Fuzzy-Suboptimal Mode MPPT Control for Three-Phase Grid-Connected PV

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Abstract- In order to maximize the conversion efficiency of a photovoltaic generator a maximum power point controller is used. In this paper, a new suboptimal sliding mode control is designed to maximize the energy delivered by a photovoltaic chain connected to a three-phase electrical grid. The proposed control law ensures a stable DC-DC converter output power and a three-phase grid voltage source inverter control is used to regulate the DC link voltage. The performances of the proposed controller are verified through simulation and the injection of zero reactive energy is guaranteed.

Keywords Second order sliding mode; suboptimal; maximum power point tracking; three-phase grid; photovoltaic generator; fuzzy logic.

1. Introduction

The temperature of our planet is in continuous increase due to what we call the greenhouse effect. Greenhouse gases exist naturally in the earth's atmosphere before the industrial revolution, their role is summed up in the assurance of an average heat of the planet to avoid the drop in temperature to certain values where life is impossible. Today and after the take-off in the industrial field, we have reached a point where our energy needs pushed us to use a very important quantity of fossil fuels and non-clean energies (petroleum, coal ...) thing that increased the amount of greenhouse gas in the atmosphere. Renewable energies present one of the solutions for satisfying our energy needs and also protect the environment from excessive and dangerous heating.

Photovoltaic solar energy is one of the most popular and used renewable energies not only in our daily lives but also in space applications and spacecraft. Despite their wide use, photovoltaic panels have a low power efficiency which cannot satisfy our energy demand besides another problem concerning the nonlinearity of the power as a function of the operating voltage. The maximum power point tracking command has been invented to control the panel operation point and make it tracks the maximum power in order to optimize the produced power.

The DC link voltage is controlled by the VSIC control (voltage source inverter control) which is based on the measurement of the three-phase currents and voltages of the utility grid and expresses them in the Park reference in order to obtain the dq components. This technique makes an easy regulation of the DC link voltage and it guarantees a robust flow control of the active power and at the same time ensures a zero reactive power injected into the grid.

The references [1,2] present a constant voltage method that is based on the fact that Vmpp (voltage corresponds to maximum power point) is proportional to Voc the panel open circuit voltage. The proportionality coefficient is between 0.72 and 0.78. The Voc must be measured in a sample time when the load is not connected, but the inconvenient of this technique is the power losses caused by the opening of the panel terminals to effectuate the measurement. In order to avoid this inconvenient a new method is proposed in [3] called pilot cell which is based on the use of a speared photovoltaic cell to measure and calculate the panels open circuit voltage without disconnecting the load.

The reference [4] proposes a constant current method method which has an operating principal same as the previous method, it is based on the proportional relation between the panel open circuit current and the Impp (current corresponds to maximum power point). The proportionality coefficient is between 0.78 and 0.92.

The curve fitting method which described in [5] is based on the non linear characteristic power-voltage or power-current of a photovoltaic panel in order to calculate the Vmpp voltage.

The method perturb and observe [6] is one of the most popular MPPT techniques because of its ease implementation and its moderate accuracy. This method based on iterative approach has one major inconvenient which is the power oscillation. The algorithm of this method makes the operation point oscillates around the maximum power point and as consequence, the power delivered by the photovoltaic panel became unstable and causes important energy losses, in addition, it can lose the maximum power point when there is a fast-changing climatic condition.

Another method called beta method is proposed in [7] to solve the previous inconvenient, it is based on the calculation of a parameter "beta" which depends on temperature, the panel cell diode quality factor and Boltzmann's constant. The algorithm of this method can be summarized on two steps: firstly the beta coefficient must be calculated using the formula in literature, in this part of the algorithm the panel operation point follows the beta parameter, at the moment when it is very near to beta a P&O or incremental conductance method is used to reach the MPP.

The incremental conductance is based on the fact that the derivative of the power against voltage at the MPP equal zero, its operating principal is to search the MPP by comparing the instantaneous conductance to the incremental conductance [8].

Load current or load voltage maximization is a technique based on the extraction of the load parameters (current or voltage) to control the output power so to control the photovoltaic panel power. This method is independent of irradiation conditions but it depends on the variation of the load [9].

The reference [10] discussed the use of one cycle method to extract the maximum power from a photovoltaic panel. The operating principle of this technique is to integrate a variable (current for example) and convert it to be a reference value.

The fuzzy logic technique is a method which based on the fuzzy set theorem. The extraction of maximum power is realized by a fuzzy controller which is built from three blocks: fuzzification, rules table or inference and defuzzification. The first block converts the numerical variables to linguistic ones, the second block compares the input linguistic variables in order to transform them to one output linguistic variable, finely the conversion of this variable to a numerical one is ensured by a defuzzification block [11,12].

Artificial neural network is also one of the techniques based on artificial intelligent, it is inspired from the interconnected neurons of central nervous system in order to form a network similar to human biological neural network [13].

A method that has attracted the interest of researchers in previous years and has been limited in the control of rotating machines has appeared in the photovoltaic fields, it is the sliding mode and exactly the high order sliding mode control. The power of the sliding mode is in its simplicity of implementation and its robustness against external disturbances. It presents good results concerning the control of electrical machines and it is well adapted to control solar panels when the temperature and the irradiation are varied quickly. The need for a high order sliding mode was appeared because of the problem faced in the first order one (chattering around the sliding surface) however, the use of a higher order requires an optimal choice of the gains, for this reason a fuzzy controller based on fuzzy logic theorem [11,14] is used to solve this inconvenience.

2. The studied system

The studied system is formed by a photovoltaic panel which converts the sunlight to electricity, a boost converter to be controlled by its duty cycle in order to command the PV voltage, a three-phase inverter to transform the DC current to an AC one.

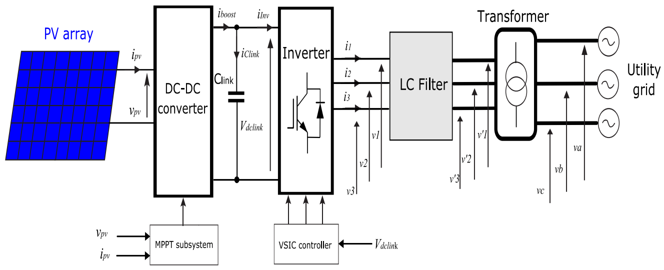

Fig. 1. The studied system.

A filter LC is used to eliminate harmonics from the inverter output, and a 100 kVA transformer is used to increase the voltage to 20 kV before interconnecting the system with the utility grid.

The control subsystem is constituted on two parts, the first one is the MPPT subsystem which controls the PV power using the proposed second-order sliding mode control to track the maximum power point. The second part is the voltage source inverter controller VSIC which used to regulate the DC link voltage and synchronize the inverter three-phase output voltages with the utility grid ones.

3. Modelization of the system

3.1. The direct current DC part of the system:

The photovoltaic array is formed by 100 panels associated in parallel, each one is constituted on 96 monocrystalline cells connected in series in order to transform the sunlight on electricity and deliver a maximum power equal 320W, the PV cell model is given on Fig. 2. The maximum power produced by this array is 32 kW.

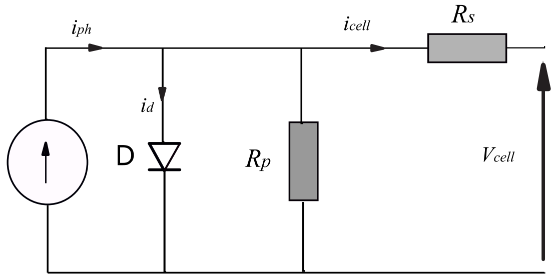

Fig. 2. Photovoltaic cell model.

The DC-DC converter utilized in the proposed simulation is the boost one, it increases the input voltage to reach the DC-link one (around 500 VDC) and controls the photovoltaic array operating point to track the maximum power point.

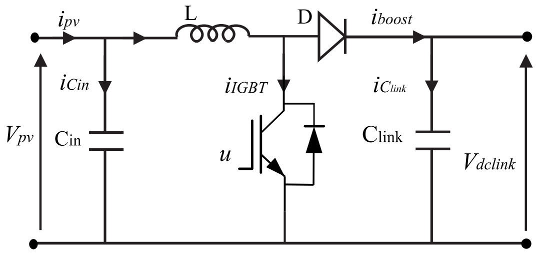

Fig. 3. Boost converter.

The equation described the boost converter is:

$$\frac{dVpv(t)}{dt} = \frac{ipv(t)}{Cin} - \frac{iL(t)}{Cin} u(t) \tag{1}$$

3.2. Inverter

The conversion of the direct current into an alternative one before injecting it in the distribution grid requires the use of a three-phase inverter (with two or three levels). In this paper we have used the three-level type because of its advantages of limiting harmonic currents and the stability of the output power, however, a filter LC is used to guaranty the injection of more stable active power. A 100 kVA transformer is used for the adaptation of the inverter output voltage with that of the three-phase medium-voltage grid (25 kV). According to Fig. 3, the photovoltaic array output power and current can be described by:

$$p_{pv} = v_{pv}.i_{pv} \tag{2}$$

$$i_{pv} = i_{Cin} + i_{IGBT} + i_{boost} \tag{3}$$

The boost output current can be written as follow:

$$i_{boost} = i_{Clink} + i_{Inv} \tag{4}$$

Where *vpv* and *ipv* are the output voltage and current of the photovoltaic array, *ppv* is the panel output power, *iCin* and *iIGBT* are the current followings through the input capacitor and through the IGBT transistor, *iboost* is the boost converter output current.

$$v - v' = R_f.i + L_f\frac{di}{dt} \tag{5}$$

$$\begin{bmatrix} v1 \\ v2 \\ v3 \end{bmatrix} - \begin{bmatrix} v'1 \\ v'2 \\ v'3 \end{bmatrix} = R \begin{bmatrix} i1 \\ i2 \\ i3 \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i1 \\ i2 \\ i3 \end{bmatrix} \tag{6}$$

Where *v* and *i* are the inverter output voltage and current, *v'* is the transformer primary voltages, *Rf* and *Lf* are the filter resistance and inductance respectively.

To control the injected active and reactive power into the utility grid it is necessary to present the studied system parameters in the rotating synchronous reference frame using the d-q components resulted from a Park transformation. For a system described by [*z1*,*z2*,*z3*], where *z1*, *z2*, and *z3* are the three-phase voltages or currents, a Park transformation is obtained by a Clarke one plus a Beta rotation with an angle equal to the utility grid voltage phase angle, the Clark transformation is defined by the system:

$$\begin{bmatrix} z0 \\ z\alpha \\ z\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} z1 \\ z2 \\ z3 \end{bmatrix} \tag{7}$$

The Park or d-q components are deduced by a rotation:

$$\begin{bmatrix} zd \\ zq \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} z\alpha \\ z\beta \end{bmatrix} \tag{8}$$

The instantaneous active and reactive injected power *p* and *q*, respectively are described by:

$$\begin{aligned} p &= v'd.id + v'q.iq \\ q &= v'q.id - v'd.iq \end{aligned} \tag{9}$$

Where *id*, *iq*, *v'd*, and *v'q* are the d-q components of the three-phase grid currents and voltages, respectively, if vector *v'q* equal zero (aligned with the d axis) we can ensure a separate control of the instantaneous active and reactive powers.

$$\begin{aligned} p &= v'd.id \\ q &= -v'd.iq \end{aligned} \tag{10}$$

The control unit is formed by the MPPT and VISC subsystems. VISC is constituted from an inner and outer loop, pulse width modulation PWM and Park transformation blocks.

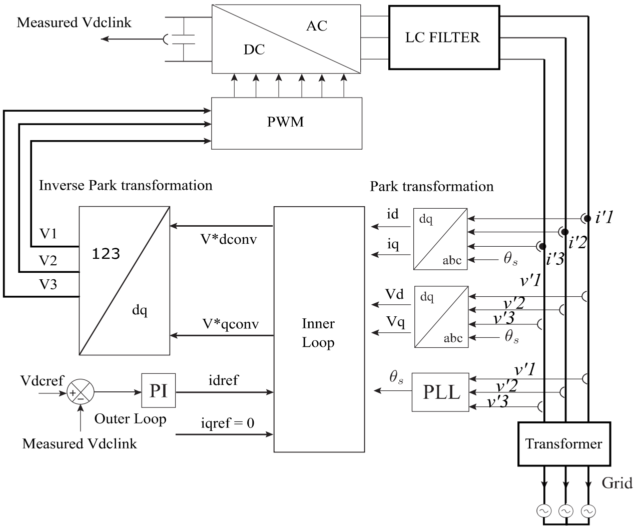

Fig. 4. Three-phase voltage source inverter control (VSIC).

Maximum Power Point Tracking: This subsystem block controls a duty cycle of a PWM signal delivered to command a DC-DC boost converter in order to track the maximum power point of the photovoltaic array by the variation of the output voltage.

Three-phase voltage source inverter control (VSIC):

Inner loop: it is constituted from two PI regulators; its role is to calculate the d-q reference line voltage components using the outer loop output variable *idref*.

Outer loop: its role is to calculate the reference current d component correspond to the DC link constant voltage which is given by 500V, the *iqref* is equal zero in order to have a null reactive power.

3.3. LC filter

The filter used to attenuate the harmonics produced (make it less than 5%) by the high-frequency switches of the inverter's IGBTs, is of the second order low pass LC type. The harmonic standard allows a 15-20% of the rated current [15].

4. Sliding mode control

4.1. Definition

The sliding mode method was introduced initially for the control of systems with a variable structure which has been appeared in the Soviet literature for the first time. It was used specifically in power electronics converters and the control of rotating machines. Currently, this command is used in maximum power point tracking techniques. In the control of systems with a variable structure by sliding mode, the state trajectory is fed to the sliding surface and then, the control law obliged the operating point to remain on this surface [16,17].

The sliding mode control is a robust control based on the concept of changing the structure of the controller with the state of the system in order to obtain the desired response [18], it is based on the proposition of obtaining a hysteresis on the sliding surface S (x,t) = 0 and consequently an almost infinite switching frequency, practically this frequency must be limited because the variable structure systems can only operate in a specific frequency range and depend on the nature of the components used, moreover it is necessary to reduce the losses by switching to avoid the destruction of the electronic components. The idea is to separate the state space by a surface called "sliding surface", all the points of the state space must be converged towards this surface, it is the condition of attractiveness. Stabilization on the sliding surface is achieved by switching at each border crossing and at the same time the operating point converges to that of equilibrium (equilibrium condition), in other words, must find the condition for which the dynamics of the system slides on the surface towards the desired equilibrium point.

On the surface, the dynamics of the system is independent of that of the initial process, which implies that this type of control enters the field of robust controls. These notions of stability are demonstrated taking into account the stability principle according to the LYAPUNOV criterion.

The objective of the sliding mode command is summarized in two essential points:

- Synthesize a surface S(x,t) such that all the trajectories of the system obey the desired behaviour of tracking, regulation, and stability.
- Determining a control law (commutation) $\boldsymbol{u}$ which is capable of attracting all the state trajectories towards the sliding surface and holding them on this surface.

The main advantage of the sliding mode control is the robustness with respect to the change of the parameters or the disturbances. In addition, sliding mode control is relatively easy to implement compared to other types of non-linear commands. These properties make this control law suitable for many industrial applications, such as in the automotive or aeronautical fields.

4.2. Second order sliding mode: suboptimal method

The technique used to extract the maximum power point of the PV array is that of the second-order sliding mode and exactly suboptimal one.

The sliding condition:

The variable structure systems are described by differential equations with a discontinuous right-hand side thing that makes them difficult to be solved by using the mathematical classical theorem, in this case, a solution in the sense of Filippov can solve the equation.

In [19] Filippov proposed the following definition: $f: R^n \rightarrow R^n$ is a locally bounded measurable vector function.

$$\Gamma(x) = \cap_{r>0,\mu(s)} conv\{f(B(x,r)|S)\} \tag{11}$$

Where B (x, r) designates the ball of radius r centered in x and S any set of Lebesgue measure zero content in B (x, r). In the simplest case, when f is continuous almost everywhere, Γ (x) is the convex closure of the set of all possible limits of f(z) as z –> x, while {z} are continuity points of f(z).

Considering a nonlinear system described by a differential equation as follows:

$$\dot{x} = f(t, x(t), u(t)) \tag{12}$$

- $x \in X \subset R^n$ is the state space.
- $u \in U \subset R$ is an uncertain input signal.
- f is a smooth function.

The purpose of the proposed control is to define a sliding surface that surrounds the equilibrium point (Maximum PowerPoint) and control the operation point to reach this surface. When the sliding surface is null, i.e $s(t) = s(x(t), t) = 0$, the operation point is the same as the equilibrium one,(MPP), so the photovoltaic array delivers its maximum power.

Filippov's approach is presented in the case of a single discontinuous surface, to find a solution on this surface S, it is necessary to look for a continuous-time function which evolves on S. For this reason, it is necessary to extend the field f on the surface S, that is to say, it is necessary that f belongs to the tangent space to S in x. As a result, velocity vectors must be directed to the S surface, in other words, the S surface must be attractive at least in a neighborhood. The state space x is characterized by:

$$x = \begin{cases} X^+ & if \;\; s(x) > 0 \\ X^- & if \;\; s(x) < 0 \end{cases} \tag{13}$$

Which gives us in the neighborhood of $S(x) = 0$ two values of f:

$$x = \begin{cases} f^+ & if \;\; s(x) > 0 \\ f^- & if \;\; s(x) < 0 \end{cases} \tag{14}$$

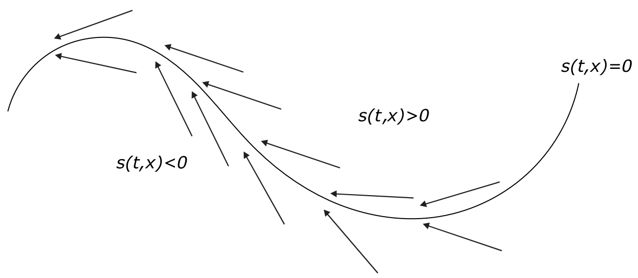

Fig. 5. State-space and trajectories to the sliding surface.

If we express the condition of existence of solution of the equation $\dot{x} = f(x, t)$ depending on the surface S, it is necessary to calculate its derivative:

$$\dot{S} = \frac{dS}{dt} = \langle \nabla S, f \rangle \tag{15}$$

which represents the scalar product of the normal to the surface $S(x) = 0$ and the vector $f(x, t)$. As a result, we deduce:

$$f^- < 0 \text{ and } f^+ > 0 \leftrightarrow \dot{S}.S < 0 \tag{16}$$

This condition, called sliding condition, represents a fundamental inequality for the synthesis of the control by sliding modes, it translates the fact that if the projections of f^+ and f^- on the vector , in a neighborhood of the surface S, have a contrary sign then the surface S is attractive.

In order to define the control law the following hypothesis must be considered [20]:

$U = \{u : |u| \leq Um\}$ where $Um > 1$ is a real constant.

$\exists u' \in [0,1]$ such that $\forall u(t)$ with $|u(t)| > u'$, $\exists t1$ such that $s(t)u(t) > 0$ for $t > t1$

$\dot{s}(x,t,u)$ is the total time derivative of the sliding function s, defined as:

$$\dot{s} = \dot{s}(x(t),t,u(t)) = \frac{\partial}{\partial t}s(x,t) + \frac{\partial}{\partial x}s(x,t)f(x,t,u) \tag{17}$$

There are positive constants s_0, $u'' < 1$, Γ_m and Γ_M such that if $|s(x,t)| \leq s0$ then:

$$\Gamma_m \leq \frac{\partial}{\partial u}\dot{s}(x,t,u) \leq \Gamma_M \quad \forall u \in U, x \in X \tag{18}$$

$\exists \phi > 0$ such that $\forall t, x \in X, u \in U$ then :

$$\left| \frac{\partial}{\partial t}\dot{s}(x,t,u) + \frac{\partial}{\partial x}\dot{s}(x,t,u)f(x,t,u) \right| \leq \phi \tag{19}$$

This second-order sliding mode is deduced from the already discussed method in the literature which is time-optimal one. The trajectories of the system in the topological state plane using this mode follow a jumping and twisting behavior. The control is defined by the following equation:

$$v(t) = K\mu(t)sign(\tfrac{1}{2}r_{1M} - r_1(t)) \tag{20}$$

$$\mu(t) = \begin{cases} \mu' & if \;\; \left[r(t) - \frac{1}{2}r_{1M}\right][r_{1M} - r_1(t)] > 0 \\ 1 & if \;\; \left[r_1(t) - \frac{1}{2}r_{1M}\right][r_{1M} - r_1(t)] \leq 0 \end{cases} \tag{21}$$

Where K is the control amplitude, r_{1M} is the last extremum of $r_1(t)$ and $\mu(t)$ is the control modulation factor. The chosen sliding surface $s(t, x)$ is defined as flow:

$$s(t, x) = g_1(t, x) + \beta g_2(t, x) \tag{22}$$

Where:

$$\begin{cases} \dot{g}_2(t,x) = g_1(t,x) \\ \dot{g}_1(t,x) = a(t,x) + b(t,x)d(t) \end{cases} \quad (23)$$

- $a(t,x)$ and $b(t,x)$ are functions that depend on $V_{pv}(t), V_{dclink}(t)$ and $iL(t)$
- $\dot{u}(t) = v(t)$.

The sufficient conditions for the finite-time convergence to the sliding surface are:

$$\begin{cases} \mu' \epsilon (0,1] \cap \left(0, \frac{3\Gamma_m}{\Gamma_M}\right) \\ K > max\left(\frac{\Phi}{\mu' \Gamma_m}, \frac{4\Phi}{3\Gamma_m - \mu' \Gamma_M}\right) \end{cases} \quad (24)$$

An upper bound for the convergence time is defined by:

$$t_{opt\infty} \leq t_{M1} + \theta_{opt1} \frac{1}{1-\theta_{opt2}} \sqrt{|r_{1M}|} \quad (25)$$

where:

$$\theta_{opt1} = \frac{(\Gamma_m + \mu' \Gamma_M)K}{(\Gamma_m K - \Phi)\sqrt{\mu' \Gamma_M K + \Phi}} \; ; \; \theta_{opt2} = \sqrt{\frac{(\mu' \Gamma_M - \Gamma_m)K + 2\Phi}{2(\Gamma_m K - \Phi)}} \quad (26)$$

To minimize the sliding surface and ensure an exact tracking of the maximum power point of the photovoltaic panel K must be equal to:

$$K = \frac{4\Phi}{3\Gamma_m - \mu' \Gamma_M}\left[1 + \sqrt{1 + \frac{3\Gamma_m - \mu' \Gamma_M}{4\Gamma_M}}\right] \quad (27)$$

In this paper we have used a fuzzy controller which is based on fuzzy logic theory in order to estimate the control amplitude *K*. The proposed fuzzy-suboptimal controller regroups the robustness of the suboptimal second order sliding mode and the fuzzy logic high speed convergence.

Practically we can estimate r_{1M} by verifying the sign of the quantity $[r_1(t-\delta) - r_1(t)]r_1(t)$, in this case the control amplitude *K* must belong to a finite domain instead of a semi-infinite one, so it must verify the following condition:

$$K \in \left(\max\left(\frac{\Phi}{\mu' \Gamma_m}, K_1(\delta, r_{1M})\right), K_2(\delta, r_{1M})\right) \quad (28)$$

Where K_1 and K_2 are the solutions of the second order equation (29):

$$\left[(3\Gamma_m - \mu' \Gamma_M)\frac{K_i}{\Phi} - 4\right]\frac{r_{1M}}{\Phi\delta^2} - \frac{K_i}{8\Phi}[\Gamma_m + \Gamma_M(2-\mu')]\left(\Gamma_M \frac{K_i}{\Phi} + 1\right) = 0 \quad (29)$$

5. Simulation results

In this article, we have proposed a method based on suboptimal second-order sliding mode and fuzzy logic to encompass the two best features of the so-called techniques and as a result, we have used a fuzzy-suboptimal controller where the variable inputs are:

- CH the chattering amplitude.
- r_{1M} is the last extremum of $r_1(t)$.

The chosen rules table for the fuzzy-suboptimal controller is as follows:

Table 1. Rules table

r_{1M} / CH	Z	S	M	L
Z	ZE	PS	PM	PL
S	NS	ZE	PS	PM
M	NM	NS	None	None
L	NL	NM	None	None

The membership functions used are shown in the following figure:

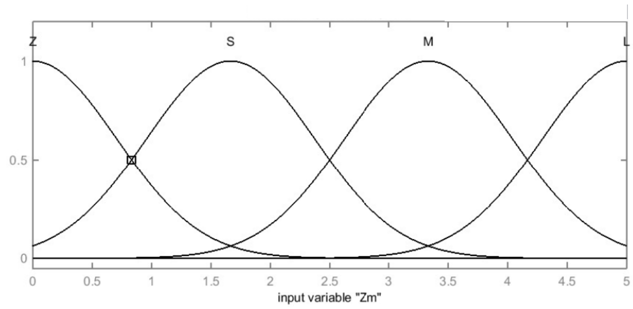

Fig. 6. Chattering amplitude membership functions.

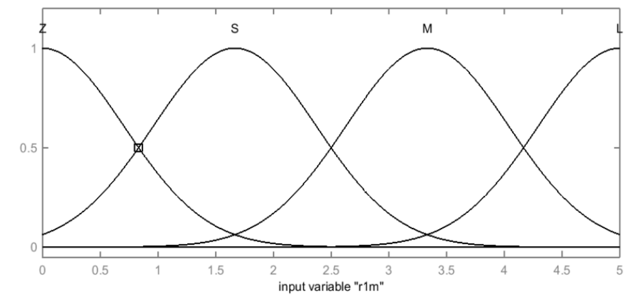

Fig. 7. The last extremum of r_1 membership functions.

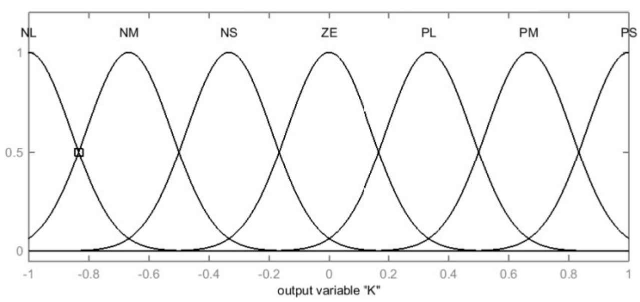

Fig. 8. The control amplitude membership functions.

In literature, most of the MPPT studies consider just the irradiation as a variable and not temperature (considered as a constant). The irradiation and temperature profiles chosen in the simulation are indicated in Fig. 9 and Fig. 10.

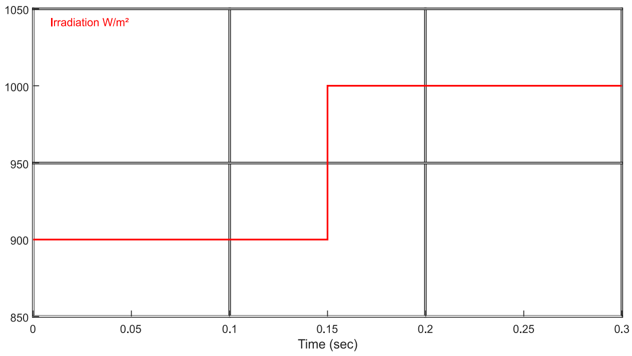

Fig. 9. The irradiation profile.

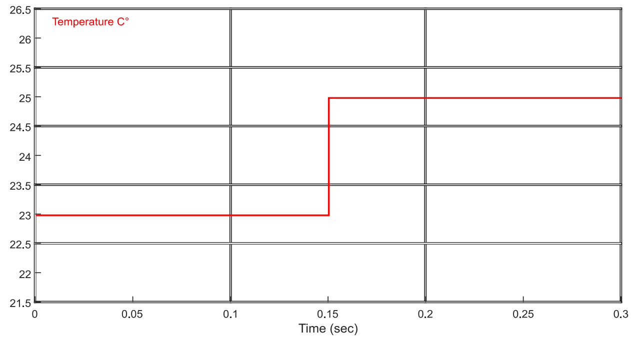

Fig. 10. The temperature profile.

First of all and before analyzing the injection of active and reactive power in the utility grid, we must improve the efficiency of the fuzzy-suboptimal controller to ensure that the photovoltaic array delivers its maximum power. Fig. 11 illustrates the array output power which tracks the maximum power in a very short time, and even the irradiation and temperature change the fuzzy-suboptimal controller follows the MPP and the array output power reaches the maximum power in standards test condition (1000 W/m² and 25 C°) which is 32 kW.

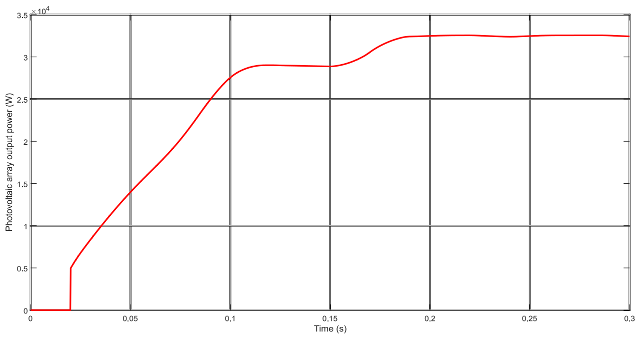

Fig. 11. The photovoltaic array output power.

We have 100 photovoltaic panels associated in parallel and Fig. 12 illustrates that the array output voltage is equal to the Vmpp value when the irradiation is 900 W/m² and also when it is 1000 W/m².

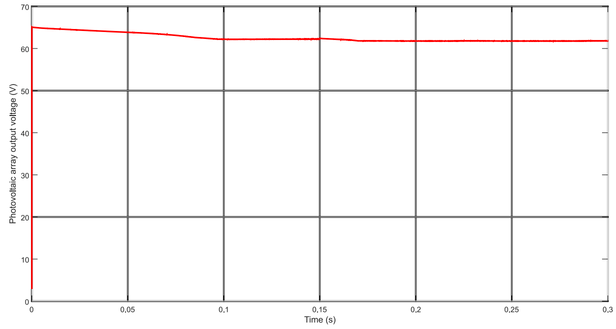

Fig. 12. The photovoltaic array output voltage.

Fig. 13 shows that the DC link voltage is constant and equal to 500 V, so the energy flow from the DC part (boost converter) to the alternative part (utility grid) is guaranteed.

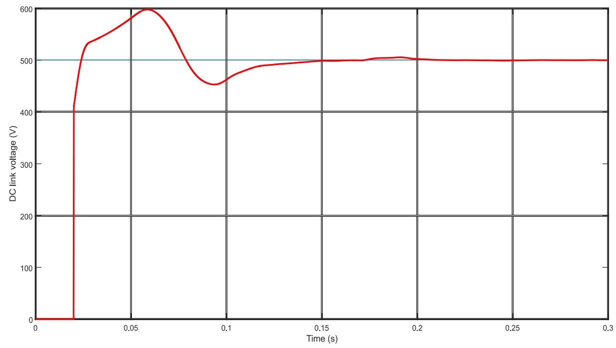

Fig. 13. The DC link voltage.

As we have mentioned in the previous paragraph, the fuzzy-suboptimal controller has the role of tracking the maximum power point of the array and as we have seen in Fig. 11 the array output power reaches the MPP, but to verify the utility of the proposed solution we must ensure that s(t,x)=0 and s'(t,x)=0, the thing that is very clear in Fig. 14 and Fig. 15.

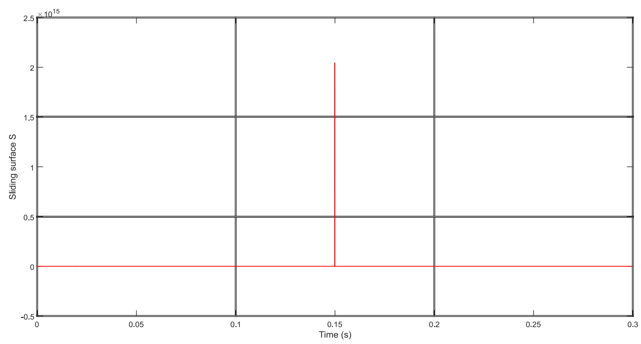

Fig. 14. The sliding surface.

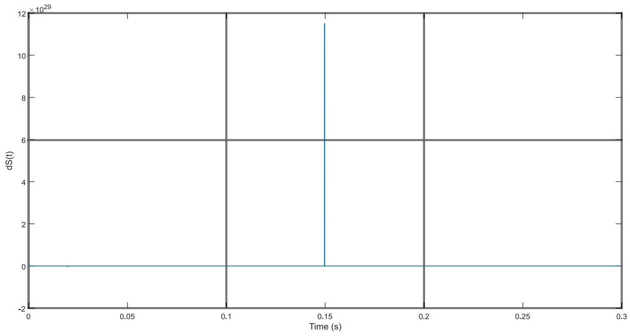

Fig. 15. The derivative of the sliding surface.

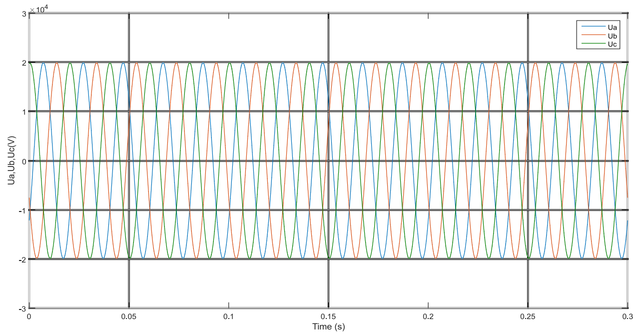

Fig. 18. The three-phase voltages.

Fig. 16 illustrates very clearly that the active injected power is equal to the maximum power point of the photovoltaic array thing which proves that the produced power is totally transferred to the utility grid and with zero injected reactive power, even when the climatic conditions vary (at 0.15 s) the system returns very quickly to its stable point (array output power tracks the MPP and the reactive injected power reaches zero), so the robustness of the proposed controller is justified.

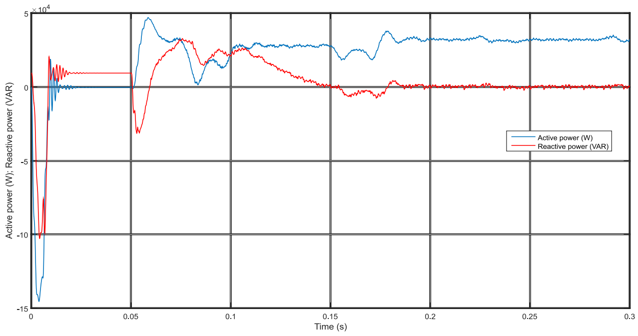

Fig. 16. The active and reactive injected powers.

The three-phase currents and voltages are mentioned in Fig. 17 and Fig. 18, they are equilibrated and sinusoidal.

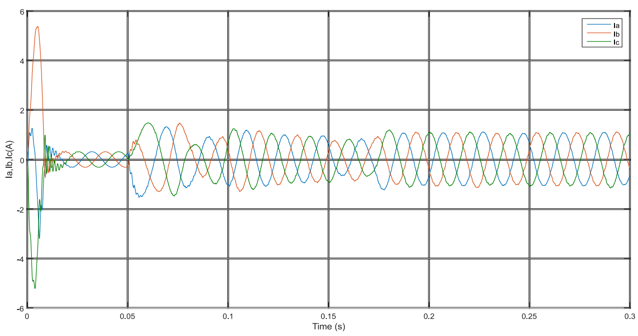

Fig. 17. The three-phase currents.

Fig. 19 illustrates the harmonic distortion rate THD that converges to 2%, the very inferior value compared to 15% the maximum allowed by the IEEE community [15].

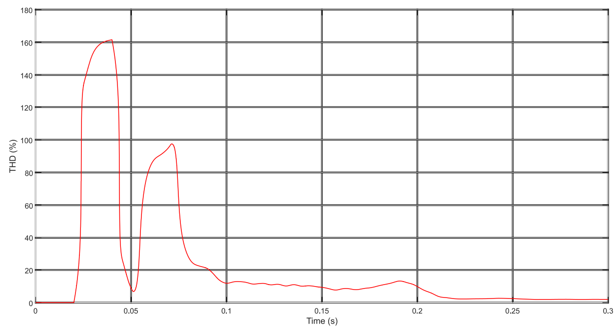

Fig. 19. The harmonic distortion rate.

6. Conclusion

This research paper presents a new results in the field of maximum power point tracking, it discuss a combination between the second-order sliding mode (suboptimal) and the fuzzy logic technique. The proposed method presents a very high convergence speed (MPP is tracked on 0.12s) and has improved a very good accuracy of the maximum power point. The voltage source inverter control has ensured a good energy flow from the DC part to the AC one (32kW) and the photovoltaic array output power is injected into the utility grid with zero injected reactive power. The proposed method can be implemented in a DSP cart for an experimental study.

References

[1] N. Hyeong-Ju, L. Dong-Yun and H. Dong-Seok, "An improved MPPT converter with current compensation method for small scaled PV-applications", 28th Annual Conference of the Industrial Electronics Society, Vol. 2, pp. 1118–19, 2002.

[2] AW. Leedy, G. Liping, KA. Aganah, "A constant voltage MPPT method for a solar powered boost converter with DC motor load", Proceedings of IEEE Southeastcon, pp. 1-6.2012.

[3] ZM. Salameh, F. Dagher,andWA. Lynch,"Step-down maximum power point tracker for photovoltaic systems", Sol Energy, Vol. 46, No. 5, pp. 279-282, 1991.

[4] SM. Alghuwainem,"Matching of a dc motor to a photovoltaic generator using a step-up converter with a current-locked loop", IEEE Trans Energy Convers, Vol. 9, No. 1, pp. 192-198, 1994.

[5] AW. Leedy, KE. Garcia, "Approximation of P–V characteristic curves for use in maximum power point tracking algorithms", Proceedings of the system theory (SSST) 45th southeastern symposium, pp. 93–88, 2013.

[6] H. Dilovan and G. Naci, "Fuzzy and P&O Based MPPT Controllers under Different Conditions", Proceedings of International Conference on Renewable Energy Research and Applications, Vol. 7, 2018.

[7] S. Jain and V. Agarwal, "A new algorithm for rapid tracking of approximate maximum power point in photovoltaic systems", IEEE Power Electron Lett , Vol. 2, No. 1, pp. 16–9, 2004.

[8] Safari, S. Mekhilef, "Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter", IEEE Trans Ind Electron, Vol. 58, No. 4, pp. 1154–61, 2011.

[9] D. Shmilovitz, "On the control of photovoltaic maximum power point tracker via output parameters", IEEE Proc Electr Power Appl, Vol. 152, No. 2, pp. 239–48, 2005.

[10] Y. Chen, KM. Smedley, "A cost-effective single-stage inverter with maximum power point tracking", IEEE Trans Power Electron, Vol. 19, No. 5, pp. 1289–94, 2004

[11] E.H.M. Ndiaye, A. Ndiaye, M.A. Tankari, G. Lefebvre, "Adaptive Neuro-Fuzzy Inference System Application for The Identification of a Photovoltaic System and The Forecasting of Its Maximum Power Point", Proceeding of International Conference on Renewable Energy Research and Applications, Vol. 7, 2018.

[12] H. Chaouali, W. Ben Salem, D. Mezghani, A. Mami, "Fuzzy Logic Optimization of a Centralized Energy Management Strategy for a Hybrid PV/PEMFC System Feeding a Water Pumping Station", International Journal of Renewable Energy Research, Vol. 8, No. 4, pp. 2190-2198, 2018.

[13] H. Maruta, D. Mitsutake, F. Kurokawa, JH. Chen, "A Neural Network Based Reference Modified PID Control with Simple Duration Design for Digitally Controlled DC-DC Converters", International Journal of Renewable Energy Research, Vol. 6, No. 2, pp. 550-560, 2016.

[14] MM. Algazar, H. Al-Monier, HA. EL-halimand M. Salem,"Maximum power point tracking using fuzzy logic control", International Journal of Electrical Power Energy Systems, Vol. 39, No. 1, pp. 221-228, 2012.

[15] IEEE Standards 519, Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, 1992.

[16] L. Yong-Chao, L. Salah, ND. Abdoul, C. Maurizio "Active-Flux-Based Super-Twisting Sliding Mode Observer for Sensorless Vector Control of Synchronous Reluctance Motor Drives", Proceeding of International Conference on Renewable Energy Research and Applications, Vol. 7, 2018.

[17] V.I. Utkin, "Variable structure systems with sliding mode", IEEE Trans Automat Conir, Vol. 22, No. 2, pp. 212–222, 1977.

[18] A. Ziouh and A. Abbou, "Fuzzy-Super Twisting Sliding Mode MPPT Control for Three-Phase Grid-Connected PV", International Journal of Renewable Energy Research, Vol. 8, No. 4, pp. 1812-1823, 2018.

[19] A.F. Filippov, Differential equations with discontinuous right-hand sides, Boston: Kluwer Academic Publishers, 1988, pp. 99-128.

[20] A. Pisano, Second Order Sliding Modes: Theory and Applications, Dipartimento di Ingegneria Elettrica ed Elettronica (DIEE), Università degli Studi di Cagliari, 2000.