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Modeling and control of photovoltaic system using sliding mode controle, comparative studies with conventional controls

***Abstract**. The case studied in this paper relates to the control of a system photovoltaic. As the output characteristic of a photovoltaic (PV) module is nonlinear and changes with solar irradiance and the load, its maximum power point (MPP) is not constant. Therefore, a (MPPT) technique is needed to draw peak power from the PV module to maximize the produced energy and voltage delivered by the PV system constant under varying conditions. In our study, we used two MPPT algorithms, the algorithm "Perturb and Observe" (P & O), then the algorithm "Increment of Conductance" (IncCond). For this, a control system is presented. The methods used for the simulation of this system are based on the use of a sliding mode control. Simulation results are presented to verify the simplicity, the stability and the robustness of this control technique against changes in weather conditions.*

Streszczenie.** Przypadek opisany w tym artykule dotyczy kontroli fotowoltaiki systemowej. Ponieważ charakterystyka wyjściowa modułu fotowoltaicznego (PV) jest nieliniowa i zmienia się wraz z natężeniem promieniowania słonecznego i obciążeniem, jego maksymalna wartość mocy (MPP) nie jest stała. Dlatego technika (MPPT) jest potrzebna do pobrania mocy szczytowej z modułu fotowoltaicznego w celu zmaksymalizowania wytworzonej energii i napięcia dostarczanego przez stałą systemu PV w różnych warunkach. W naszym badaniu wykorzystaliśmy dwa algorytmy MPPT, algorytm "Perturb and Observe" (P & O), a następnie algorytm "Increment of Conductance" (IncCond). W tym celu przedstawiono system kontroli. Metody użyte do symulacji tego systemu opierają się na zastosowaniu sterowania w trybie ślizgowym. Przedstawiono wyniki symulacji, aby zweryfikować prostotę, stabilność i odporność tej techniki sterowania przed zmianami warunków pogodowych. **Modelowanie i sterowanie systeme fotowoltaicznym metodą ślizgową – porówanie z systemami konwencjonalnymi

Słowa kluczowe:Fotowoltaika, MPPT, sterowanie w trybie ślizgowym, konwerter DC / DC.
Keywords: Photovoltaic, MPPT, Sliding mode control, DC/DC converter.

Introduction

Among all renewable energy such as wind energy, fuel cells, ocean energy, etc., solar energy seems to be a promising source of energy due to its many advantages: these devices require a short time for installing a new system, their output power matches with peak load demands, they have a static structure and longer lifetime, they contain no moving parts, and they are a noise-free clean source of energy [1].

Photovoltaic cells have a single operating point where the values of the current and voltage of the cell result in a maximum power output. These values correspond to a particular resistance which is equal to the division of the maximum voltage and maximum current. A maximum power point tracker (MPPT) is a device capable of search for the point of maximum power and, using DC-DC converters, extracts the maximum power available by the cell. By controlling the duty cycle of the switching frequency of the converter we can change the equivalent voltage of the cell [2-8-22].

Multiple types of methods have been designed and implemented to search for this operation point ,which differ in complexity, number of sensors needed for operation, convergence speed, cost-effective range, etc. [9]. Two of the most commonly used MPPT techniques are Perturb and Observe (P & O) and Incremental Conductance (IC) [7]. Classical P&O algorithms tend to measure the converter's output power in order to modify the input voltage by modifying the converter's duty cycle. Another common method is the hill climbing method [10-11].This method is based on a trial and error algorithm in where the voltage is increased until you reach such voltage where the PV exhibits maximum power. The reason for this popularity is its implementation simplicity and its relatively good performance [12, 13]. Other MPPT algorithms are based on using fractional values of the open circuit voltage and operate the PV module at a fixed percent of this voltage. The main advantages of those solutions are the low cost and implementation simplicity since they only require a single (voltage or current) sensor [14, 15]; But their efficiency is low comparison to the P & O and IC algorithms. In contrasts, techniques based on computational intelligence, such as neural networks and fuzzy logic, offer speed and efficiency in tracking the MPP [16, 17]; however its complexity and implementation costs are high compared with the P&O and IC algorithms.

In this paper, a sliding mode control is applied to track maximum power of photovoltaic system.

PV module

There have been different types of models to estimate the non linear equations of the photovoltaic module. Models like Anderson's, Blesser and the most common used the one diode model because it provides a good compromise between the accuracy and the simplicity [18]. All these models present a good approach into estimating the solar cell voltage and currents. The double-diode model is having better accuracy [19] [20] because it takes into account some physical phenomena of semiconductor, viz., charge diffusion and recombination in the space charge layer.

In Fig.1, the current source is used to model the incident solar irradiance, a diode representing the polarization phenomena, a series and parallel resistances to represent the power losses.

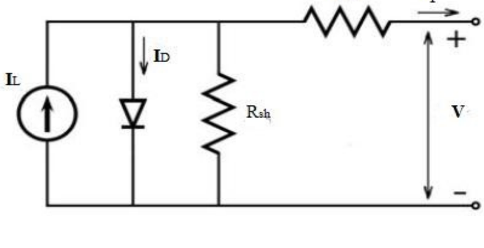

Fig.1. Equivalent circuit of solar cell

The mathematical equations describing the cases in Fig.1 are given respectively by:

(1) $$I = I_{ph} - \underbrace{I_{sat}\left(e^{\frac{V}{N_s A V_T}} - 1\right)}_{I_D}$$

(2) $$I = I_{ph} - I_{sat}\left(e^{\frac{V+IR_s}{N_s A V_T}} - 1\right) - \frac{V+IR_s}{R_p}$$

(3) $$I = I_{ph} - I_{sat1}\left(e^{\frac{V+IR_s}{N_s V_T}} - 1\right) - I_{sat2}\left(e^{\frac{V+IR_s}{N_s 2V_T}} - 1\right) - \frac{V+IR_s}{R_p}$$

where: I is PV module terminal current "A", I_{ph} is the Photo generated current "A", V is the PV module terminal voltage "V", R_s is the equivalent series resistance "Ω", R_p is the equivalent parallel resistance "Ω", I_{sat} is the diode saturation current "A", N_s is the number of cells connected in series, V_T is the diode thermal voltage, k is the Boltzmann's constant, T is the temperature "ºK", q is the charge of electron "C", A is the diode ideality factor "1 ≥ A ≥ 2" [3].

The change of irradiance has an effect on the performance of the PV module according to the following set of equations [4]:

(4) $$I_{sc}(G) = \left(\frac{G}{G_{stc}}\right) I_{sc}(G_{stc})$$

(5) $$V_{oc}(G) = V_{oc}(G_{stc}) + N_s V_T \log\left(\frac{G}{G_{stc}}\right)$$

The GPV is heavily influenced by the variation irradiance and temperature.

Indeed, in Figure 2 is the GPV subjected to changes in irradiances where it appears clearly the reduction of the power and the change the MPP.

In figure 3 the photovoltaic generator GPV is subject to temperature variations under irradiance constant; there also the point of maximum power MPP exchange.

We must reconcile these behaviors with the load. During the source-load connection, it is therefore essential to take into account the variable nature of the power delivered by the PV generator, but also from the characteristic of the charge for a point of operation is possible. The operating point corresponds to the intersection of these two characteristics (Fig.4).

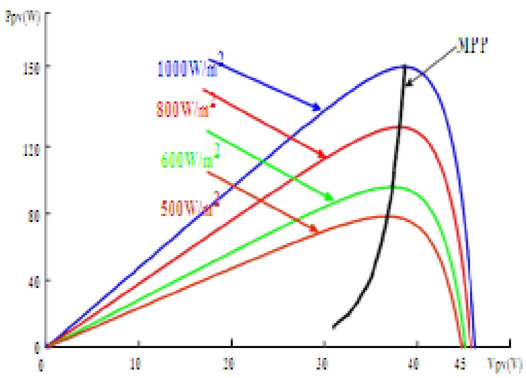

Fig.2. Changing the MPP during solar irradiance variations.

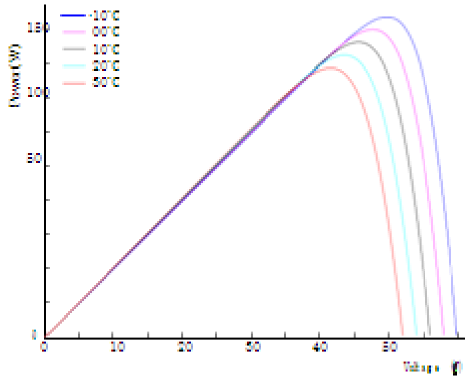

Fig.3. Influence of temperature on MPP

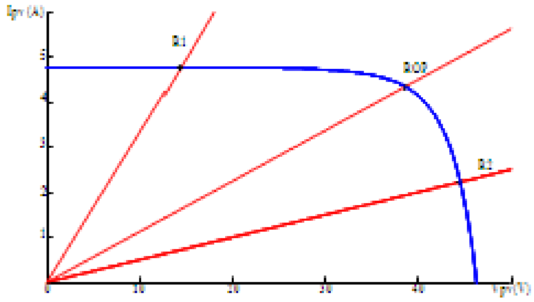

Fig.4. Influence of the load on the MPP

The operation of the generator depends heavily on characteristics of the load with which it is connected. In addition, for different values of R, adaptation optimal occurs for a single operating point (Rop) named maximum power point (maximum point power) MPP.

As a result, for the generator to work the more often than not, the solution commonly used is to introduce a converter DC / DC which plays the role of load source adapter (Fig.4), in this case, the generator delivers maximum power.

System photovoltaic

The complete studied system is schematically shown in figure 5.

The MPPT principles are to control the duty cycle for the pulse width modulation block that controls the power converter to deliver maximum power.

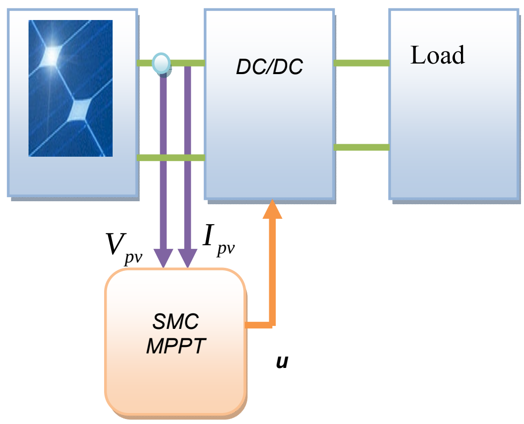

Fig.5. Block Diagram of the Proposed System.

The photovoltaic system is controlled by the command MPPT, Different topologies and different design approaches could be used for DC/DC converters. In this study boost converters is introduced as shown in Figure 6 , the switching period of "T" and duty cycle "D" for this converter.

The switch will open and close to control the voltage across the inductor, essentially operating the panels at their optimum power level.

Assuming continuous conduction mode, the state space average equations can be written on (0<t<*T*) as the following [3]:

$$\begin{cases} \dot{x} = \lambda_1 V_{in} - \lambda_1 x_2 u \\ \dot{x}_2 = \lambda_2 x_1 u - \lambda_3 x_2 \end{cases} \quad (6)$$

Where: $\lambda_1 = 1/L$; $\lambda_2 1/C$; $\lambda_3 = 1/R.C$; $u = (1-D)$ and $[x_1 \quad x_2] = [i_L \quad V_{out}]$

For a dc-dc boost converter, by using the averaging concept, the input–output voltage relationship for continuous conduction mode is given by:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (7)$$

Since the duty ratio "*D*" is between 0 and 1 the output voltage is higher than the input voltage in magnitude.

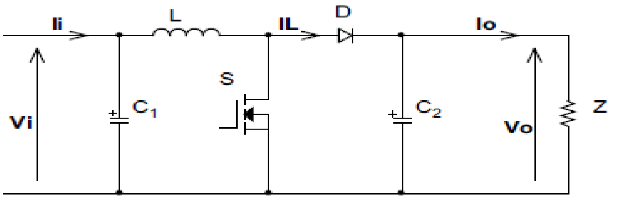

Fig.6. DC/DC boost converter

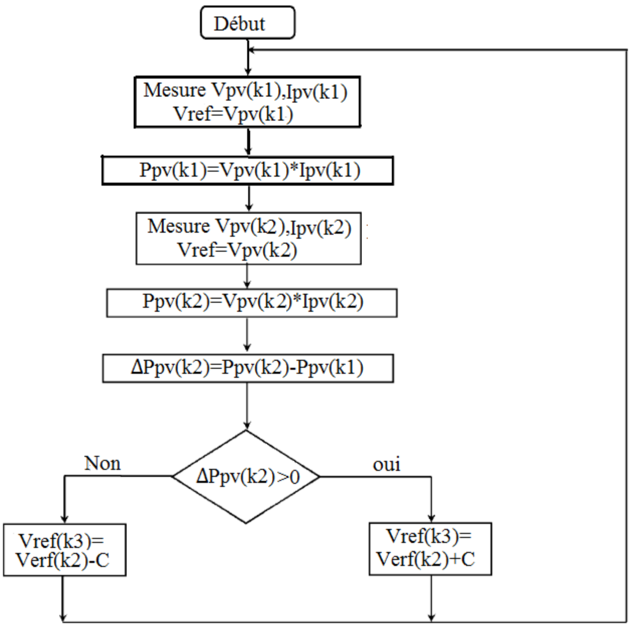

Fig.7. P&O Algorithm global structure

P&O Algorithm

The principle of this controller is to provoke perturbation by acting (decrease or increase) on the PWM duty cycle command and observe the output PV power reaction. If the actual power P (k) is greater than the previous computed one P (K-1), then the perturbation direction is maintained otherwise it is reversed [3].

The ΔD crisp value is chosen by trial and tests in simulation. The P&O diagram is: If the crisp value ΔD is very big or very small then we may lose information. Despite the P&O algorithm is easy to implement it has mainly the following problems

- The PV system will always operates in an oscillating mode.
- The PV system may fail to track the maximum power point and as result operate in current or voltage zones.

At first, the simulation is run under with irradiance changed from 400 W/m^2 to 1000 W/m^2 at time 4second. The results obtained are as shown in Figure 8. an increase in tension that induces a decrease in the power, the fonctionnement point of the system moves away of the MPP, after 0.7s.

The order goes back the point of operation is the MPP stabilizer with a certain oscillation that is caused by the algorithm of command.

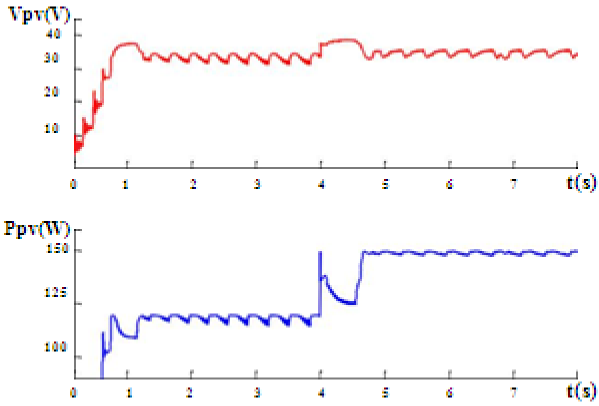

Fig.8.voltage and power characteristics under different irradiance .

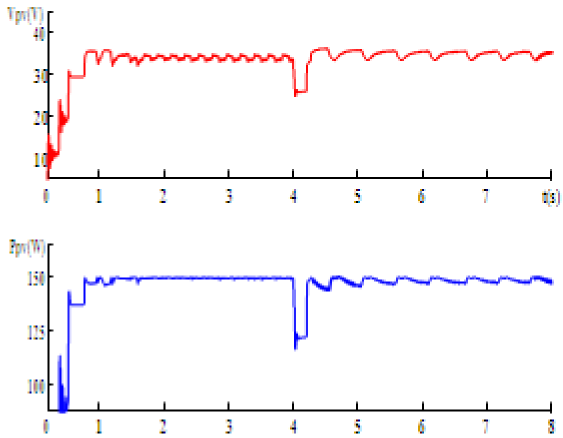

Fig.9. shape voltage and power against a variation of load

In a second simulation , to verify the system behavior in the face of load variation we changed it from 10 Ω to 15 Ω at the timet = 4s,and we constant irradiation from (1000 W / m2) , the results of simulation are shown in Fig.9

The increase in the load causes the decrease of voltage and power (Fig.9), the point of operation (MPP) moves away and moves in the left of the power characteristic (Fig.9).After 0.2s the system converges towards MPP despite the presence of the perturbation.

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incremental conductance method

The incremental conductance maximum power tracking algorithm is an attracted method; it is based on the fact that the slope of the PV array power curve *dP/dV* is zero at the MPP, positive on the left of the MPP, negative on the right of the MPPT

(8) $$\frac{dP}{dV}=\frac{d(IV)}{dV}=I+V\frac{dI}{dV}$$

The previous equation can be transformed to the following equation.

(9) $$\begin{cases}\frac{dI}{dV}=-\frac{I}{V} & at\ MPP\\ \frac{dI}{dV}>-\frac{I}{V} & \text{left of } MPP\\ \frac{dI}{dV}<-\frac{I}{V} & \text{right of } MPP\end{cases}$$

The principle of this algorithm is shown in the Figure 10.

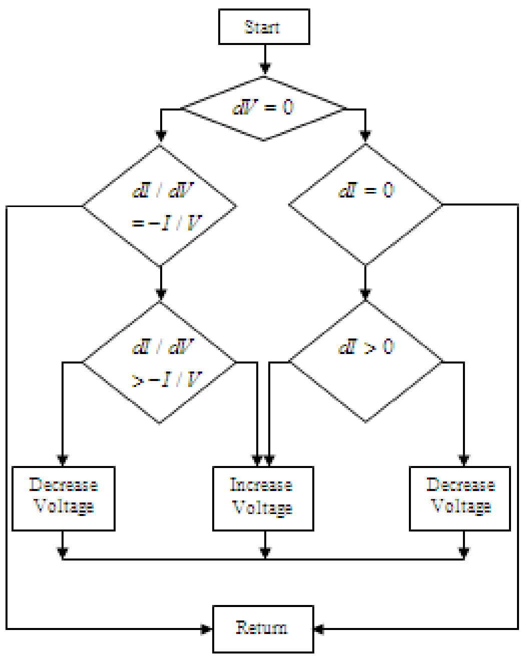

Figure 10. Increment Conductance

After introducing the incremental algorithm conductance in our system and keeping the same simulation conditions applied to the P & O system, the simulation results are shown in Fig.11 and Fig. 12.

We find that the algorithm offers a good follow-up against changes in irraduation and load, nevertheless, the ripple of the voltage is important in the second case (Fig.12), because the time constant of the filter of Boost converter output has changed value, while MPP search of the system is faster.

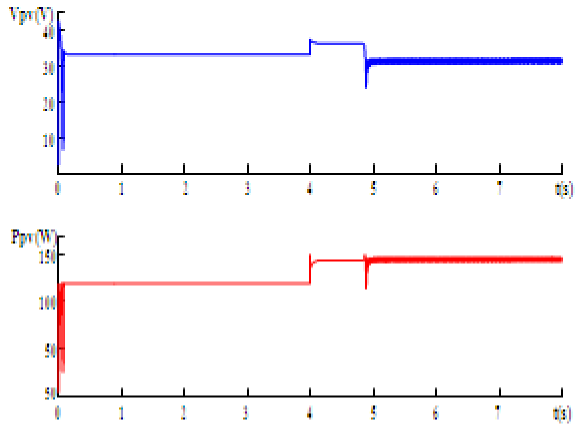

Fig.11.voltage and power face a variation of irradiance .

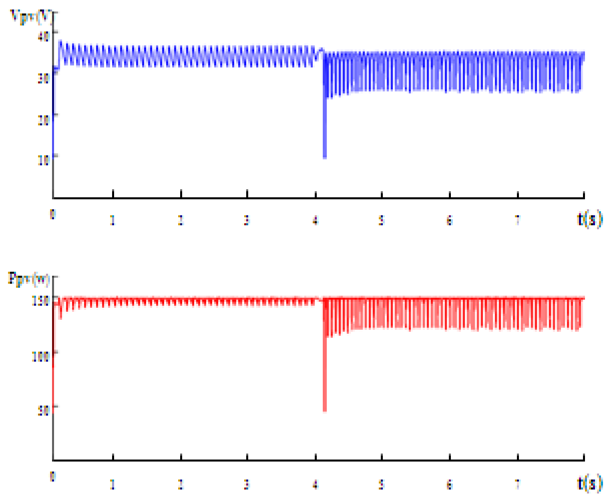

Fig.12 allure of vovltage and power facing a load variation.

Second order sliding mode MPPT control

A sliding mode controller is a variable structure control where the dynamics of a non linear system is altered via the application of a high frequency switching control[]..To reach the Maximum Power Point, V_{out} must track the V_{ref}. This is done by modifying duty cycle of the *DC/DC* boost converter. In order to do that, second order sliding mode control based on super twisting algorithm is applied[23]..

The sliding mode control consists of two phases: first, we determine a sliding surface *S(x)* upon which the control objectives are realized. Next, we derive a control law in order to bring the state trajectory to this output and maintain it there at all time. In the case, the problem is to generate a second order sliding mode on an appropriately chosen sliding surface and, thus, to constrain the trajectories system to evolve in finite time on *S ={x: S = Ś = 0}*.

Consider a system whose dynamics is given by

(10) $$\begin{cases}\dot{x}=f(x,t)+g(x,t)u\\ S=S(x,t)\end{cases}$$

where: $x \in R^n$ is the system state variable, $u \in R$ is the control, *f*, *g* are sufficiently smooth vector fields, $S = S(x,t) \in R$ is the output function, called sliding variable .

By differentiating *S* with respect to time, *t*, we have:

(11) $$\ddot{S}_t = \varphi\left(t,S,\dot{S}\right) + \varphi\left(t,S,\dot{S}\right)u$$

The control u is bounded function $|u| \leq v_{max}$

The dynamic in equation (6) are assumed to satisty the following bounding conditions[11]

(12) $$0 \leq K_m \leq \left|\varphi\left(t,S,\dot{S}\right) \leq K_M\right|$$
$$\left|\varphi(x,t)\right| \leq \beta_0$$

The set *{t,x,u :|S(t,x)|< s_0}* is the linear region where: K_m K_M, and β_0 are some positive constants.

The super twisting algorithm is defined by the following constants law [14]:

u = $u_1 + u_2$

(13) $$\begin{cases} \dot{u}_1 = -\alpha_1 sgn(S) \\ u_2 = -\alpha_2 |S|^{\rho} \operatorname{sgn}(S) \end{cases}$$

Where: Sis the sliding variable, and α_1, α_2 and ρ is the verifying the following inequalitiies:

(14) $$\begin{cases} \alpha_1 \rangle \dfrac{\beta_0}{K_m} \\ \alpha_2^2 \geq \dfrac{4\beta_0 K_M(\alpha_1+\beta_0)}{K_m^2 K_m(\alpha_1-\beta_0)} \\ 0 \langle \rho \leq 0.5 \end{cases}$$

The control law consists of two continuous terms that, again, do not depend on the first time derivative of sliding variable.

For the *DC-DC* boost converter we choose:

(15) $$\begin{cases} e = \left(x_2 - \dot{x}_2\right) \\ s = e + K_1 \int edt \end{cases}$$

where : $\acute{S}_2 = V_{ref}$

According to the theory of high order sliding mode control, the second derivative of the sliding variable can be written as follows:

(16) $$\ddot{S} = \left(\ddot{e} + K_1 \dot{e}\right) = \varphi\left(t,S,\dot{S}\right) + \varphi\left(t,S,\dot{S}\right)\dot{u}$$

with

(17) $$\varphi\left(t,S,\dot{S}\right) = \lambda_1\lambda_2 V_{in} u - \lambda_1\lambda_2 x_2 u^2 + K_1\lambda_2 x_1 u - K_1\lambda_3 x_2 - \left(k_1 \dot{x}_2 + \ddot{x}_2\right)$$

(18) $$\varphi\left(t,S,\dot{S}\right) = \lambda_1 x_1$$

The control of the DC-DC converter is a bounded function $0 \leq |u| < 1$

Then the super twisting control is given by:

(19) $$u = u_1 + u_2$$

where:

(20) $$\begin{cases} \dot{u}_1 = -k_{11} sgn(S) \\ u_2 = -k_{22} |S|^{0.5} \operatorname{sgn}(S) \end{cases} \quad ($$

and $k_{11} > 0$; $k_{22} > 0$

The use of the second order sliding mode guarantees the finitr time convergence to:

(21) $$S = \left\{x : S = \dot{S} = 0\right\}$$

A classical MPPT algorithm using O& V and I&C has been developed for the same PV power system in order to evaluate the proposed SMC controller. The comparison is illustrated in Fig.13 and 14.

In terms of achieved operating points. For the proposed SMC controller, it is noticeable that the operating point is at the top of each curve which indicates MPP operations during solar irradiance and load variations. Also it can be shown that the constant voltage operation has been achieved. Moreover, it is clearly shown that the proposed SMC obtains higher efficiency than the incremental condition.

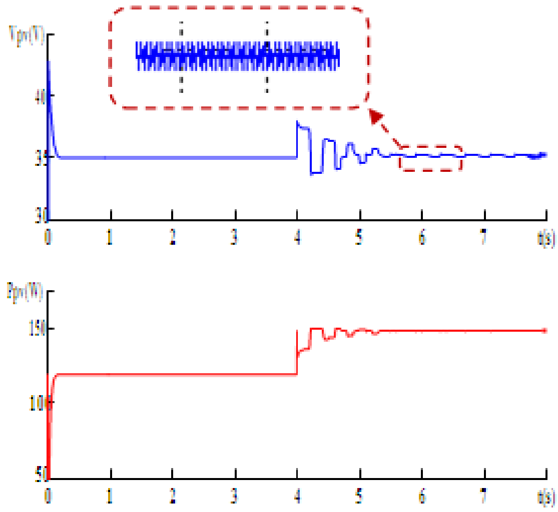

Fig.13. Shape of voltage and power front a variation of irradiance.

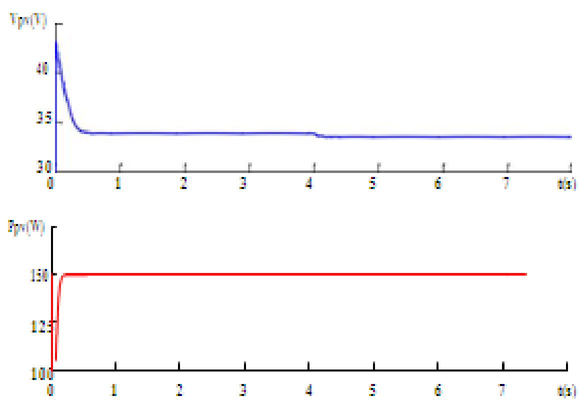

Fig.14. Shape of voltage and power front to a variation in load

Conclusion

In this work, a complete study of PV systems integrating an MPPT controller was studied by different smart algorithms of commands. A MPPT controller has been designed and simulated based on SMC scheme, the main objective of the controller is to force the operating point to be at during the variations of the atmospheric and load conditions.

As the control law of SMC changes during the control process according to some defined rules that depend on the state of the system, it is suitable for non-linear systems. The SMC controller here regulates the panel output character as well.

The disadvantage of this technique is chattering which is generally undesirable because it adds a high frequency components to the spectrum of the GPV voltage and current. To overcome this drawback, high order sliding mode control or a combination with techniques like fuzzy sliding mode should be considered... etc.

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