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Coupling A Photovoltaic Generator With A Low Voltage Electric Network Through An Inverter

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***Abstract*—This paper described a study about the connection of a photovoltaic generator (PVG) to an electrical network through a DC/AC converter followed by an inductive filter in order to improve the produced energy quality. After system modeling, the fuzzy logic method of Mamdani was used to extract the optimal values of the voltage and the current enabling the photovoltaic generator to produce the optimal power whatever the sudden changes in temperature and solar radiation. A Takagi-Sugeno (T-S) fuzzy control strategy was also proposed to control the inverter power generation. The inverter controller gains were calculated using the linear matrix inequality (LMI) resolution and the perturbation effect was reduced by the H-infinite method. The simulation results under the Matlab-Simulink environment demonstrate the proposed methods performances. Thus, the suggested controllers can extract the optimal produced energy whereas operating the photovoltaic panel at its maximum power point (MPP) and supply enough energy to the network.**

Keywords—Photovoltaic Generator (PVG), Maximum Power Point Tracking (MPPT), FLC Mamdani, Takagi-Sugeno (T-S) fuzzy Controller, Linear Matrix Inequality (LMI), H infinite method.

I. INTRODUCTION

Over the previous decades, several countries have been focusing on the development of renewable energy sources in order to partially replace the conventional ones for the production of electricity. These energies include a certain number of technological sectors depending on the energy source and the useful energy obtained. There is a variety of renewable energies among which the photovoltaic solar energy is the main focus of this study.

This energy has witnessed an unprecedented attention during the recent years because it is an inexhaustible, non-polluting, silent and very easy to integrate into buildings.

Its major disadvantage, however, is that it is not regularly available since it depends on the irradiation level fluctuations between the day and the night, and it varies seasonally, which affects the stabilization of the solar energy system.

In order to compensate for the absence of nocturne production, it would require considerable storage capacity means. The coupling of the photovoltaic generator (PVG) with the alternative electricity network makes it possible to avoid these means and to take advantage of the "storage capacity" of the network. The connection of the PV production to a grid is, therefore one of the main developments in solar energy applications. The major problem in this association is the PVG maximum power transfer to the grid, which often suffers from a bad adaptation.

To minimize this difficulty, a control algorithm that seeks the maximum power point (MPP) is used before coupling the PVG to the network through a static converter. Ideally, power monitoring should be achieved automatically to adapt to the changing weather conditions. Many algorithms for tracking the maximum power point for the solar cell have been developed [1,2,3,4,5,6] and compared [7,8,9,10,11,12,13]. These comparatives study show the fuzzy logic algorithm effectiveness which achieves very good performances regardless of the rapid variations in irradiance and temperature values. Moreover, this model doesn't require the exact PV model knowledge [11].

The conversion of the direct current coming from the modules into sinusoidal alternating current injected to the grid can be achieved using the current source inverter. To reduce the total harmonic distortion (THD) to improve the produced energy quality, the multi-level inverter is the most appropriate choice since it offers several advantages compared to its conventional counterparts [14]. However, the multilevel converter design suffers from a significant problem that lies in the complexity of its control.

The Pulse Width Modulation (PWM) method is an efficient technique used to control the inverter switchers [15-18] and allow reducing the harmonic distortion in the three-phase inverter output variables to good utilization of the DC bus [19].

To obtain a good quality of energy injected into the network, it is necessary to reduce the effect of the variations produced by the presence of electronic power interface. Therefore, it is crucial to introduce a filter at the inverter output which would discard the switching harmonics and thus improve the injected energy quality into the network [20,21].

In the grid-connected PV inverter, the injected current and also the produced power need to be controlled in order to meet the grid requirements [19]. Different solutions were previously proposed [14,19,22,23,24,25].

A comparative study of the fuzzy logic, sliding mode and proportional-integral controllers is given in [25]. During external disturbances, [25] proves that FLC performs satisfactorily in regulating the inverter output. Therefore, the FLC is a trustworthy controller for power converters applications [24,25].

However, [26] shows that fuzzy controller T-S is much more efficient than the traditional PI controllers and the fuzzy Mamdani controllers. Hence, to eliminate the harmonics and improve the inverter dynamic performance, the TS fuzzy controller is a good candidate [26].

In order to achieve our paper's objective for an effective energy conversion structure, a Takagi-Sugeno intelligent control strategy has been proposed and developed. Here we were inspired by the conversion control system suggested in [27,28,29,30].

The remaining of this paper was arranged as follows: The first section presented the used structure of the coupling of the renewable energy source to the electricity grid. In sections II and III, the modeling of the PV generator components was achieved by describing the fuzzy method of Mamdani used to optimize the power generation. Then we represented the DC/AC converter used in the conversion system, its mathematical model as well as its LMI algorithm-based control.

A T-S fuzzy controller was proposed in section IV to improve the performance of the PV inverter connected to the network.

The Matlab-Simulink environment was used to analyze and interpret the simulation results of this system and consequently to show the good performance of the used algorithms. The concluding remarks were forwarded in Section VII.

II. THE PROPOSED STRUCTURE OF THE STUDIED SYSTEM

The proposed system consists of a solar panel field connected to the continuous bus of a three-phase voltage inverter to inject the generated power to the grid. The MPPT controller detects the maximum power from the solar generator and produces the optimal voltage and current that will be used as reference quantities for the direct components of the inverter. The inverter transforms a DC input into an AC sinusoidal output. In order to connect the voltage inverter to the electrical network and make it work as a current source, it is required to use an inductive filter consisting of a resistive load R_f in series with an inductance L_f. This type of filter reduces the harmonics around the switching frequency.

The proposed configuration of the PV generator connected to the network is illustrated in Fig. 1.

A. Electric characteristic of PV generator

The photovoltaic solar energy is produced by the direct conversion of a part of the solar radiation into electrical energy through a photovoltaic (PV) cell. This cell is made up of an ideal current source, producing a photovoltaic current I_{ph} proportional to solar irradiations, associated in parallel with a diode D, parallel resistance Rsh and a series resistance Rs which must be as small as possible to limit its influence

on the current of the cell. while the parallel resistance Rsh should be as high as possible.

The association of a few PV cells in series/parallel creates a photovoltaic generator (PVG) whose output components current-voltage are designed respectively by I_{pv} and V_{pv}.

The PVG used, includes N_p parallel branches and N_s solar cells connected in series in each branch [5,12,14,20,21]. According to the weather conditions, a photovoltaic current can be expressed as:

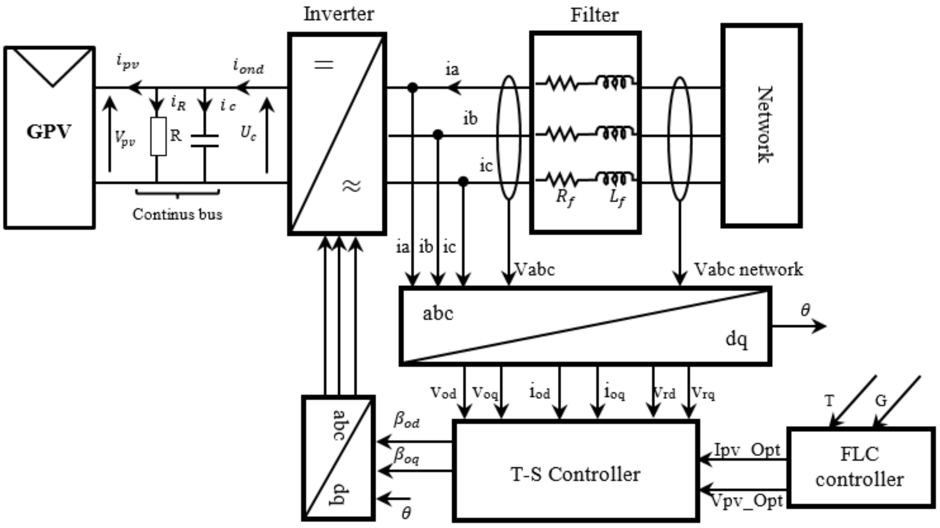

Fig. 1 *Studied system structure.*

$$I_{pv} = N_p\left(I_{ph} - I_{rs}\exp\left(\frac{k_{pv}V_{pv}}{N_s}\right) - 1\right) \qquad (1)$$

with $k_{pv} = \frac{q}{p.k.T}$ where $1 < p < 2$ (2)

where I_{ph} is the photocurrent and I_{rs} is the reverse saturation current of the diode, respectively denoted by [5,22]:

$$I_{ph} = \left(I_{sc} + K_I\left(T - T_r\right)\right)\frac{G}{G_r} \qquad (3)$$

$$I_{rs} = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{gp}}{pk}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \qquad (4)$$

where I_{sc} and I_{rr} are respectively the reverse saturation and the short-circuit cell currents at the radiation-temperature reference values $(G_r = 1000W/m^2,\ T_r = 25°C)$. K_I is the short-circuit current temperature coefficient, G is the solar radiation $\left(W/m^2\right)$, $q = 1{,}6.10^{-19}C$ is the electron charge, E_{gp} is the semiconductor band-gap energy used in the cell, p is the diode ideality factor, $k = 1{,}38.10^{-23}JK^{-1}$ is the Boltzmann constant.

The PV cells temperature T (°C) varies according to the global solar radiation and the ambient temperature T_a (30°C), using the following relationship:

$$T - T_a = \frac{\left(NOCT - 20\right)}{800}.G \qquad (5)$$

where NOCT is a Normal Operating Cell Temperature [4].

Given the photovoltaic module non-linear current-voltage characteristics and their sensitivity to external conditions, such as illumination and temperature, the PVG can't operate at its maximum power point (MPP) and also generates energy losses. So, to maximize the PV produced power exploitation at any time, and to achieve a perfect coupling between the PVG and the inverter, the use of an adaptation stage is highly recommended.

Many maximum powers point tracking (MPPT) methods have been established allowing the PVG to operate at its maximum power. In section III, we developed the MPPT based on the fuzzy model of Mamdani.

B. *Inverter modeling*

The electronics power converters are an enabling technology needed to convert the PV generator's continuous power supply into AC power for the grid [18].

The two levels three-phase inverter used consists of three arms made up of two electronic transistors to form the switching cells. Each arm has two bidirectional complementary power components with diodes mounted in parallel. The freewheeling diodes ensure the current continuity in the network once the switches are open.

If we consider the direct and quadratic components of the current ($i_{od}(t)$, $i_{oq}(t)$) and also of the LMI laws ($\beta_{od}(t)$, $\beta_{oq}(t)$) calculated with the PARK transform to control the inverter, we can state the inverter current $i_{ond}(t)$ as in the following form:

$$i_{ond}(t) = \frac{3}{4}\beta_{od}(t)i_{od}(t) + \frac{3}{4}\beta_{oq}(t)i_{oq}(t) \qquad (6)$$

Using the PARK transform enables us to express the inverter direct and quadratic voltage components as follows:

$$\begin{cases} v_{od}(t) = -L_f \dfrac{di_{od}(t)}{dt} - R_f\, i_{od}(t) + L_f\, w\, i_{oq}(t) + V_{rd}(t) \\ v_{oq}(t) = -L_f \dfrac{di_{oq}(t)}{dt} - R_f\, i_{oq}(t) - L_f\, w\, i_{od}(t) + V_{rq}(t) \end{cases} \tag{7}$$

that can be also expressed in the next form:

$$\begin{cases} v_{od}(t) = \dfrac{1}{2}\beta_{od}(t)u_c(t) \\ v_{oq}(t) = \dfrac{1}{2}\beta_{oq}(t)u_c(t) \end{cases} \tag{8}$$

where R_f and L_f design the filter's resistance and inductance. w designates the angular electric speed.

V_{rd} and V_{rq} are the network direct and quadratic voltage values.

This allows us to write the dynamics of the inverter currents in the following form:

$$\begin{cases} \dfrac{di_{od}(t)}{dt} = -\dfrac{R_f}{L_f} i_{od}(t) + w\, i_{oq}(t) - \dfrac{u_c(t)}{2L_f}\beta_{od}(t) + \dfrac{1}{L_f}V_{rd}(t) \\ \dfrac{di_{oq}(t)}{dt} = -w\, i_{od}(t) - \dfrac{R_f}{L_f} i_{oq}(t) - \dfrac{u_c(t)}{2L_f}\beta_{oq}(t) + \dfrac{1}{L_f}V_{rq}(t) \end{cases} \tag{9}$$

In order to command the conduction times of each transistor forming the voltage inverter, we use the PWM command whose purpose is to reduce the harmonics generated by the inverter in the currents [18,20].

The advantage of this method is to obtain an inverter output voltage proportional to the used modulator value, during a switching period. However, it does not completely solve the current harmonics problem.

In order to attenuate the high order harmonics and thus reduce the voltage distortion at the connection point, a passive filter is then connected in series with the supply network [20].

This filter consists of a resistor ($R_f = 0.5\,\Omega$) in series with an inductance ($L_f = 10^{-3}$ H).

III. MPPT FUZZY MODEL OF MAMDANI

In this section, we used Mamdani's fuzzy algorithm to determine the optimal current *(I_Opt)* and the optimal voltage *(V_Opt)* values extracted from the PV array.

This controller has three main phases described as follows:

As an input, we chose the temperature T and sunshine G applied to the photovoltaic generator, and as an output, we opted for the optimal current and the optimal voltage delivered by the panel.

A. Fuzzification

This first step consists in transforming the input and output variables into fuzzy variables (also called linguistic variables) and defining the universe of the discourse for each. Thus, for each linguistic variable, the corresponding accessible area is divided into linguistic values.

Then, we introduce the notion of membership function that characterizes fuzzy sets. In general, it is a relation that links a number to each element of the discourse universe, denoted by μ. A membership function can take many forms such as triangular, trapezoidal, sigmoid or Gaussian. In our case, we chose a Gaussian membership function as shown in Fig. 3.

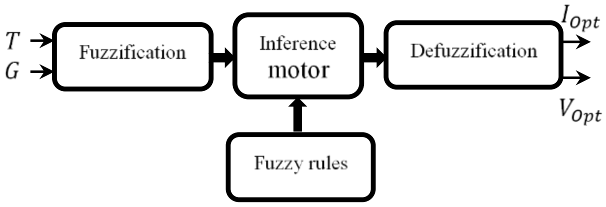

Fig. 2 *MPPT fuzzy controller structure*

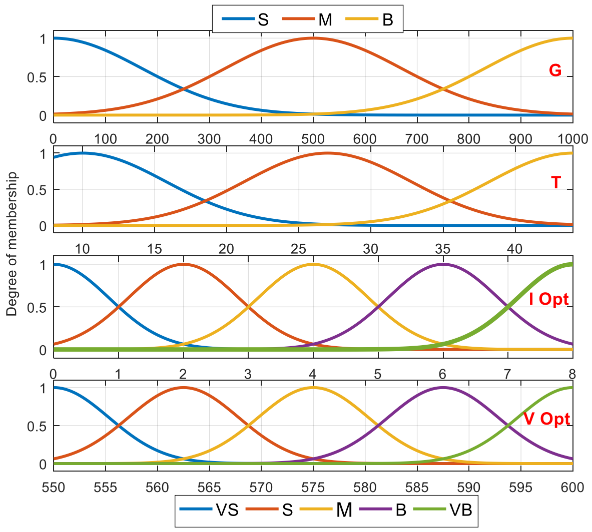

Fig. 3 Gaussian membership functions of input-output variables

The universes of discourse of the inputs (T, G) are divided into three membership functions named: S (Small), M (Medium) and B (Big). As for the output, we use five classes to represent the speech universe given by: VS (Very Small), S (Small), M (Medium), B (Big) and VB (Very Big).

B. Fuzzy Inference System

The most basic operations on the fuzzy sets are achieved at this level by connecting the input and the output variables using fuzzy rules. In fact, this block groups all the fuzzy rules were developed to decide about the output value that would be taken. For the rule's implementation, we use the if-then syntax as described in the table I.

A linguistic description is constructed from the various rules as shown when developing rule ***R2***:

If ***G*** is ***S*** and ***T*** is ***M*** then I_{Opt} is ***S*** and V_{Opt} is ***VS***.

Thus, there are nine rules for each output. It can be noted that the optimal current grows with increasing inputs values; whereas the optimal voltage lessens with the temperature rise and varies slightly with *G*.

C. Defuzzification

Unlike the first block, this block allows associating each fuzzy value corresponding with the desired output, a real and concrete value. This step can be carried out through several ways, depending on the chosen mathematical concept. In our case, the gravity center method was used to calculate the numerical value of the output from the membership functions. This technique calculates the average of the weighted values w_i.

TABLE 1 Fuzzy Inference table

	Input variables		**Output variables**	
Rules	***G***	***T***	I_{Opt}	V_{Opt}
R1	S	S	VS	S
R2	S	M	S	VS
R3	S	B	S	VS
R4	M	S	M	M
R5	M	M	M	M
R6	M	B	M	M
R7	B	S	B	VB
R8	B	M	B	B
R9	B	B	VB	B

Now, the solar power generation system is represented by the Mamdani fuzzy model using IF–THEN fuzzy rules. The MPPT block gives the optimal continuous characteristics V_{opt} and I_{opt}, provided by the PVG, and injected them to the inverter as a reference input.

In this step, it is required to use a control method to improve the PV inverter performance in order to increase its insertion rate in the distribution network.

IV. T-S FUZZY CONTROLLER

We consider the state vector noted by: $x(t)=\left[i_{od}(t) \quad i_{oq}(t) \quad u_c(t)\right]^T$ (10)

and the control signal described by:

$$u(t)=\left[\beta_{od}(t) \quad \beta_{oq}(t)\right]^T \qquad (11)$$

According to the nodes law applied in Fig. 1 and using (6), we can write the following relation:

$$\frac{du_c}{dt}=\frac{3}{4C}i_{od}\beta_{od}+\frac{3}{4C}i_{oq}\beta_{oq}-\frac{1}{RC}u_c-\frac{1}{C}i_{pv} \qquad (12)$$

To reduce the fuzzy rules number, we must limit the premises variables. So, we note that $i_{pv}=i_{pvm}+i_{pv1}$ where i_{pv1} is a perturbation and (12) becomes as:

$$\frac{du_c}{dt}=\frac{3}{4C}i_{od}\beta_{od}+\frac{3}{4C}i_{oq}\beta_{oq}-\frac{1}{RC}u_c-\frac{1}{C}\left(i_{pvm}+i_{pv1}\right)$$
(13)

Hence, the global system model can be written in the following form:

$$\begin{cases}\dfrac{di_{od}(t)}{dt}=-\dfrac{R_f}{L_f}i_{od}(t)+wi_{oq}(t)-\dfrac{u_c(t)}{2L_f}\beta_{od}(t)+\dfrac{1}{L_f}V_{rd}(t)\\ \dfrac{di_{oq}(t)}{dt}=-wi_{od}(t)-\dfrac{R_f}{L_f}i_{oq}(t)-\dfrac{u_c(t)}{2L_f}\beta_{oq}(t)+\dfrac{1}{L_f}V_{rq}(t)\\ \dfrac{du_c}{dt}=\dfrac{3}{4C}i_{od}\beta_{od}+\dfrac{3}{4C}i_{oq}\beta_{oq}-\left(\dfrac{1}{RC}+\dfrac{i_{pvm}}{Cu_c}\right)u_c-\dfrac{1}{C}i_{pv1}\end{cases}$$

(14)

Which can be noted in the matrix form represented by:

$$\dot{x}(t)=A(x).x(t)+B(x).u(t)+D.h(t) \qquad (15)$$

where: $A=\begin{bmatrix}-\dfrac{R_f}{L_f} & w & 0\\ -w & -\dfrac{R_f}{L_f} & 0\\ \dfrac{3}{4C}\beta_{od}(t) & \dfrac{3}{4C}\beta_{oq}(t) & -\dfrac{1}{RC}-\dfrac{i_{pvm}}{Cu_c}\end{bmatrix}$,

$B=\begin{bmatrix}-\dfrac{u_c(t)}{2L_f} & 0\\ 0 & -\dfrac{u_c(t)}{2L_f}\\ 0 & 0\end{bmatrix}$, and $D=\begin{bmatrix}\dfrac{1}{L_f} & 0 & 0\\ 0 & \dfrac{1}{L_f} & 0\\ 0 & 0 & -\dfrac{1}{C}\end{bmatrix}$

with $i_{pv1}=\dfrac{i_{pvm}}{2}$ and $h(t)=\left[V_{rd}(t) \quad V_{rq}(t) \quad i_{pv1}(t)\right]^T$ is a disturbance vector.

The premises variables are selected as follows:

$q_1(t)=\beta_{od}(t)$, $q_2(t)=\beta_{oq}(t)$, and $q_3(t)=u_c(t)$.

So, the premises variables vector can be expressed by:

$$q(t)=\left[q_1(t) \quad q_2(t) \quad q_3(t)\right] \qquad (16)$$

Thus, the nonlinear global system can be defined by a set of 2^3 fuzzy T-S rules expressed as follows:

If $q_1(t)$ is F_{1i}, $q_2(t)$ is F_{2i} and $q_3(t)$ is F_{3i} then $\dot{x}(t)=A_i.x(t)+B_i.u(t)+D.h(t)$ (17)

with $i = 1, \dots, r$, $r = 8$ is the fuzzy rules number and F_{ji} are the fuzzy sets.

The weighted sum of the T-S fuzzy system is so in the next form:

$$\dot{x}(t) = \sum_{i=1}^{r} \mu_i\left(q(t)\right)\left\{A_i.x(t) + B_i.u(t) + D.h(t)\right\} \qquad (18)$$

where matrices A_i and B_i are given by the following expressions:

$$A_i = \begin{bmatrix} -\dfrac{R_f}{L_f} & w & 0 \\ -w & -\dfrac{R_f}{L_f} & 0 \\ \dfrac{3q_{1i}}{4C} & \dfrac{3q_{2i}}{4C} & -\dfrac{1}{RC} - \dfrac{i_{pvm}}{Cu_c} \end{bmatrix},$$

$$B_i = \begin{bmatrix} -\dfrac{q_{3i}}{2L_f} & 0 \\ 0 & -\dfrac{q_{3i}}{2L_f} \\ 0 & 0 \end{bmatrix}.$$

The activation degree for each rule i, is given by the normalizing form: $\mu_i\left(q(t)\right) = \dfrac{w_i\left(q(t)\right)}{\sum_{i=1}^{r} w_i\left(q(t)\right)}$ (19)

which implies that: $\sum_{i=1}^{r} \mu_i\left(q(t)\right) = 1$ for all t.

$$\text{with } w_i\left(q(t)\right) = \prod_{j=1}^{3} F_{ji}\left(q(t)\right) \qquad (20)$$

The membership functions are given in the following general form: $f_{aj} = \dfrac{q_j(t) - qm_j}{qM_j - qm_j}$ and $f_{bj} = 1 - f_{aj}$.

where qM_j and qm_j are the maximum and the minimum values of the variable $q_j(t)$ for *j=1, .,3*.

Table II represents the Fuzzy rules form.

V. AUGMENTED SYSTEM

By defining the state reference vector by:

$$x_r(t) = \left[i_{odr}(t) \quad i_{oqr}(t) \quad u_{cr}(t)\right]^T \qquad (21)$$

and the augmented vector by: $\bar{x} = \left[x^T \quad e_I^T\right]^T$ thus

$$\dot{\bar{x}} = \left[\dot{x}^T \quad e^T\right]^T \qquad (22)$$

and the error vector by:

$$e(t) = y(t) - y_r(t) = C\bar{x}(t) = C\left(x(t) - x_r(t)\right) \qquad (23)$$

Which allow us to describe the augmented vector by the following expression:

$$\dot{\bar{x}}(t) = \sum_{i=1}^{r} \mu_i\left(q(t)\right)\left\{\bar{A}_i.x(t) + \bar{B}_i.u(t) + \bar{D}.\bar{h}(t)\right\} \qquad (24)$$

where: $\bar{A}_i = \begin{bmatrix} A_i & 0 \\ C & 0 \end{bmatrix}$, $\bar{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}$, $\bar{D} = \begin{bmatrix} D & 0 \\ 0 & -C \end{bmatrix}$,

and, $\bar{h}(t) = \left[h^T \quad x_r^T\right]^T$.

A. *Command strategy*

The control purpose is to force the active and reactive powers, generated by the PV panel and controlled by a T-S fuzzy controller, to follow the reference values which are chosen as: the reference active power is equal to the optimal power calculated with the FLC controller, while the reference reactive value is imposed equal to zero.

TABLE II Fuzzy rules from 1 to 8

Fuzzy ***sets of rules***			***Parameters of then-part***		
F_{1i}	F_{2i}	F_{3i}	q_{1i}	q_{2i}	q_{3i}
f_{a1}	f_{a2}	f_{a3}	qM_1	qM_2	qM_3
f_{a1}	f_{a2}	f_{b3}	qM_1	qM_2	qm_3
f_{a1}	f_{b2}	f_{a3}	qM_1	qm_2	qM_3
f_{a1}	f_{b2}	f_{b3}	qM_1	qm_2	qm_3
f_{b1}	f_{a2}	f_{a3}	qm_1	qM_2	qM_3
f_{b1}	f_{a2}	f_{b3}	qm_1	qM_2	qm_3
f_{b1}	f_{b2}	f_{a3}	qm_1	qm_2	qM_3
f_{b1}	f_{b2}	f_{b3}	qm_1	qm_2	qm_3

The principle of this control is also to maintain a stable voltage at the DC bus terminals while acting on the inverter control signals (β_{od}, β_{oq}).

The active P and reactive Q powers produced and injected to the network are respectively expressed by:

$$P = \frac{3}{2}\left(V_{rd}\, i_{od} + V_{rq}\, i_{oq}\right) \qquad (25)$$

$$Q = \frac{3}{2}\left(V_{rd}\, i_{oq} - V_{rq}\, i_{od}\right) \qquad (26)$$

We impose that the quadratic components voltage and current of the network are equal to zero ($V_{rq} = 0$, $i_{oqRef} = 0$), and we act on the PARK transform angle to control V_{rq}. So, we get the following expressions:

$$Q = \frac{3}{2}V_{rd}\, i_{oq} = 0 \text{ and } P = \frac{3}{2}V_{rd}\, i_{od} \qquad (27)$$

Thus, the currents components i_{od} and i_{oq} allow to respectively control the active and reactive powers.

Considering the power losses in the filter resistances and in the inverter transistors resistances, the supplied active power to the network is so:

$$P = \frac{3}{2} V_{rd}\, i_{od} = v_{Opt}\, i_{Opt} - \frac{3}{2} R_T \left(i_{od}^2 + i_{oq}^2 \right) \qquad (28)$$

with: $v_{Opt}\, i_{Opt}$: is the maximum power provided by the photovoltaic generator, and $\frac{3}{2} R_T \left(i_{od}^2 + i_{oq}^2 \right)$ is the lost power in the filter resistors and those of the inverter transistors.

Using both active power expressions, we can express the direct current reference component as follows:

$$i_{od\,Ref} = \frac{\frac{2}{3} v_{Opt}\, i_{Opt} - R_T \left(\frac{4}{3} \frac{i_{Opt}}{\beta_{od}} \right)^2}{V_{rd}} \qquad (29)$$

where $i_{ond}(t)$ is approximated by:

$$i_{ond}(t) \approx i_{Opt}(t) = \frac{3}{4} \beta_{od}(t)\, i_{od}(t)\ . \qquad (30)$$

B. T-S fuzzy model

The system control law is given by the following equation:

$$u(t) = -\sum_{j=1}^{8} \mu_j k_j \bar{x}(t) \qquad (31)$$

where k_j is the controller gain of each sub-model.

So, the system dynamics get the following form:

$$\dot{\bar{x}}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \mu_i \left(q(t) \right) \mu_j \left(q(t) \right) \left\{ \left(\bar{A}_i - \bar{B}_i k_j \right) \bar{x}(t) + \bar{D}.\bar{h}(t) \right\}$$

(32)

The H_∞ criterion, expressed by (33), and the Lyapunov quadratic function, noted by (34), are considered in order to ensure a good control while rejecting the disturbances effect and to calculate the fuzzy controller gains.

$$\int_0^\infty e_I^T e_I\, dt < \delta^2 \int_0^\infty \bar{h}^T \bar{h}\, dt \ \text{ with } \delta > 0 \qquad (35)$$

$$V(\bar{x}) = \bar{x}^T P \bar{x} \ \text{ with } P = P^T > 0$$

$$\text{and } \dot{V}(\bar{x}) < 0 \qquad (36)$$

So, the deduced stability condition is denoted in the form:

$$\dot{V}(\bar{x}) + e_I^T e_I - \delta^2 \bar{h}^T \bar{h} < 0 \qquad (37)$$

which can be noted in the following matrix form:

$$\begin{bmatrix} \left(\bar{A}_i^T - k_j^T \bar{B}_i^T \right) P + P \left(\bar{A}_i - \bar{B}_i k_j \right) + C_e^T C_e & P\bar{D} \\ \bar{D}^T P & -\delta^2 I \end{bmatrix} < 0$$

(38)

$$\text{with } e_I = C_e \bar{x} = C_e \begin{bmatrix} x \\ e_I \end{bmatrix} \qquad (39)$$

$$\text{where } C_e = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (40)$$

On both sides of equation (41), we multiply by $\begin{bmatrix} P^{-1} & 0 \\ 0 & I \end{bmatrix}$ and we put $X = P^{-1}$ and $M_j = k_j P^{-1}$, we then obtain:

$$\begin{bmatrix} X\bar{A}_i^T + \bar{A}_i X - M_j^T \bar{B}_i^T - \bar{B}_i M_j + X C_e^T C_e X & \bar{D} \\ \bar{D}^T & -\delta^2 I \end{bmatrix} < 0$$

(42)

Finally, the Schur complement lemma use, allows us to get the following inequality:

$$\begin{bmatrix} X\bar{A}_i^T + \bar{A}_i X - M_j^T \bar{B}_i^T - \bar{B}_i M_j & X C_e^T & \bar{D} \\ C_e X & -I & 0 \\ \bar{D}^T & 0 & -\delta^2 I \end{bmatrix} < 0$$

(43)

The controller gains, denoted by $k_j = M_j X^{-1}$, will be calculated using the matrix inequality resolution (44)

VI. SIMULATION RESULTS

The proposed PV power generation inverter has two loops: the FLC MPPT loop allowing to deduce the optimal output power according to the optimal values of voltage and current extracted from the PV array, whereas the T-S fuzzy controller loop is used to deduce the regulated control laws of the inverter (β_{od} and β_{oq}).

In order to evaluate and verify the performance of this algorithm, we expose the simulation results obtained in a Matlab/Simulink environment.

The used three-phase inverter has the following specifications:

Input DC voltage $U_c = V_{pv\_opt}$ which is divided in two parts through two capacitors $C_1 = C_2 = 10\ \mathrm{mF}$. We used a three-phase low voltage network ($Vm = 128V$ and $f = 50\ \mathrm{Hz}$) per phase.

The obtained simulation results were with a step variation of the solar radiation and the temperature represented in the table III.

Figs. 5-7 represent the optimal output voltage, current and power generated from the PV system and deduced by the FLC algorithm.

Fig. 5 shows the system efficiency in producing a constant PV panel voltage, which then allows the continuous bus voltage value to be maintained.

Figs. 6-7 show that, with each change in solar

variables (T, G), the proposed method allows the PV system to adapt quickly with these variations.

TABLE III Climatic Variations

Time (s)	0	2.2	3	4	5	6	7	8	9
G*100 (w/m^2)	6	7	8	9	10	9	8	7	6
T (°C)	24	25	26	27	28	27	26	25	24

Consequently, it can be deduced that the proposed method is not affected by the climatic variations.

Therefore, the different electrical quantities (voltage, current, power) at the output of the photovoltaic generator converge to a new optimum operating point, which depends on the irradiation and the temperature as can be seen in the Figs. 8-9.

The simulation results show the proper functioning of the MPPT adaptation system based on the Mamdani fuzzy method. This algorithm can track the MPP progressively with a good robustness despite sudden variations of irradiation and temperature Figs. 10-11 show that the quadratic current $i_{oq}(t)$ as well as the direct current $i_{od}(t)$ follow well the respective reference currents $i_{oqRef}(t)$ and $i_{odRef}(t)$ calculated with the MPPT.

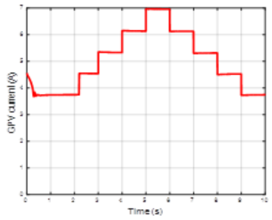

Fig. 6PVG current (A)

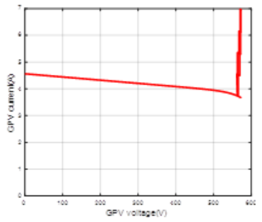

Fig. 9Current-Voltage characteristics of PVG

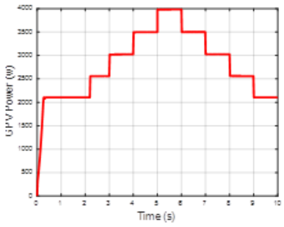

Fig. 7PVG power (w)

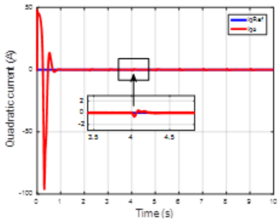

Fig. 10 Quadratic current (A)

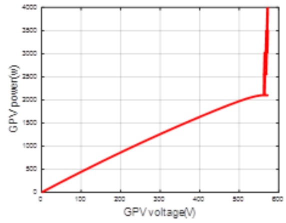

Fig. 8Power-Voltage characteristics of PVG

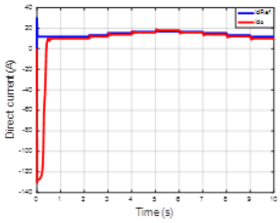

Fig. 11 Direct current (A)

From the grid voltage evolution in Figs. 12-13, it can be observed that $V_{oq}(t)$ is almost equal the reference value imposed to zero while $V_{od}(t)$ is constant and tend to its phase reference which is -127V.

According to the power curves for the panel and the network (Fig. 14), it is clear that these powers are varied following the climatic variations. However, the active power generated by the PVG will not be totally injected into the network because part of it will be dissipated in the filter R_f resistances and in those of the inverter transistors.

Furthermore, the injected power varies with the d-q currents variations. Since, the inverter current is generated with a low harmonic, which produces slight oscillations in the inverter power and so in the network power. These oscillations will be reduced by the T-S fuzzy controller.

Figs. 15-16 represent the sinewave forms of the PVG-grid voltages and the abc currents. A strong current i_{od} is observed in the beginning in Fig. 16 which will be reduced when the voltage delivered by the inverter reaches the grid voltage

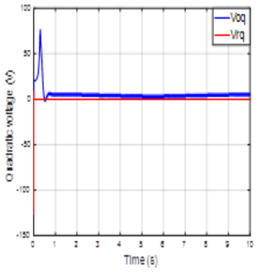

Fig 12 Quadratic voltages (V)

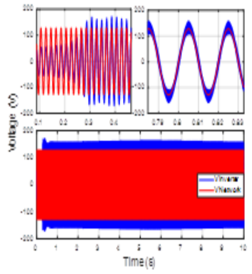

Fig. 15 PVG-grid voltages (v)

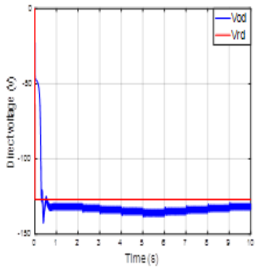

Fig. 13 Direct voltages (V)

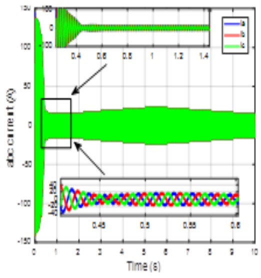

Fig. 16 abc currents (A)

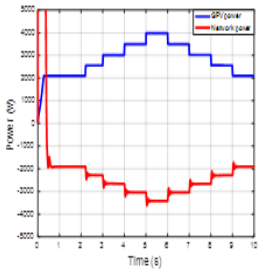

Fig. 14 Active power (w)

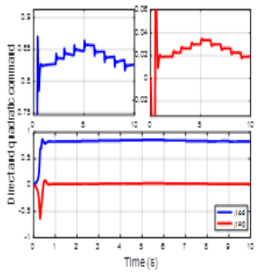

Fig. 17 d-q components command

For different values of G and T, it is observed that the control laws (β_{od}, β_{oq}) varies (Fig. 17) making the generator to operate at its maximum power and to control the energy transfer towards the electrical network.

VII. CONCLUSION

In this paper, a smart control strategy based on the Mamdani fuzzy logic system was proposed to calculate the MPPT of a PV energy generation system. The PV system was described by nine local models to extract the optimal current and voltage. Centroid type membership functions were used to calculate the weight of each local model.

However, the implementation of this type of algorithm is more complex than conventional algorithms. In addition, the effectiveness of this algorithm greatly depends on the inference table.

An efficient control strategy based on a blurred T-S controller was developed to control the active and reactive power delivered by the PV modules via an inverter to the utility grid.

The task of the inverter consists in transforming the continuous signal supplied by the photovoltaic generator into an alternating signal having the same characteristics as the network. Then, the maximum power produced by the PVG is injected into the network. To reduce the harmonics and improve the quality of the inverter output signals, an RL filter was applied.

We can conclude that the introduction of an intelligent MPPT in PV systems is actually a promising technique. Needless to remind that the MPPT based on a fuzzy model does not require an expert knowledge on the exact PV model. The used fuzzy logic algorithm is robust and efficient and allowed the generator to operate at its maximum power with very small oscillations around the optimal values.

From the simulation results, it can be clearly noticed that the responses are fast, the overshoots are negligible and there are fewer fluctuations for rapid irradiance changes. So, very good performances were achieved.

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