Maximum Power Point Tracking for Photovoltaic Panel based on T-S Fuzzy Systems

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ABSTRACT
In this paper we are interested in Maximum Power Point Tracking (MPPT) for Photovoltaic (PV) Panels Based on T-S type Fuzzy Systems. The PV panel model structure is represented by the Takagi-Sugeno (T-S) type fuzzy system. It is described by four local models. Each of them is characterized by an optimal operating point. The power generated by the PV panel depends on the temperature and irradiation. An algorithm based on T-S fuzzy systems is proposed to extract the maximum power generated by the PV panel. The optimal operating point for the PV panel is computed based on the optimal operating point for each local model. A Boost dc-dc converter has been connected between the PV panel and the load to allow the operating point to be varied. The duty cycle for the converter is computed based on the coordinates of all the local models of the PV panel. The operating point is thus optimally tracked based on the MPPT algorithm. Some simulations have been done to check the performance of the proposed algorithm.

General Terms
Fuzzy system, Photovoltaic power, MPPT Algorithm.

Keywords
Photovoltaic panel, MPPT, T-S Fuzzy systems, Boost converter.

1. INTRODUCTION
In In the last few decades, photovoltaic (PV) energy has been the subject of several research projects. It has been considered as a clean form of energy because it does not emit toxic gases into the atmosphere. It is well known that the energy extracted from a PV array panel depends on the operating point. In order to increase the output power of a PV energy system, it is crucial to force the PV array panel to work at the maximum power point (MPP). In this case, a DC-DC converter must be used to link the PV array panel to the load. However, the maximum power produced by the PV array varies with climatic parameters, essentially solar irradiation and temperature, as shown in figures 4 and 5.

In addition, the photovoltaic system has a highly nonlinear current-voltage characteristic. Its output power mainly depends on the load connected to the PV system. Most papers dealing with the MPPT control algorithms are based on the Incremental Conductance method as in [9], or on perturb and observe (P&O) as in [11]. The basic idea is to modify slightly the operating voltage of the PV panel and observe how the power changes. If the power increases, the perturbation should be kept in the same direction, otherwise, it should be reversed. Mamdani type fuzzy logic controllers (FLC) have also been investigated [1][4][10]. In this paper the Takagi-Sugeno type fuzzy system has been used to model the PV array panel. Then, an MPP tracker algorithm based on the Takagi Sugeno fuzzy system has been developed. The main contribution of this work, which deals with Maximum Power Point Tracking for Photovoltaic Panels, uses a T-S fuzzy system, whereas most papers using fuzzy systems use a Mamdani type fuzzy system. In this paper, the T-S fuzzy system has been used in both the modelling phase and the control phase. The optimal duty cycle, which permits the maximum power to be extracted from the photovoltaic array panel, is computed based on the T-S fuzzy system. This paper is organised as follows: In Section 2, we recall the photovoltaic panel model and then we show the influence of climatic parameters such as temperature and irradiation on the electrical characteristic of the PV array panel.

In the third section, we present a photovoltaic energy system. In the first part we recall the basic schema for a boost DC/DC converter, and then we state the expression of the duty cycle which permits the maximum energy to be transferred between the source and the load. In the second part, we describe the photovoltaic energy system by a state model.

In section four, we recall the T-S fuzzy system, and then we present the photovoltaic energy system through a T-S fuzzy model to develop the MPPT tracker algorithm. The simulation results of the photovoltaic energy system show the performance of the proposed MPPT algorithm tracker in Section 5. Conclusions are drawn in the final section.

2. MODELLING OF PHOTOVOLTAIC PANEL

Several research studies have focused on the modelling of photovoltaic cells. So there are many models in the literature; such as, the model with one diode [5], the model with two diodes [12] and the model with four parallel branches [6]. Each of them has its own advantages and disadvantages. In the literature, the most used model is given in figure 1 [5]. It includes a current generator, in parallel with a diode, connected to an internal parallel and series resistor called, respectively, Rsh and Rs.

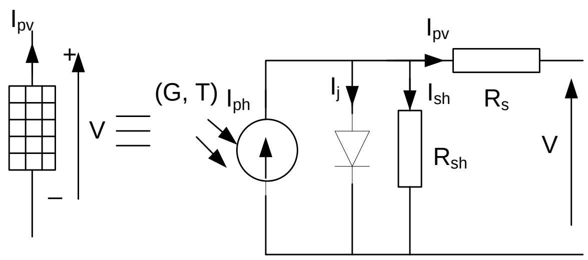

Fig 1: Equivalent circuit for PV cell

The PV cell model can be described by the following equations:

$$I_{sh} = \frac{V + R_s I_{pv}}{R_{sh}} \quad (1)$$

$$I_{pv} = I_{ph} - I_o\left[\exp\left(\frac{V + R_s I}{V_t}\right) - 1\right] - \frac{(V + IR_s)}{R_{sh}} \quad (2)$$

$$V_t = \frac{n_s kT}{q} \quad (3)$$

The current generated by the photovoltaic panel varies with temperature and irradiation, and its expression is given by the following equation:

$$I_{ph} = \left(I_{ph,n} + K_I \Delta T\right)\frac{G}{G_n} \quad (4)$$

where $I_{ph,n}$ is the rated current generated by the PV panel under standard conditions of temperature and irradiation (T=25°C and G=1000 w/m^2).

$$I_o = \frac{\left(I_{ph} + K_I \Delta T\right)}{\exp\left(\frac{V_{oc} + K_v \Delta T}{V_t}\right) - 1} \quad (5)$$

where I_o is a reverse saturation current

$$V_{oc} = n_s \frac{KT}{q} Log\left(\frac{I_{sc} + I_s}{I_s}\right) \quad (6)$$

$$V_c = n_s \frac{KT}{q} Log\left(\frac{I_{sc} + I_s - I_{pv}}{I_s}\right) \quad (7)$$

where V_{oc} is the open circuit voltage and I_{sc} is the short circuit current.

The main electrical characteristics that specify the I-V and P-V curves of PV panels are I_{sc}, V_{oc}, V_{max}, and I_{max}.

The I-V curve characteristics and cell junction temperature of PV panels are adjusted for any change in environmental conditions.

Figures 2, 3, 4 and 5 show the evolution of the electrical parameters, namely current-voltage and power-voltage as a function of changes in the climate parameters.

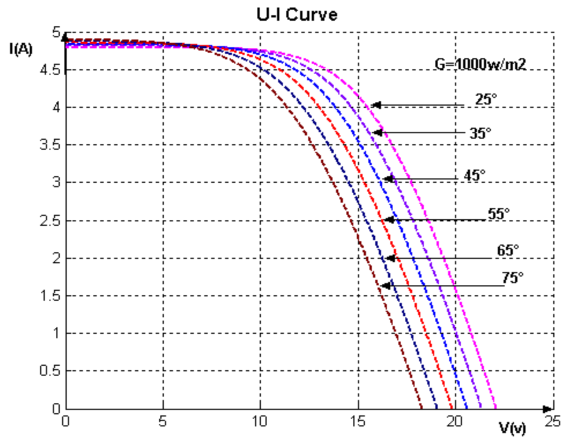

Fig 2: I-V curve characteristics

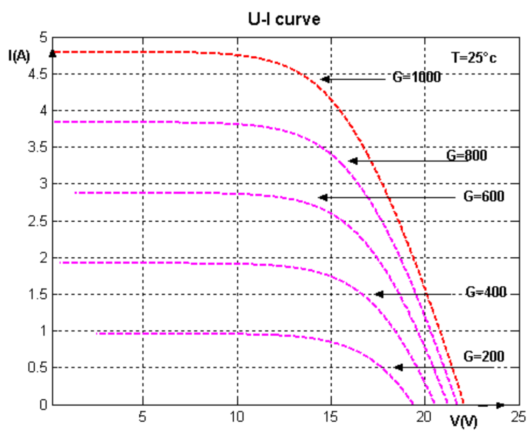

Fig 3: I-V curve characteristics

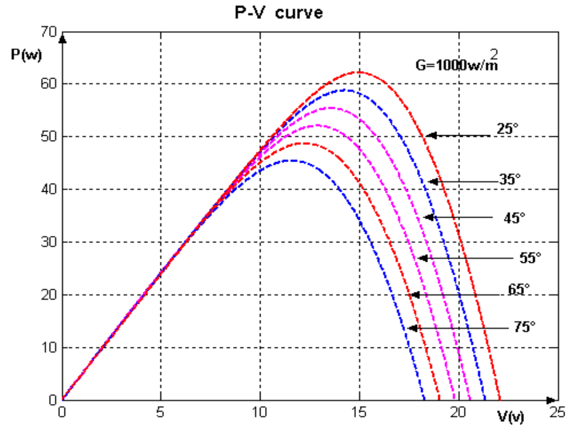

Fig 4: P-V curve characteristics

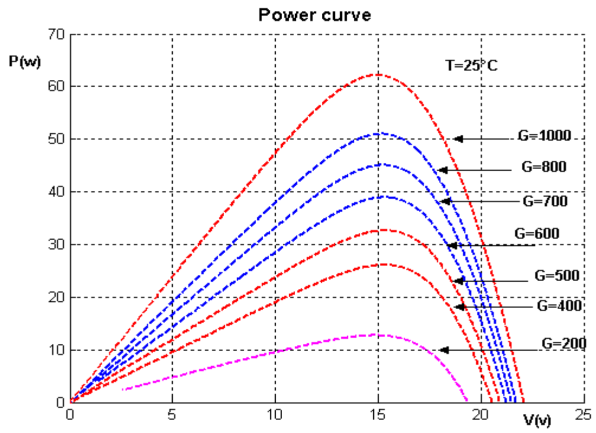

Fig 5 : P-V curve characteristics

Figure 2 shows the evolution of the I-V curve characteristics for a PV panel with different values of temperature and constant irradiation. It should be noted that the voltage across the panel is inversely proportional to the temperatures.

Figure 3 shows the evolution of the I-V curve characteristics for a PV panel with different values of irradiation and a constant temperature. It should be noted that the current generated by the panel is proportional to the irradiation.

Figure 4 shows the evolution of the P-V curve characteristics for a PV panel with different values of temperature and constant irradiation. It should be noted that the power generated by the panel decreases when the temperature increases. In addition, the voltage giving the maximum power decreases when the temperature increases.

Figure 5 shows the evolution of the P-V curve characteristics for a PV panel with different values of irradiation and a constant temperature. It should be noted that the power generated by the panel is proportional to the irradiation. In addition, the voltage VMP, giving the maximum power, increases slightly when the radiation decreases.

In conclusion, we can say that the PV array panel is a non-linear and time-variant system. Temperature is essentially found to affect the voltage, while the irradiation mainly affects the intensity of the PV array panel. The output power of the PV array panel increases as the solar radiation increases; and it decreases with an increase in temperature, as shown in Figures 4 and 5. For each P-V curve, there exists only one Maximum Power Point (MPP). In order to extract the maximum power from the PV array panel, the MPP must be tracked using a specific algorithm tracker.

3. PHOTOVOLTAIC ENERGY SYSTEM

The conventional photovoltaic system consists of a photovoltaic array panel connected to a DC-DC converter which provides energy to the load as shown in the following figure:

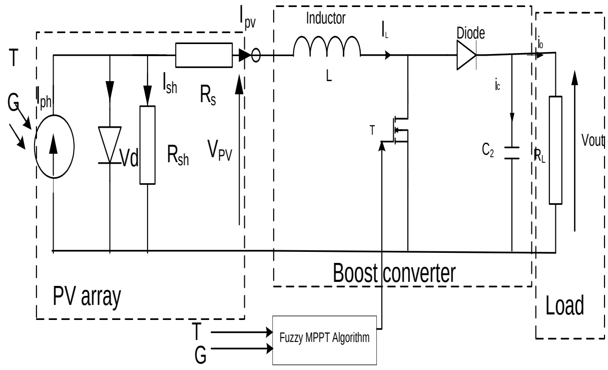

Fig 6: Photovoltaic system

3.1 Boost converter

The main function of the boost converter is to track the MPP by tuning its duty ratio D ($0 \leq D \leq 1$). The MPPT algorithm compute the optimal duty ratio. The pulse witch drives the switcher of the boost converter is generated on the basis of the pulse width modulation method and the compute duty ratio.

The output voltage of the typical DC-DC boost converter is given by the following equation:

$$V_{out} = \frac{1}{1-D} V_{in} \qquad (8)$$

where, D is the duty cycle of the switcher of the converter.

The optimal load for the PV panel which permits the maximum power to be extracted is described as:

$$R_{opt} = \frac{V_{MPP}}{I_{MPP}} \qquad (9)$$

where, V_{MPP} and I_{MPP} are respectively the voltage and current at the MPP.

The objective of the MPPT algorithm is to make the impedance of the load match the optimal impedance of the PV.

As shown in figure 7, the impedance seen by the PV array panel is the input impedance of the converter (Rin) which can compute as:

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_{out}}{I_{out}}(1-D)^2 = R_L(1-D)^2 \qquad (10)$$

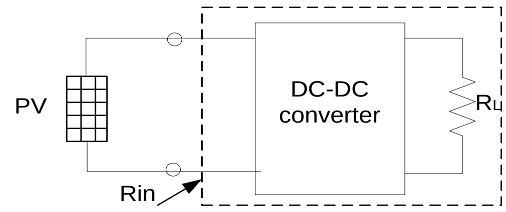

Fig 7

By adjusting the duty cycle (D), the value of R_{in} can be adjusted with that of R_{opt}. Therefore, the impedance of the load can be change as long as the duty cycle is adjusted accordingly.

According to the power transfer theory, the power delivered to the load from the PV array is maximized when the output resistance of the PV array (R_{opt}) is equal to the input impedance of the converter (R_{in}). From equation (9) and (10) we obtain:

$$\frac{V_{MPP}}{I_{MPP}} = R_L\left(1-D_{op}\right)^2 \qquad (11)$$

$$D_{op} = 1-\sqrt{\frac{V_{MPP}}{R_L I_{MPP}}} \qquad (12)$$

3.2 Modeling of photovoltaic system

The average dynamic model of the photovoltaic system given by figure 6 can be expressed in continuous conduction by the following equations:

$$\begin{cases} \dfrac{dI_L}{dt} = \dfrac{1}{L}\left[V_{pv} - V_{c2}(1-D)\right] \\ \dfrac{dV_{c2}}{dt} = \dfrac{1}{C_2}\left[I_L(1-D) - \dfrac{V_{c2}}{R_L}\right] \end{cases} \qquad (13)$$

$I_{pv} = I_L$ and $V_{c2} = V_o$

The state variables are I_L and V_{c2}, the input is V_{PV} and D is the duty cycle.

This can be written in state variable as:

$$\dot{x} = Ax + B\,u \qquad (14)$$

where,

$$A = \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{(1-D)}{C_2} & \frac{-1}{R_L C_2} \end{bmatrix} \; B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix},\; u = V_{PV},\; x = \begin{bmatrix} I_L \\ V_{c2} \end{bmatrix}$$

where C_2 is the capacitance of the output, L is the inductor, and R_L is the load resistor; V_{pv} and V_{C2} are respectively, the voltage of the PV array panel and the voltage of the output; I_{pv}, I_D, I_L and I_o are the current through the PV array, the diode D, L, and the load, respectively; I_{ph} is the photon current.

4. T-S FUZZY MODEL OF THE PHOTOVOLTAIC SYSTEM

4.1 T-S Fuzzy model

The continuous non-linear system (13) can be presented by a T-S fuzzy logic system, whose basic configuration is shown in figure 8. The fuzzy system is represented by a collection of fuzzy IF-THEN rules of the form [2],[3]:

$$\begin{aligned} &IF\ z_1\ is\ M_{i1}\ and\ z_2\ is\ M_{i2}\ and\ ..\ and\ z_n is\ M_{in} \\ &THEN \quad y_1 = y_1^i \ \ and \ \ y_2 = y_2^i,\ i = 1,2...c \end{aligned} \qquad (15)$$

where, $\{M_{ij}\}$ are the fuzzy sets, $x(t)$ is the state vector, $u(t)$ is the input vector, A_i is the state matrix, B_i is the input matrix and $z_1(t)\ldots\ldots z_n(t)$ are the premise variables. $x(t)\in R^n$; $A_i \in R^{nxn}$; $B_i \in R^{nxm}$, $y(t)\in R^m$; and c is the number of fuzzy rules.

For each rule R_i a weight $w_i(z(t))$ is attributed which depends on the grade of membership function of the premise variables $z_j(t)$ in the fuzzy sets M_{ij} :

$$w_i(z(t)) = \prod_{j=1}^{n} M_{ij}(z_j(t));$$

where $M_{ij}(z_j(t))$ is the grade of membership of $z_j(t)$ to the fuzzy set M_{ij}.

$$h_j(z(t)) = \frac{w_j(z(t))}{\sum_{i=1}^{c} w_i(z(t))}; \quad 0< h_i(z(t)) <1; \; i = 1, \ldots c$$

$w_i(z(t)) > 0$; for $i = 1, \ldots$ c ;

$$\sum_{i=1}^{c} w_i(z(t)) > 0; \quad \sum_{i=1}^{c} h_i(z(t)) = 1$$

The output of the fuzzy system can then be written as :

$$y_i(t) = \frac{\sum_{j=1}^{c} y_i^j \prod_{i=1}^{n} M_{ij}(z_i)}{\sum_{j=1}^{c}\prod_{i=1}^{n}} \qquad (15)$$

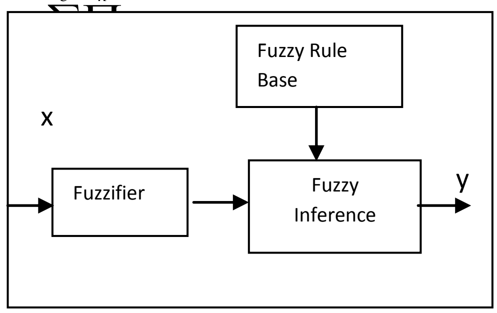

Fig 8: The Basic configuration of a Takagi-Sugeno fuzzy system

4.2 MPPT algorithm based on T-S Fuzzy logic

The optimal duty cycle which allows the converter to transfer maximum power from the PV array panel to the load is given by equation (12). We know that the V_{MPP} and I_{MPP} vary in times according to the variation of temperature and/or irradiation. So the optimal duty cycle is variable in times and does not have a unique value. In other words, it is necessary to know the optimal corresponding values of tension and current (V_{MPP}, I_{MPP}) for each pairs of values (G, T), which is extremely difficult or impossible to determine. To overcome this difficulty we use the T-S model.

The nonlinearity of the system comes from temperature and irradiation, so we choose them as two premise variables..

$$Z(t) = \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix}$$

where the membership functions are given by the following figures:

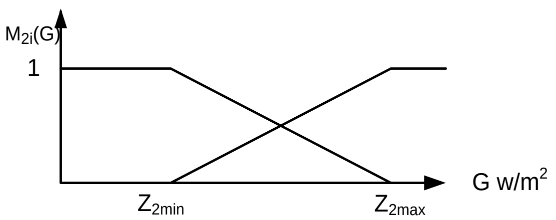

Fig 9: membership function of irradiation

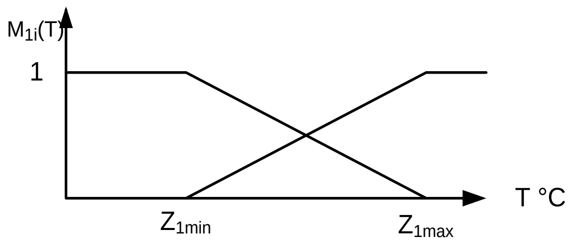

Fig 10: membership function of temperature

$$M_{11}(z_1(t)) = \frac{z_{1\max} - z_1(t)}{z_{1\max} - z_{1\min}}$$

$$M_{12}(z_1(t)) = \frac{z_1(t) - z_{1\min}}{z_{1\max} - z_{1\min}}$$

$$M_{21}(z_2(t)) = \frac{z_{2\max} - z_2(t)}{z_{2\max} - z_{2\min}}$$

$$M_{22}(z_2(t)) = \frac{z_2(t) - z_{2\min}}{z_{2\max} - z_{2\min}}$$

with $z_{1\min} = 5°c$, $z_{1\max} = 75°c$, $z_{2\min} = 200w/m^2$, $z_{2\max} = 1000w/m^2$

We obtain four sets. The T-S Fuzzy model of system is defined by the following four fuzzy rules: $y_{1i} = V_{MPPi}$, $y_{2i} = I_{MPPi}$ (for i =1 to 4).

Plant rules

Rule 1: IF z_1 is M_{11} and z_2 is M_{22} THEN $V_{MPP}=V_{MPP1}$ and $I_{MPP}=I_{MPP1}$

Rule 2: IF z_1 is M_{12} and z_2 is M_{22} THEN $V_{MPP}=V_{MPP2}$ and $I_{MPP}=I_{MPP2}$

Rule 3: IF z_1 is M_{11} and z_2 is M_{21} THEN $V_{MPP}=V_{MPP3}$ and $I_{MPP}=I_{MPP3}$

Rule 4: IF z_1 is M_{12} and z_2 is M_{21} THEN $V_{MPP}=V_{MPP4}$ and $I_{MPP}=I_{MPP4}$

So,

$$V_{MPP} = \sum_{i=1}^{c} h_i(z(t)) V_{MPPi} \qquad (16)$$

$$I_{MPP} = \sum_{i=1}^{c} h_i(z(t)) I_{MPPi} \qquad (17)$$

then, $D_{op} = 1 - \sqrt{\frac{V_{MPP}}{R_L I_{MPP}}}$ (18)

4.3 Simulation results

To measure the temperature and irradiation, we propose to use, respectively, LM35 and LDR whose resistance depends on the irradiation.

We choose the value of the premise variables as:

$z_{1\min} = 5°c$, $z_{1\max} = 75°c$, $z_{2\min} = 200w/m^2$, $z_{2\max} = 1000w/m^2$

The four local consequence outputs of the PV array panel (V_{MPPi}, I_{MPPi}) for i=1 to 4 are:

V_{MPP1}=16.348 ; I_{MPP1}=4.234

V_{MPP2} =11.576 ; I_{MPP2}=3.925;

V_{MPP3} =16.527 ; I_{MPP3}=0.866;

V_{MPP4} =10.838 ; I_{MPP4}=0.8181;

In order to check the performance of the proposed MPPT algorithm we propose the following evolution of irradiation and temperature given by figures 11 and 12.

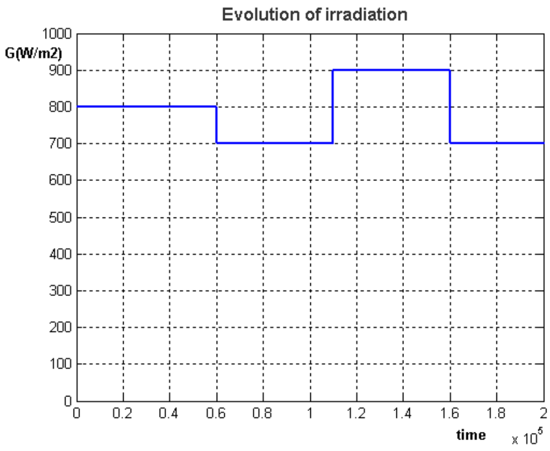

Fig 11: evolution of irradiation.

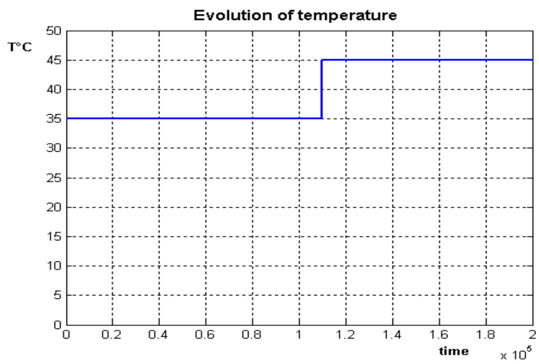

Fig 12: evolution of temperature.

In this test we have four pairs of irradiation and temperature, which are: (G1= 800, T1=35°), (G2=700, T2=35°) (G3=900, T3=45°) and (G4=700, T4=45°). For each pair there is only one ideal optimal operating point which can be determined from the power-voltage characteristics of the PV array panel, although this is not always available for each pair (G,T). It is important to mention that it is not possible to know the appropriate coordinates (V_{MPP}, I_{MPP}) of the ideal optimal operating point for all the pairs (G,T) as there are infinite number of pairs (G,T).

Thus the corresponding ideal optimal operating point (V_{MPP}, I_{MPP}) for each previous pair (G,T), are: (14.445, 3.343), (14.5195, 2.904), (13.6563, 3.7052) and (13.794, 2.917).

The computed coordinates for optimal operating point (V_{MPP}, I_{MPP}) based on the proposed algorithm, for each previous pairs (G,T), are: (14.2494, 3.2875), (14.2226, 2.8805), (13.578, 3.6551), (13.4918, 2.8504). It is obvious that the computed coordinates of optimal operating point, based on the proposed algorithm are almost the same as the ideal optimal operating points. This allows the performance of the proposed algorithm to be demonstrated.

The 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22 show, respectively, the evolution of the V_{MPP} voltage, the V_{MPP} voltage error, the output voltage of the converter, the error of the output voltage of the converter, the delivered power, the error of delivered power, the panel current, the panel current error, the duty cycle and the duty cycle error.

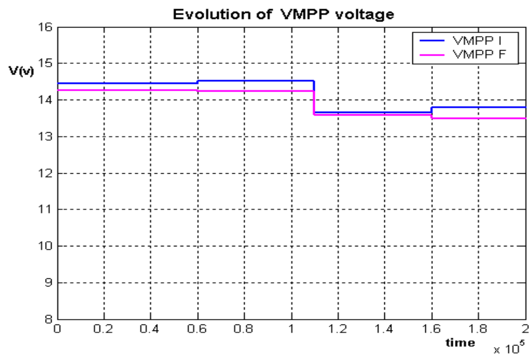

Fig 13: evolution of the MPP voltage

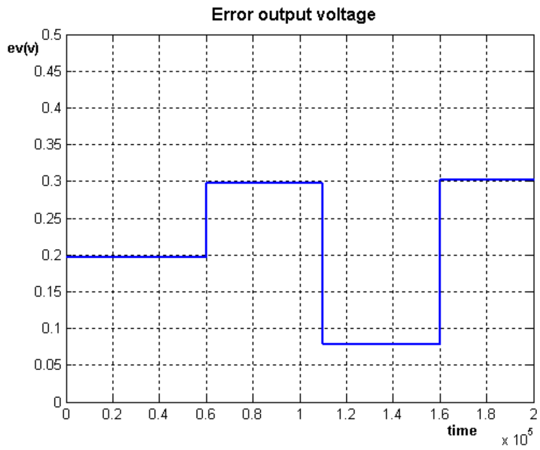

Fig 14: evolution of the voltage error E_V.

where, $E_V = V_{MPP\,I} - V_{MPPF}$.

V_{MPPI} is the ideal optimal operating voltage

V_{MPPF} is the computed optimal operating voltage.

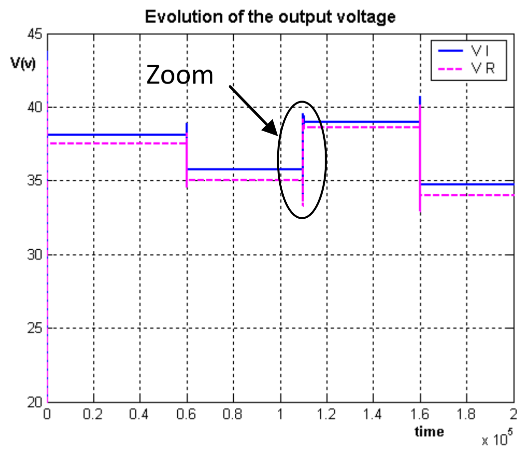

Fig 15: evolution the output voltage of converter

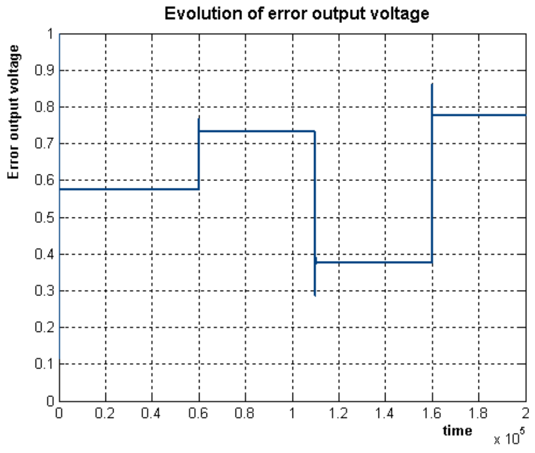

Fig 16: evolution of the output voltage error E_{VO}

where, $E_{VO} = V_I - V_F$

V_I is the ideal output voltage for the converter

V_F is the output voltage for the converter based on the MPPT algorithm.

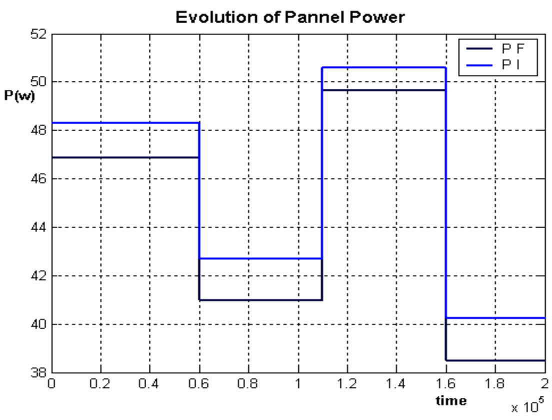

Fig 17: evolution the delivered power

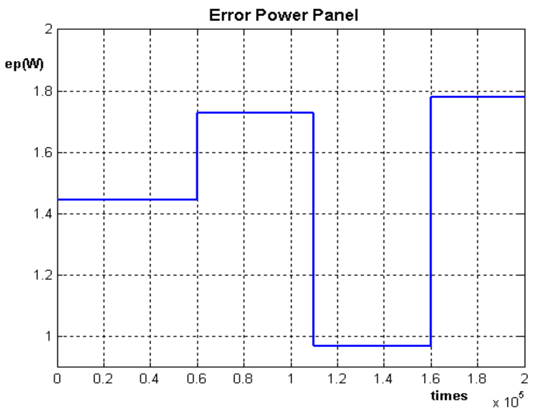

Fig 18: evolution of the delivered power error E_P

where, $E_P = P_I - P_F$

P_I is the ideal delivered power from panel to the load

P_F is the delivered power from panel, to the load, based on the MPPT algorithm.

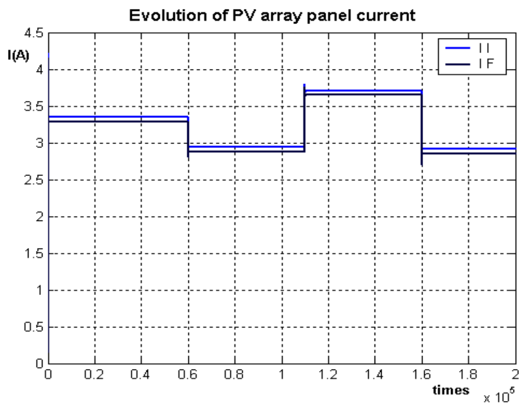

Fig 19: evolution of the panel current

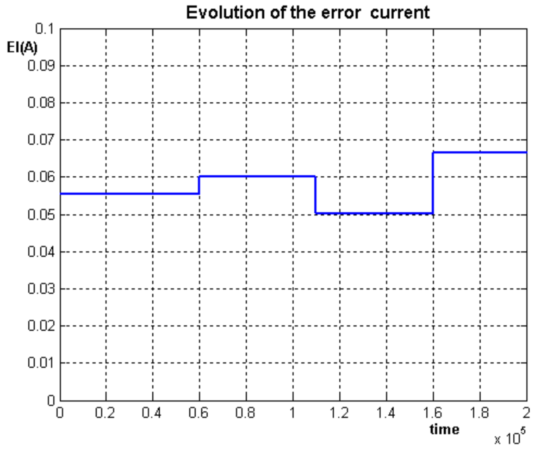

Fig 20: evolution of the current error E_I

where, $E_I = I_I - I_F$

I_I is the ideal delivered current from panel

I_F is the current from panel based on the MPPT algorithm

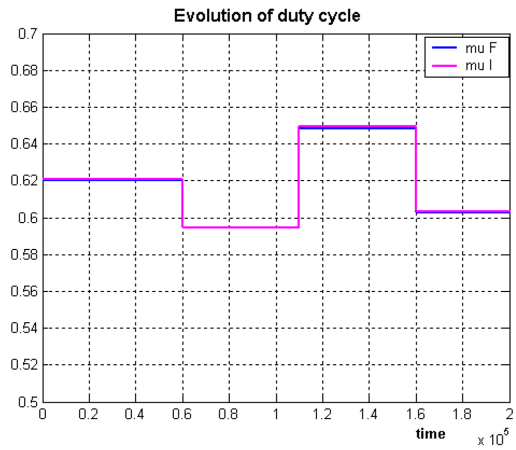

Fig 21: evolution of the duty cycle

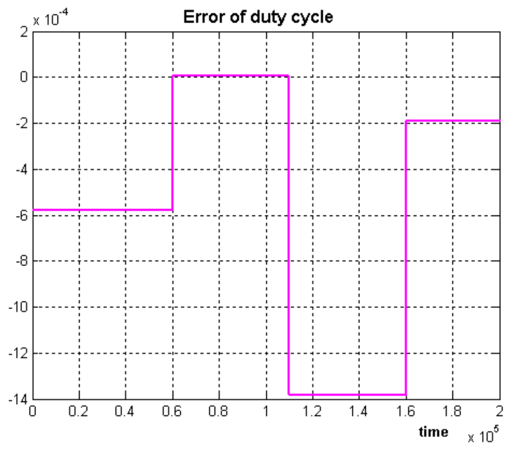

Fig 22: the duty cycle error

Mu_I is the ideal delivered current from panel

Mu_F is the current from panel based on the MPPT algorithm

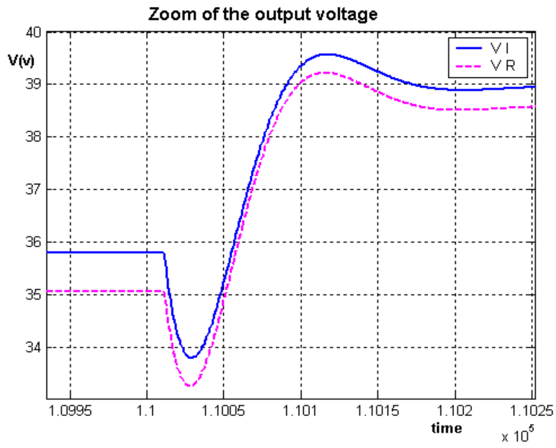

Fig 23.: zoom of the figure 15.

4.4 Commentaries

The figures 14, 16, 18, 20 and 22 show that the errors between the ideal variable, as in the V_{MPP} voltage, output voltage, panel power and panel current, and the variable based on the proposed MPPT algorithm are very small and can be neglected. In some figures such as 15, 16, … peaks can be observed. Actually, they are not real peaks, this is due to the compression of the time axis. Indeed, figure 23, which represents a zoom of figure15 confirms this.

In addition, in the previous trials it was assumed instantaneous and sudden changes of climatic variables such as temperature and irradiation are not really feasible because temperature varies slowly over time. Despite these variations the algorithm gives results very close to the ideal system.

4.5 Characteristics of the PV array panel:

The characteristics of the used PV array panel are:

Np=1

Ns=36

q=1.6e-19c

A=1.92

Eg=1.1

T_r=298.18°K

Tr=25°c

I_{or}=9.579e-6 A

V_{co}=27.4 V

R_s=0.09Ω

R_{sh}=100Ω

R_{load}=30Ω

P_{max}=51watts

I_{sc}=4.8 A

K_I=0.00171 A/°c

F=10 khz

K: Boltzmann's constant ($1,38.10^{-23}$ J/K),

C_2=68µF

5. CONCLUSION

In this paper, an intelligent control strategy based on the Takagi-Sugeno type fuzzy system has been proposed for the MPPT of a PV energy system. The PV system was described by four local models to compute the coordinates of the optimal operating power point. The trapezoidal type membership functions have been used to compute the weight of each local model. The simulation results show that the Fuzzy algorithm can track the MPP quickly and steadily exhibits good robustness despite sudden variations of temperature and irradiation. It is worth noting that there are no oscillations in the various figures compared with traditional algorithms.

6. ACKNOWLEDGMENTS

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