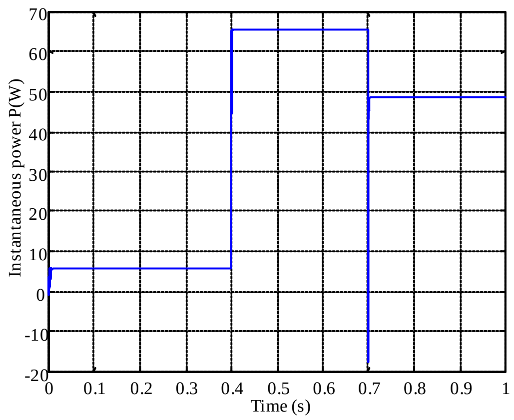
This section discusses the simulations of the proposed photovoltaic system shown in figure 3. The MPPT was controlled by using Fuzzy Logic Controller. Simulations are performed using equations 1, 2, 3, 8, 9, 10 and 11. In this simulation, in one hand, irradiation level λ is changed from 100 to 1000 W/m^2 at 0.4 s and the temperature is changed from 270.18 K to 320.18 K at 0.7s [Figs. 14 (a), (b) and (c)]. And in the other hand, a second simulation study was made to illustrate the response of the proposed method to rapid change of temperature *T* and solar irradiance λ, which λ and *T* are initially 1000 W/m^2 and 320.18K, are switched, at 0.4 s and 0.7 s, to 100 W/m^2 and 270.18 K respectively [Figs. 15 (a), (b) and (c)].



(a)



(a)



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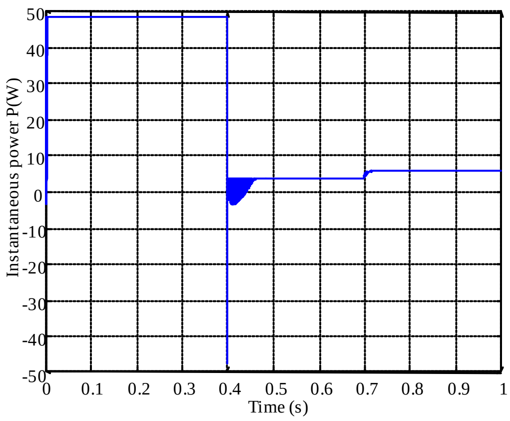

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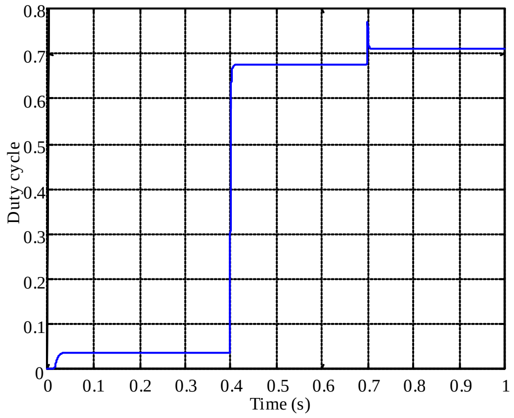
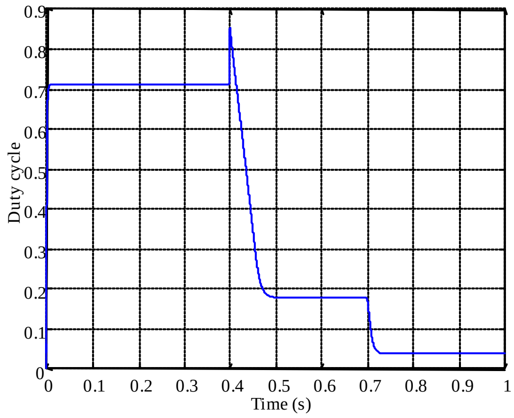


(c)



(c)

Fig. 14. Variation of PV output voltage (a), instantaneous PV power (b) and duty cycle (c) for a step change on irradiation and temperature from 100 W/m^2 to 1000 W/m^2 and 270.18 K to 320.18 K

Fig. 15. Variation of PV output voltage (a), instantaneous PV power (b) and duty cycle (c) for a step change on irradiation and temperature from 1000 W/m^2 to 100 W/m^2 and 320.18 K to 270.18 K.

In figure 14(a) and figure 15(a), the variation of PV output voltage is shown. The PI Fuzzy Logic Controller brings the system into the maximum power point after some oscillations and the steady state is then reached. In the steady state, it is shown that the average voltage of the PV is very close to its optimal values (Table II).

The variation of instantaneous power of PV is shown in figure 14(b) and figure 15(b). In a similar way to the voltage, the PV power also varies during the tuning of the PI controller. The steady state average values are close to optimal power values. Another result, which demonstrates the efficient maximum power tracking ability of the method, is shown in figure 14(c) and figure 15(c). The duty cycle of the switch changes rapidly as the irradiation and temperature change.

The simulations of the MPPT show that the system is stable. The transients between operating points are natural for a dynamic system which is controlled by a PI Fuzzy Logic Controller.

VI. CONCLUSION

In this paper, a MPPT system has been proposed and tested by simulations in Matlab Software. It follows the irradiance and the temperature level change rapidly and tracks the MPP. For a given temperature *T* and solar irradiance λ, we have calculated the corresponding optimal values α_m, V_m and P_m. The optimal values obtained by programming coincide with ones obtained by simulation. The simulation gives good results. Thus, the relative error between the theoretical and simulated results varied between 2% and 4%. The simulations show that the regulation is robust against disturbances.

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