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RESEARCH ARTICLE

HARMONIC POLLUTION COMPENSATION BY CONNECTED PHOTOVOLTAIC SYSTEMS USING THE INSTANTANEOUS POWER METHOD.

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Abstract

This paper discusses the potential for photovoltaic systems to compensate the grid harmonics pollution by using the instantaneous power method. The objective is to develop an optimal algorithm of the control allowing both the active power transfer to the electrical grid and an optimal compensation of the harmonic pollution resulting from unbalanced non-linear loads as well as the compensation of the reactive energy involved. The studied system includes a photovoltaic generator (PV), a DC-DC converter that steps up the PV output to the DC link voltage level with maximum power point tracking (MPPT) control and an inverter that links the system to the grid with a variety of non-linear loads. This method consists in extracting the AC components of the active and reactive instantaneous powers which are related to the harmonics and to optimize the algorithm of the inverter control in order to compensate the disturbing currents caused by these powers. The study was realized according to different regimes that are related to both: the harmonic rate caused by the non-linear charges and the level of solar power received. The obtained results show the benefits of such optimization of the active filter compensation method, in order to improve the quality of the energy (THD $\leq$2.02%), while limiting the repercussions of the filter on the photovoltaic station and by automatically adapting to the variation of the solar irradiation and the unbalanced load without risk of resonance with the impedance of the grid that can be caused by the passives filters.

Introduction:-

The electrical grid pollution by harmonic currents is an unavoidable consequence of the increasing utilization of non-linear loads which cause many disturbances, such as generating the distortion of the voltage within the electrical grid and contributing to poor quality of the energy supplied to consumers. To overcome this problem, the use of photovoltaic systems; in order to substitute the conventional filtering systems at different points of the grid; proves to be an adequate and efficient solution. Indeed, solar energy captured using photovoltaic modules represents a viable alternative energy that will allow; in addition to the injection of active energy into the grid; to compensate the different disturbances present in this grid.

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In this work, we propose to optimize the control of an array of photovoltaic generators connected to the distribution grid in order to ensure; in addition to the injection of the active power; an optimal compensation of the harmonic pollution (both voltage and current), the voltage dips and reactive energy and within minimizing the effects of the filter on the photovoltaic station for various operating conditions.

Studied configuration

The studied system in this work (figure 1) consists of two stages conversion system, the first one includes a DC-DC converter that steps up the photovoltaic output voltage to the DC link voltage level using the maximum power point tracking (MPPT) control, the second stage is an inverter that connects the compensation system to the (380V / 50Hz) distribution grid through a shock self-inductance. During sufficient irradiation, the proposed compensation system acts as an active shunt filter with active power supplying in the electrical grid. During low irradiation, it performs the function of a reactive power compensator.

According to various operating conditions imposed by the irradiation fluctuation on the one hand, and by the variation of the load on the other hand, an analysis of the power transits is made at the level of the photovoltaic source, the load and the grid.

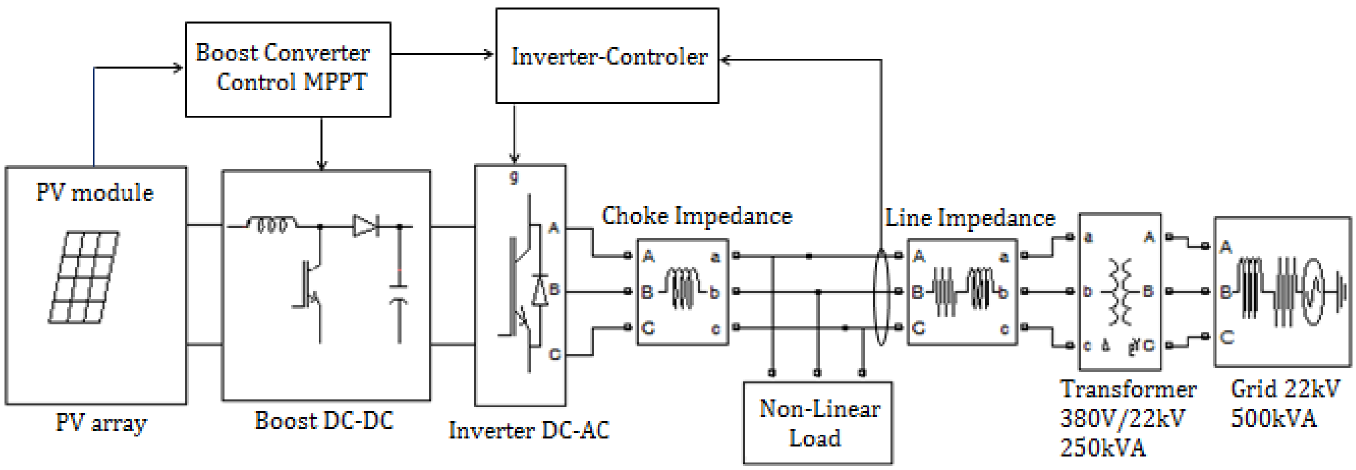

Figure 1:-Bloc diagram of the photovoltaic compensation system connected to the electrical grid.

The system adopted to transfer the photovoltaic power into the grid is used also; without any supplementary investment; to fulfill the role of an active filter in order to improve the quality of energy at several connection points on the grid. This is thanks to a control algorithm of the voltage inverter, which is adapted to ensure simultaneously the compensation of harmonic currents, the reactive power, the imbalanced loads effects and the transfer of the active power supplied by photovoltaic array into the distribution grid.

System model and control approach

Photovoltaic system modelling

To reach the desired power level, the photovoltaic array is constituted of N_p parallel groups of N_s serial modules. Each solar module is made up of n_p line compounded of n_s serial cells. The equivalent scheme model of one cell leads to the development of the global photovoltaic array model. The cells receive solar irradiation in the form of photons each carrying a quantity of energy (W_{ph}) given by:

$$W_{ph} = \frac{h.c}{\lambda} \quad (1)$$

where:

λ : The wavelength. h : Planck's constant.

c : The light's speed.

Each photovoltaic cell is modeled by the scheme diagram of figure 2.

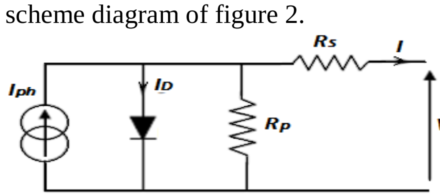

Figure 2:-Electrical equivalent circuit Model of a photovoltaic cell

The mathematical model for the current-voltage characteristic of the cell is:

$$I = I_{ph} - I_o\left[exp\left(\frac{q}{m.k.T_c}(V + R_s.I\right) - 1\right] - \frac{V+R_s.I}{R_P} \quad (2)$$

where:

$I_{ph}(A)$: Photo generated current,$I_0(A)$: the saturation current, $k = 1.28.10^{-38} J.K^{-1}$: Boltzmann's constant, $T_c(°K)$: Absolute temperature of the cell, m: Ideality factor of the diode ($m \in [1,2]$) with typical value 1.3. [1]

For a cell with a good quality (great value of R_p), the current-voltage equation (2) can be reduced to:

$$I = I_{ph} - I_o\left[exp\left(\frac{q}{m.k.T_c}(V + R_s.I)\right)\right] \quad (3)$$

The short-circuit current $I_{cc} \approx I_{ph}$ and the voltage at open-circuitV_o constitute two important characteristics of the cell, this voltage is given by:

$$V_o = \frac{m.k.T_c}{q}.ln\left(\frac{I_{ph}}{I_o}\right) = V_{th}.ln\left(\frac{I_{ph}}{I_o}\right) \quad (4)$$

where V_{th} *is the thermodynamic voltage.*

Then, the current-voltage equation (3) of the cell becomes:

$$I = I_{ph}\left[1 - exp\left(\frac{V - V_o + R_s.I}{V_{th}}\right)\right] \quad (5)$$

Either for a module of n_s serial cells:

$$I = I_{ph}\left[1 - exp\left(\frac{V - n_s(V_o + R_s.I)}{V_{th}}\right)\right] \quad (6)$$

The equations giving the variation of the open-circuit voltage V_o and the short-circuit current I_{cc} according to the irradiation$E_c(w.m^{-2})$ and the cell temperature$T_c(°C)$, relatively to standard conditions $T_{co} = 25°C, E_{co} = 1000\ w.m^{-2}$), are given by : [2].

$$I_{cc} = C_1.E_c[1 + 5.10^{-4}.(T_c - T_{c0})] \quad (7)$$

where

$$C_1 = \frac{I_{cc}(T_{co}, E_{co})}{E_o} \quad (8)$$

$$V_o = V_o(T_{co}, E_{co}) + C_3.(T_c - T_{co}).V_{th}.ln\left(\frac{E_c}{E_{co}}\right) \quad (9)$$

The coefficient C_3 represents the correction factor of the open-circuit voltage according to the temperature. The typical value of this factor equals :

$$C_3 = -2.3.10^{-3}(V.°C^{-1}) \quad (10)$$

The cell temperature T_c depends on the irradiation E_c and the ambient temperature T_a [2].

$$T_c = T_a + C_2.E_c \quad (11)$$

where C_2 is approximately $3.10^{-6}(m^2w^{-1})$.

The characteristic $I = f(V)$ of a photovoltaic cell, strongly dependon the solar irradiance E_c and the temperature T_c. Figure 3 shows that the currentI_{pv} of a module is significantly influenced by irradiation variation while the voltage V remains approximately constant. On the other hand, when the temperature changes, one can observe that the voltage varies considerably but the current remains almost constant under normal conditions (figure 4).

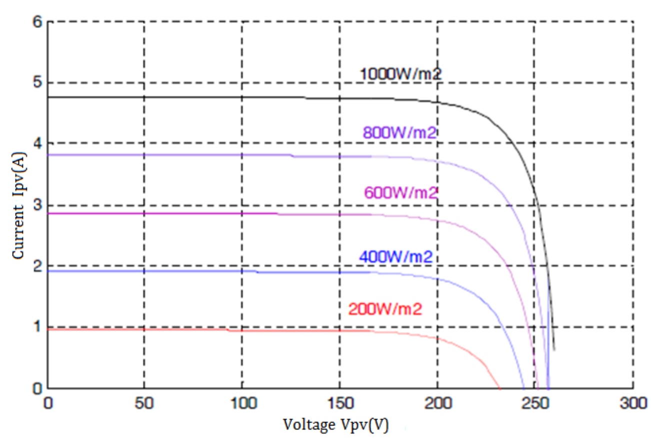

Figure 3:-Characteristic I_{pv} = f (V_{pv}) under variable irradiation and fixed temperature 20 °C

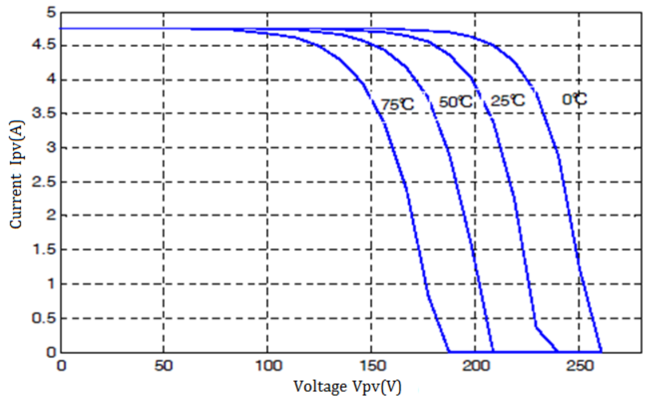

Figure 4:-Characteristic $I_{pv} = f(V_{pv})$ under variable temperature and fixed irradiation 1000 $w.m^{-2}$

Maximum power point tracking and regulating DC-link voltage

In order to extract efficiently all the electrical power from the photovoltaic generator and transfer it to the load via the grid and to obtain a better performance of the PV station, the maximum power point tracking (MPPT) method is used to control the DC-DC converter [3] (figure 5).

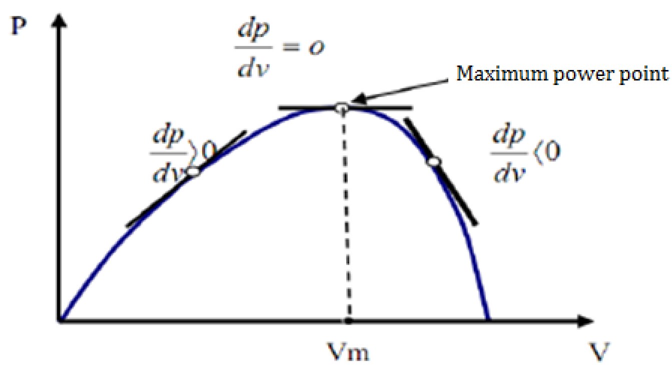

Figure 5:-Location and tracking of the maximum power point

To locate and track this maximum power point, the method used in this work is the control by incremental conductance method [4] with proportional integral (PI) controller. The MPPT is obtained when:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv} \cdot I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} = 0 \quad (12)$$

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad (13)$$

The term $\frac{I_{pv}}{V_{pv}}$ represents the instantaneous conductivity of the photovoltaic array, and $\frac{dI_{pv}}{dV_{pv}}$ represents the increment-term of conductance.

The PI regulator minimizes the error $\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}}$ and elaborates an adjustment of the duty cycle to control the DC-DC converter.

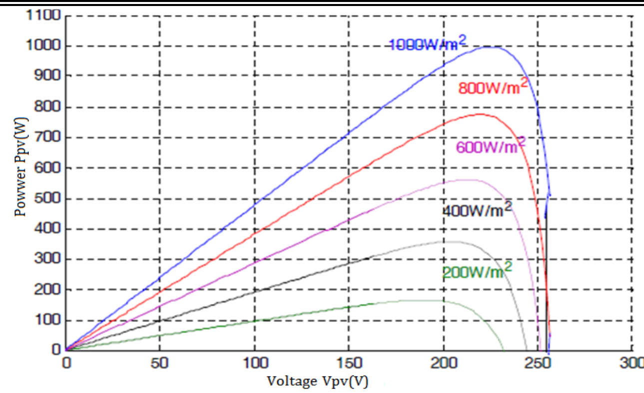

Figure 6:-Characteristic P_{pv} = f (V_{pv}) under variable irradiation and fixed temperature 20 °C

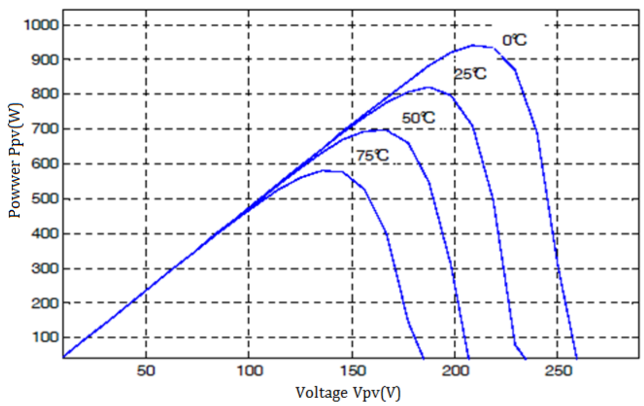

Figure 7:-P_{pv}=f(V_{pv}) characteristic under variable temperature and fixed irradiation 1000 w.m^{-2}

The estimation of the DC-link voltage reference value is based on the maximum power point search technique of the photovoltaic generator. The objective is to maintain a constant voltage on the DC-link under stable irradiation conditions or during changes of these atmospheric conditions. The MPPT algorithm adapts the reference voltage $V_{dcréf}$ depending on the meteorological conditions. [5]

Identifying harmonic currents by the instantaneous power method.

To compensate the harmonic currents generated by the non-linear loads and the unbalanced currents [6] caused by the unbalanced loads, the technique used is aimed at controlling the three-phase inverter with detection of these polluting currents by the instantaneous power method. The first stage is to bring back the grid voltages v_{abc} and currents $i_{abc}$to the coordinate plane α, β using the Concordia transformation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ v_b \\ v_c \end{bmatrix} \qquad (15)$$

According to equations (14) and (15), the instantaneous active powers p and reactive q are calculated:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (16)$$

These instantaneous powers$p$ and $q$can be composed in two components: the continuous components (DC) related to the fundamental components $(\bar{p}, \bar{q})$ and the alternative components (AC) related to the harmonics$(\tilde{p}, \tilde{q})$ as following [7]:

$$\begin{cases} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{cases} \qquad (17)$$

A power filter is used to separate the harmonic's power component from the fundamental power component. After separating these components, the disturbing currents in the reference α, β is calculated by using expressions (16) and (17):

$$\begin{bmatrix} I_{\alpha ref} \\ I_{\beta ref} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} P_o - \tilde{p} \\ -\tilde{q} \end{bmatrix} \qquad (18)$$

where $\Delta = V_\alpha^2 + V_\beta^2$

P_o is the active power supplied by the photovoltaic cells, this power is required to regulate the voltage of the DC- bus.

The relation (18) is used to eliminate unwanted harmonics. Moreover, this technique allows to compensate the reactive energy due to the fact that the reactive power's absorption is a result of a non-zero continuous component ($\bar{\iota_\alpha}$) along the axis α. The filter current; which allows to compensate simultaneously the reactive power and the whole harmonics; is therefore:

$$\begin{bmatrix} I_{\alpha ref} \\ I_{\beta ref} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} . \begin{bmatrix} P_o - \tilde{p} \\ -\bar{q} - \tilde{q} \end{bmatrix} \quad (19)$$

In the (α, β) axis, it is possible to express the current with three components: the active currentI_{ref_a}, the fundamental reactive current$I_{ref_r}$and the set of other harmonics I_{ref_h}:

$$\begin{bmatrix} I_{\alpha ref} \\ I_{\beta ref} \end{bmatrix} = \begin{bmatrix} I_{\alpha ref\_a} \\ I_{\beta ref\_a} \end{bmatrix} + \begin{bmatrix} I_{\alpha ref\_r} \\ I_{\beta ref\_r} \end{bmatrix} + \begin{bmatrix} I_{\alpha ref\_h} \\ I_{\beta ref\_h} \end{bmatrix} \quad (20)$$

where:

$$\begin{bmatrix} I_{\alpha ref\_a} \\ I_{\beta ref\_a} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} . \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I_{\alpha ref\_r} \\ I_{\beta ref\_r} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} . \begin{bmatrix} 0 \\ -\bar{q} \end{bmatrix}$$

$$\begin{bmatrix} I_{\alpha ref\_h} \\ I_{\beta ref\_h} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} . \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix}$$

The Three-phase disruptive currents which represent the identified currents; referred as the reference currents I_{ref}; are calculated from the Concordia inverse transform. These currents are given by the following relation:

$$\begin{bmatrix} I_{a\_ref} \\ v_{b-ref} \\ v_{c\_ref} \end{bmatrix} = \sqrt{\frac{2}{3}} . \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} I_{\alpha ref} \\ I_{\beta ref} \end{bmatrix} \quad (21)$$

Results and discussion:-

System without photovoltaic compensator

In a first stage, the system operates without compensation filter, the grid supplies to the non-linear loads an active power of$22.43kw$and a reactive power of$15.24kvar$. Figures 8 and 9 illustrate the phase current waveform, the instantaneous active and reactive powers absorbed without photovoltaic compensator.

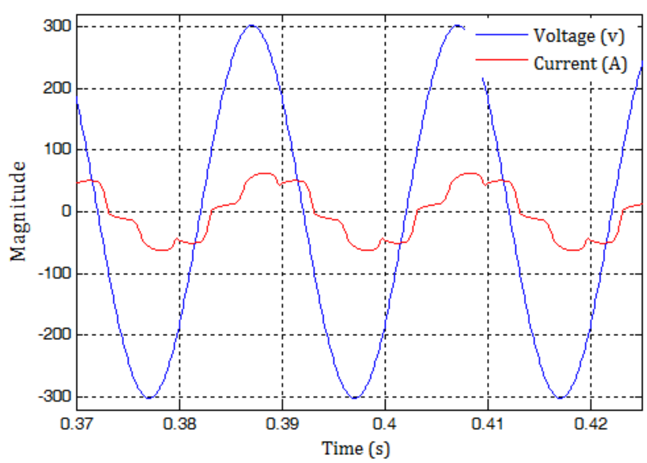

Figure 8:-Waveform of the grid current without compensation

The grid current with the RMS value ($I_{eff} = 43.54A$)matches the non-linear load current, the latter is characterized by a shape distortion, a frequency spectrum containing only odd order harmonics (non-multiple of three) and a total harmonic distortion rate ($THD = 24.93\%$)(figure 11).

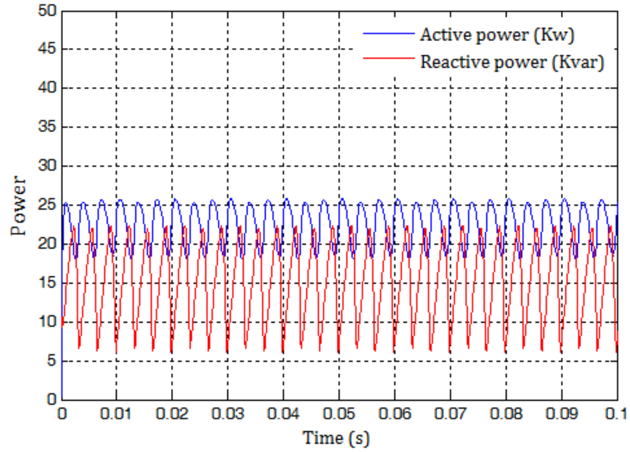

Figure 9:-Instantaneous powers evolution without compensation

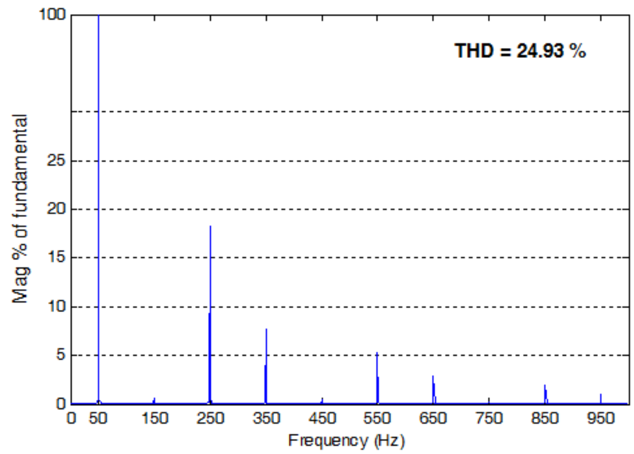

Figure 10:-Harmonic spectrum of the grid current without Compensation

System with photovoltaic compensator under a constant irradiation of $1000\ w.m^{-2}$

In this stage, the temperature and the irradiation level are fixed at standard conditions($T_{co} = 25°C, E_{co} = 1000\ w.m^{-2}$) in order to evaluate the performance of the entire system. The waveforms of the phase current, the instantaneous active and reactive instantaneous powers existing in the presence of the photovoltaic compensator are given in figures 11 and 12.

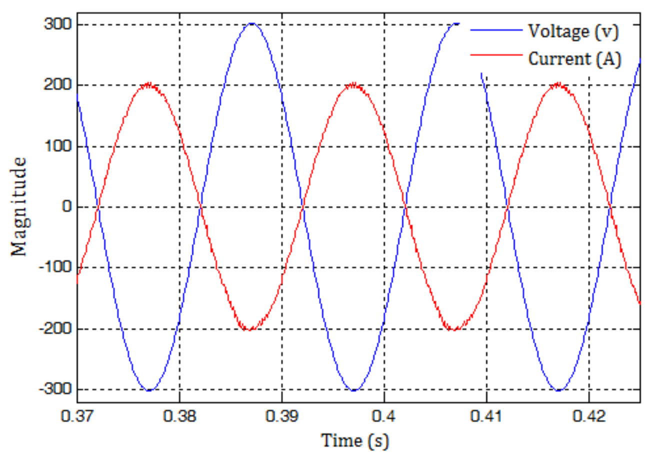

Figure 11:-Current waveform supplied to the grid

Following the start of the compensation system under an irradiation of $1000\ w.m^{-2}$, we observe that after a transitional time $\Delta t = 25ms$, the grid current (figure 11) becomes perfectly sinusoidal and is characterized by a phase-opposition with the corresponding voltage. This phase-opposition between voltage and current indicates the injection of active energy into the supply grid without exchange of the reactive power. This latter is completely compensated by the filter (figure 12).

For a load absorbing an active power of $24.98Kw$and a reactive power$11.86Kvar$, the active power injected into the grid (marked by negative sign) becomes stable in a steady state at a value of $\mathrm{P} = -91.24\mathrm{Kw}$ while the reactive energy tends towards the zero value. This energy is perfectly compensated by the photovoltaic filter which generates all the active power absorbed by the load and that supplied into the grid (Figure 12).

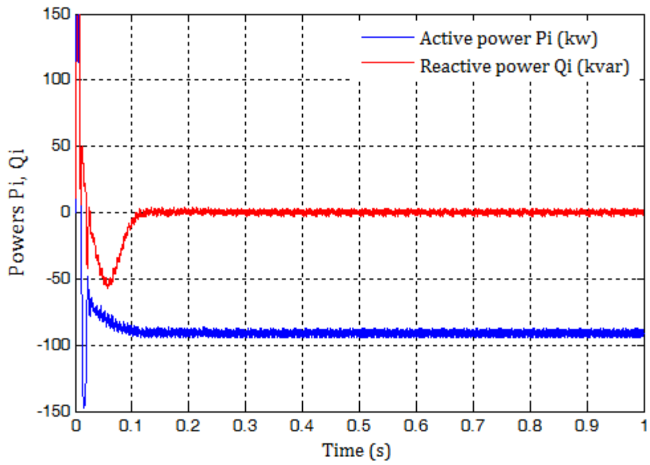

Figure 12:-Evolution of instantaneous powers with compensation

After a transitional time $\Delta t = 140ms$ required for the stability of the system, the total harmonic distortion rate (THD) of the grid current (figure 13) is significantly improved and equals 2.02% (figure 14)

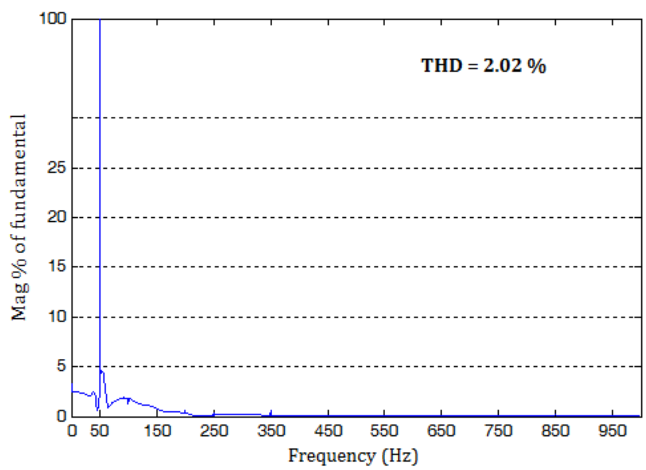

Figure 13:-Current harmonic spectrum with harmonic compensator

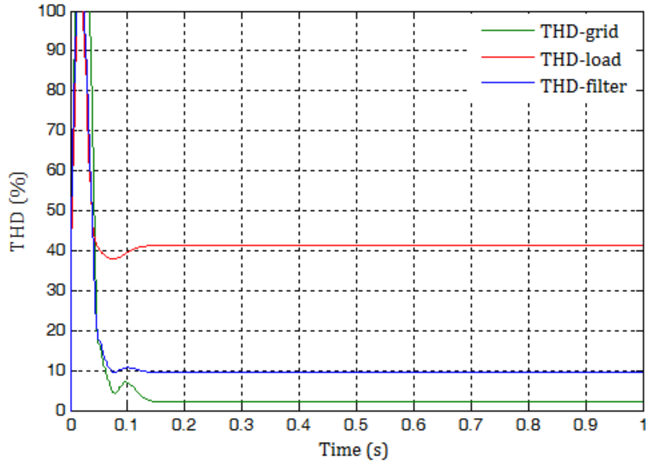

Figure 14:-Evolution of the THD after start of the compensation

System with photovoltaic filter under variable irradiation

In this part, an irradiation fluctuation cycle is applied and the behavior of the whole system is evaluated. Figure 15 shows the evolution of the voltage and the phase current, load current and compensator current during the variation of the solar irradiation.

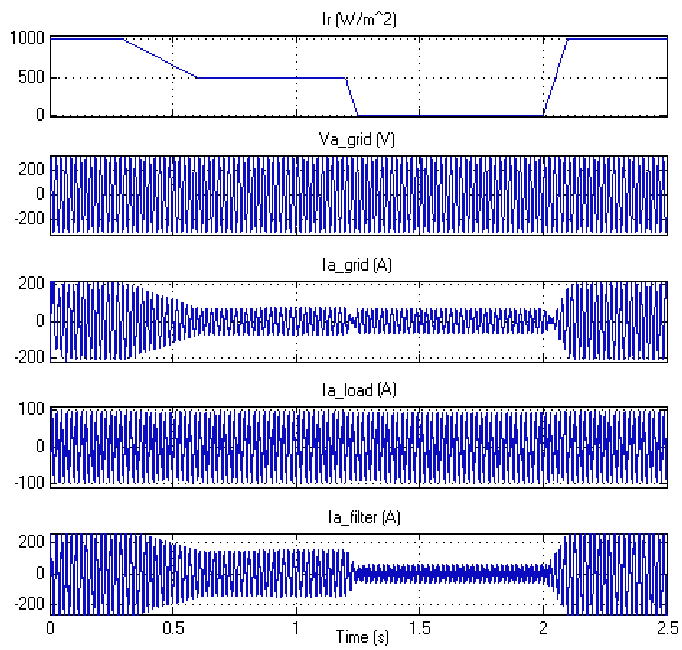

Figure 15:-Evolution of currents of the grid, the load and the filter

At constant and sufficient irradiation, the current provided to the grid remains almost sinusoidal before undergoing a decrease at $t = 0.3s$due to the fact that the power supplied by the photovoltaic generator to the grid has decreased. In the case of low solar irradiation, the load current is supplied by the grid, it resumes its initial value when the irradiation is at its initial value.

Figure 16 shows that the current$I_{pv}$of the photovoltaic generator is considerably influenced by the change of solar irradiation, whereas; for a non-zero irradiation; the voltage$V_{pv}$of photovoltaic generator remains approximately constant.

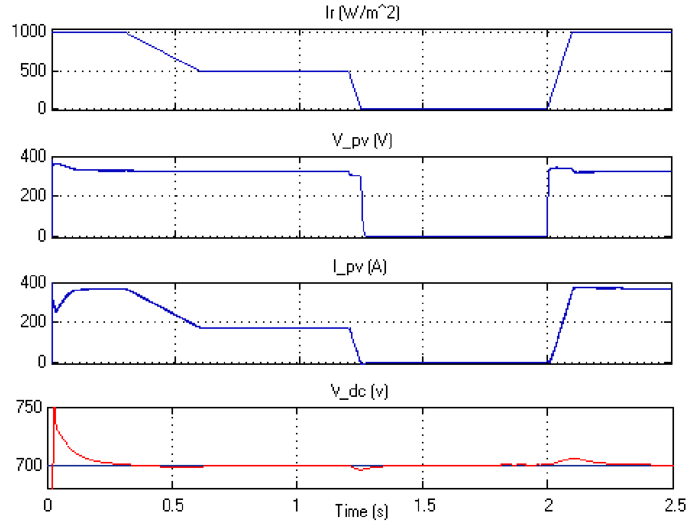

Figure 16:-Evolution of voltage and current of the photovoltaic generator

As far as the DC-bus voltage is concerned, it tends towards its reference after a transient time $\Delta t = 35ms$ (figure 16), it follows perfectly its reference during all the variation's intervals of the solar irradiation to ensure an excellent compensation of the reactive power which stills approach to zero (figure 17).

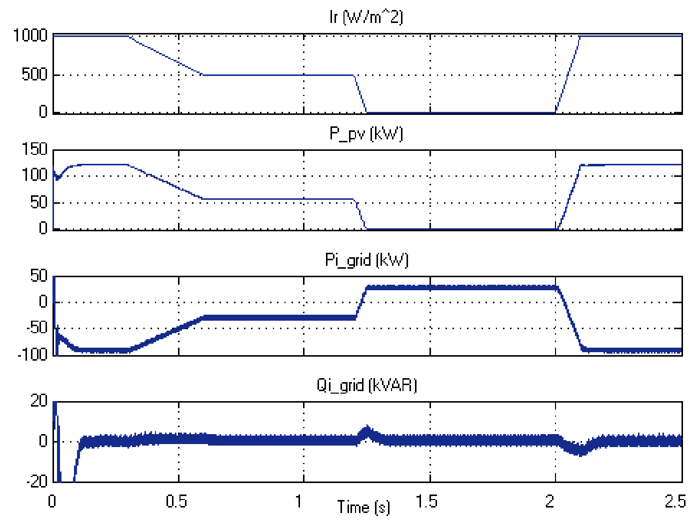

Figure 17:-Evolution of instantaneous powers

The evolution of THD (figure 18) shows that at steady state, the THD remains almost constant with peaks presence only at the moments of the swift changes in irradiation. This proves a better compensation of the harmonic grid currents during all the intervals of variation of solar irradiation.

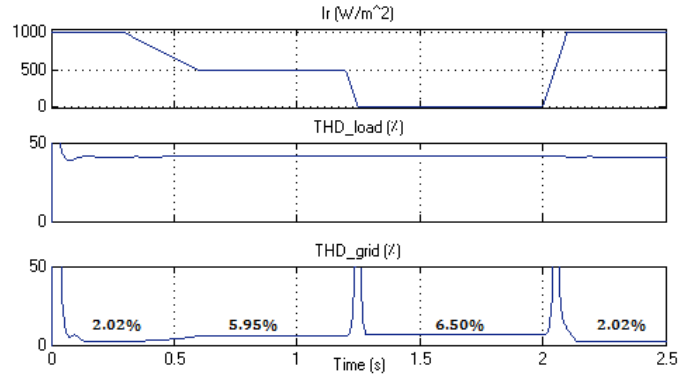

Figure 18:-Evolution of the THD during the variation of the illumination

Conclusion:-

The objective of this study is to optimize the performances of a compensation system made up of a parallel active filter and a photovoltaic generator connected to the distribution grid in order to compensate all disturbances generated by non-linear loads, such as the harmonics currents, the reactive currents and the unbalanced currents while transferring to the grid the power produced by the photovoltaic array.

The obtained results show the robustness of the control technique based on the identification of the different disturbances using the instantaneous powers method. This method allows a better control of the active and reactive instantaneous powers, as well as a significant improvement of the total harmonic distortion rate of the current even in the presence of several drifts such as the variation of the solar irradiation and the load.

Compared with other control techniques such as the hysteresis current control method that is characterized by its non-linearity, this instantaneous power method is an excellent one to improve the quality of the energy in the electrical distribution grids while limiting the filter's repercussions on the photovoltaic station for various exploitation regimes.

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