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Original scientific paper

DESIGN OF AN EFFECTIVE CONTROL FOR GRID-CONNECTED PV SYSTEM BASED ON FS-MPC

Nadjah Attik[1], Abd Essalam Badoud[1], Farid Merahi[1], Abdelbaset Laib[2], Yahya Ayat[1]

[1]Automatic laboratory of Setif, Electrical engineering department, university of Ferhat Abess, Setif-1, Algeria
[2]LEPCI laboratory, Electronics department. university of Ferhat Abess, Setif-1, Algeria

Abstract. *This paper is deals in part of research that has been conducted on modern means in the basis of power electronics. Harmonic cancellation of distribution network is currently a serious problem, especially in high electrical industry. The main source of harmonic currents injected into the network requires attention to reduce the current harmonic levels. Energy quality is a fairly broad concept which covers both, the quality of power supply (voltage wave) and these of the currents injected into the electrical grid. In this context, a modern approved preventive solution in purpose to limit the rate of harmonic disturbance caused by the deferent power electronics systems connected to the grid must take action. It appears necessary to develop the quality and stability of the grid and develop curative devices such as converters provided with a control device making the current drawn on the most sinusoidal network possible. This paper proposes a control of tow stage grid tied PV system established on finite set model predictive control (FS-MPC). The design of FS-MPC is developed depending on the structure and operating principle associated to three-phase inverter tied to the grid. In this context, we have also employed the structure of MPPT controller (P&O) and PI controller for adjustment of the DC-bus voltage. To set the proposed control scheme, numerical simulations are carried out using Matlab/Simulink 2013b. The obtained results demonstrate that the proposed control scheme assure the tracking of MPP and the injection of extracted PV power into the grid with high current quality under irradiation changes.*

Key words: *Photovoltaic system, Two-level inverter, Finite Set Model Predictive Control FS-MPC, THD, Grid-connected*

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Corresponding author: Yahya Ayat
Automatic laboratory of Setif, Electrical Engineering Department, University of Ferhat Abess, Setif 1, Algeria
E-mail: yahya.ayat@yahoo.fr

1. INTRODUCTION

The use of renewable energies is experiencing significant growth in the world, faced with the growing demand for electrical energy mainly for the needs of remote areas lacking reliable electricity. Among the sources of renewable energy, photovoltaic energy is rapidly becoming competitive to the conventional sources and has become a real alternative to boost renewable energy penetration into the energy mix [1], [2]. Electric generators, control theory and power electronic converters are the most important elements to enable the safe, reliable, and high performance. The photovoltaic energy is the most renewable energy source used in the word due to their great advantage [3], [4], [5] that's why Solar Energy Grid Integration Systems (SEGIS) concept will be the key to achieving high penetration of the photovoltaic (PV) systems into the utility grid [6]. There are various topologies of PV installations connected to a power grid. Nevertheless, all these topologies are based on a photovoltaic generator connected to the grid by means of inverters which transfer and shape solar electric energy. The progress made in recent years in the development of inverters dedicated to photovoltaics have made it possible to greatly improve these management systems [7]. Inverters are no longer just limited to converting the DC power produced by the solar panels into AC power in the form of a sinusoidal voltage of the desired frequency, but they also exploit the power delivered by the GPV by forcing it to operate at its point of maximum power. In addition, they provide reliable network monitoring to protect the network against outages and interrupt the power supply in the event of problems arising, either in the network or in the installation [2], [7].

For a medium voltage network, it is difficult to directly connect a single power semiconductor switch. As a result, multilevel inverters have been introduced as an alternative in high power and medium voltage applications because they offer several advantages. The increase in the number of the level makes it possible to improve the waveforms at the output of the converter, in particular in terms of harmonic content, but this requires a much more complex control and a large number of semiconductors used. The present challenge is to achieve the maximum power from photovoltaic system and deliver it to the power system with high current quality. For this reason, many researches work with the technological advancements in digital signal processors. Due to greater reliability and improved performance, which leads to increased production rates, the use of power converters with high performance adaptable variable speed drives has gained increased presence in in a wide range of applications.

In this tendency, power converters have become an emerging paradigm with many applications in a wide range of systems [8]. Today, in view of the new need for quality, energy efficiency and the increasing demand for energy, the control and management of power generation systems is a very attractive research area.

In recent years, new control schemes, novel topologies and new semiconductor devices are being developed in order to meet these requirements. In the literature, several inverter control techniques have been suggested. Some of these are well developed and reasonable, while modern control methods, generally among these fresh process control, predictive control sound is a very attractive possibility for the control of power converters. A very large family of controllers with various approaches included by the predictive controller [9], [10].

The principle of predictive control is to use a system-controlled model within the controller in real time to predict the future behavior of the controlled variables. This information is used by the controller to obtain the desired optimal control, of course taking into account the optimization criterion predefined previously.

Predictive control has a number of advantages over other methods, including: its principle is intuitive and easy to understand. The corrector obtained is a linear control law easy to implement and which requires little computation time. Allows to respect the constraints on the controlled and manipulated variables. Allows automatic adaptation of the system in the event of measurable disturbances. It is intrinsically capable of compensating for delays or downtime. It is very useful when the instructions to be followed are known in advance [8]. Published research works in the field of static converters and power electronics applications in general, shows that this kind of techniques especially the predictive control based on an MPC model is often used in current control applications. inverters.

The model predictive design (MPC) approach has arisen in power electronics as an easy favorable method of digital control. Electrical drive and power converter predictive control is a serious move towards a new approach that will improve the reliability of alternative energy control and management systems [10], [11]. Through the use of switching mode operation, in which power semiconductor devices are operated in ON / OFF mode, the key characteristics of modern power electronic converters (fast operation and high power densities, high performance, reduced weight and size) are obtained [3], [6], [13]. Based on an accurate agreement that clarifies the various safety standards that must be followed during the connection, concluded between the consumer and the utility company, the PV system is connected.

This paper proposes a control of the tow stage grid linked PV system founded on predictive control of the finite set model (FS-MPC). The aim goal of the FS-MPC technical is to ensure that PV power with a high grid current factor is injected into the grid. In addition, the P&O MPPT controller and PI controller are used to track the MPP under change of irradiation and regulate the DC-bus voltage respectively.

Moreover, levels PV inverter connected to the grid is organized as follows. Firstly, a general block diagram of model simulating the architecture of the finite set FS-MPC Strategy of two-levels PV inverter connected to the grid on Matlab/Simulink environment. Secondly, the control predictive proposed of three-phases two-levels inverter will be studied. Finally, the simulation results are investigated.

2. GLOBAL SYSTEM CONFIGURATION

This paper gives the impact of the two-control strategy of three-phases two-Level PV inverter tied grid as illustrated in Fig 1. The system studied is composed of PV generator, DC-DC adaptor (boost), DC-bus and three-phase two-level inverter. MPPT control extract the maximum output power from PV generator; the aim of the DC voltage regulation loop is to maintain this voltage at the reference value. The regulation of the DC voltage is affected by adjusting the amplitude of the current references by PI regulator. A phase locked loop (PLL) outputs a unitary signal synchronized in phase and frequency with the input signal and the RL filter connected to the network through two levels inverter. We explore an intelligent stochastic FS-MPC for an optimal utilization of solar energy.

3. Global System Control

The outline control of this work is given with these follow steps technique:
The boost converter is used to realize the (P&O) MPPT for PV systems recovering the maximum of energy [15] [14].

For optimal operation, the installation needs a constant voltage across this capacity. The regulation of DC voltage V_{dc} is implemented by supplying the active power into the network. The correction of this voltage must be done by adding the active fundamental current to the reference current. A proportional-integral regulator (PI) is implemented in the DC voltage regulation loop in order to reduce the fluctuations across the DC capacitor and maintain it at its desired value V_{dc} *.

The PLL (phase locked loop) ensures that the error in the phase between input and output is kept to zero, and the input and output frequency is the same.

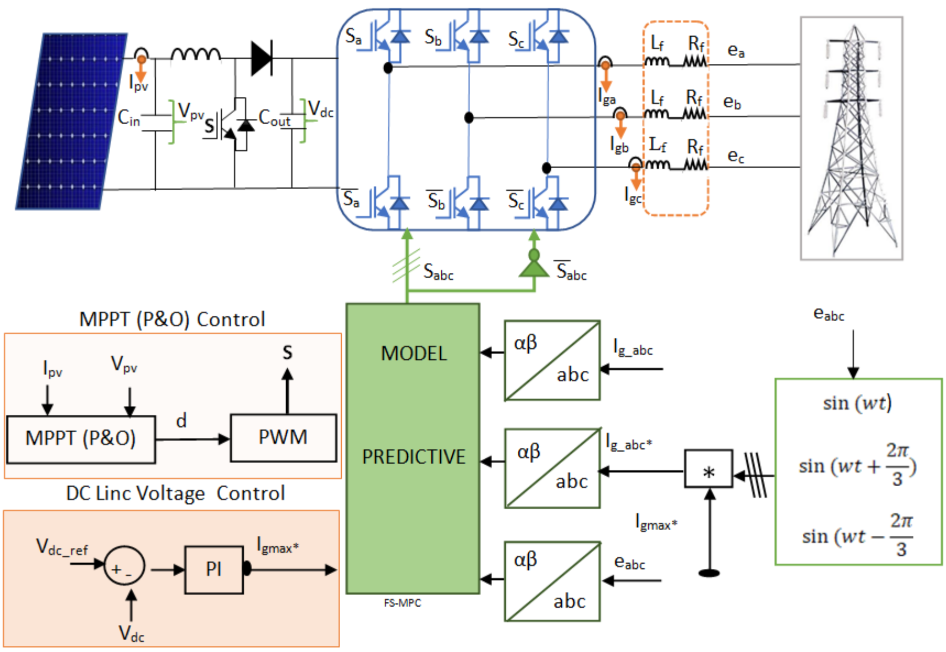


Fig. 1 Complete control strategy used in the proposed system

3.1. DC-AC Converter

The power circuit of the three phase two-level inverter is illustrated in Fig 1. It uses six bidirectional switches to connect the three-phase directly. Each bidirectional switch is have of an IGBT with a parallel diode, as shown in Figure 1. The two switches of each inverter leg must operate in a complementary mode to avoid short-circuit of the DC link. It is assumed that the switches and diodes are ideal devices. The inverter output voltages can be expressed in terms of DC-link voltage and switching states as follows [16], [17]:

In this modeling, we assume that the components of the inverter are perfect switches, having an image of the logic control signals Si (i = a, b, c) such that:

- If $S_i = 1$ the top switch is closed and the bottom one is open.
- If $S_i = 0$ the top switch is open and the bottom one is open.

In these terms, we can deduce the three-phase output voltages of the inverter (v_{aN}, v_{bN}, v_{cN}) as shown by the following equation system (1):

$$\begin{cases} v_{aN} = S_a V_{dc} \\ v_{bN} = S_b V_{dc} \\ v_{cN} = S_c V_{dc} \end{cases} \quad (1)$$

v_{aN}, v_{bN}, v_{cN}: are the phase-to-neutral (N) voltages of the inverter.
S_a, S_b, S_c: are the switching signals of the inverter.
V_{dc}: is the inverter input voltage (V).

For a the inverter with six switches, the switches of the each arm are controlled in a complementary manner, there are therefore eight possible combinations of the switch states (S_a, S_b, S_c) corresponding to eight voltage states [3], as shown in the figure (2) below . On the basis of the notion of the rotating vector [4], [6], we can associate with each of these combinations the instantaneous spatial lever defined by (2):

$$v = \frac{2}{3}(v_{aN} + a v_{bN} + a^2 v_{cN}) \quad (2)$$

With: $a = e^{j2\pi/3} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$

The possible number of combinations for the gating signals (S_a, S_b, S_c) becomes eight (2^3), and consequently eight voltage vectors for the inverter are obtained. A space vector diagram that contains these eight combinations is shown in Fig (2).

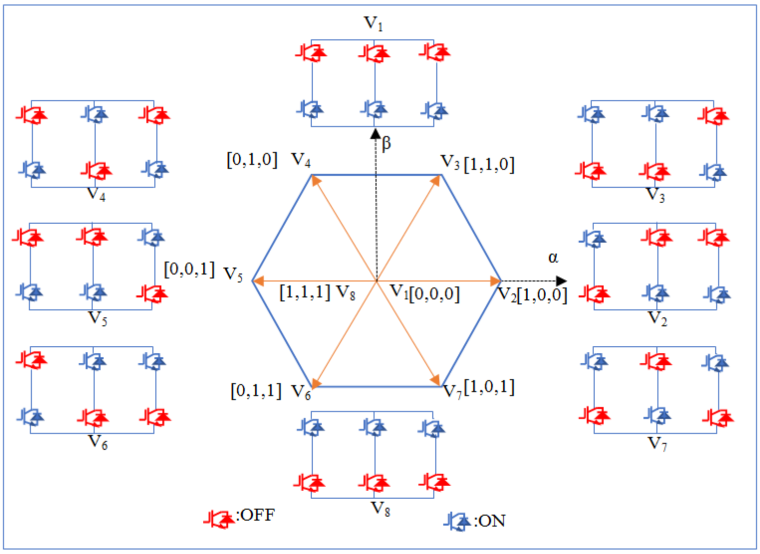


Fig. 2 Voltage vectors in the complex plane

With:

$V_1 = 0$; $V_2 = 2/3$ Vdc; $V_3 = 1/3\ V_{dc} + j\ \sqrt{3}/3V_{dc}$; $V_4 = -1/3\ V_{dc} + j\ \sqrt{3}/3$Vdc,

$V_5 = -2/3\ V_{dc}$, $V_6 = -1/3\ V_{dc} - j\sqrt{3}/3V_{dc}$; $V_7 = 1/3\ V_{dc} - j\ \sqrt{3}/3V_{dc}$; $V_8 = 0$.

3.2. Philosophy of predictive control

The synthesis of predictive control is based essentially on two stages: predicting future behavior of the system and quadratic optimization.

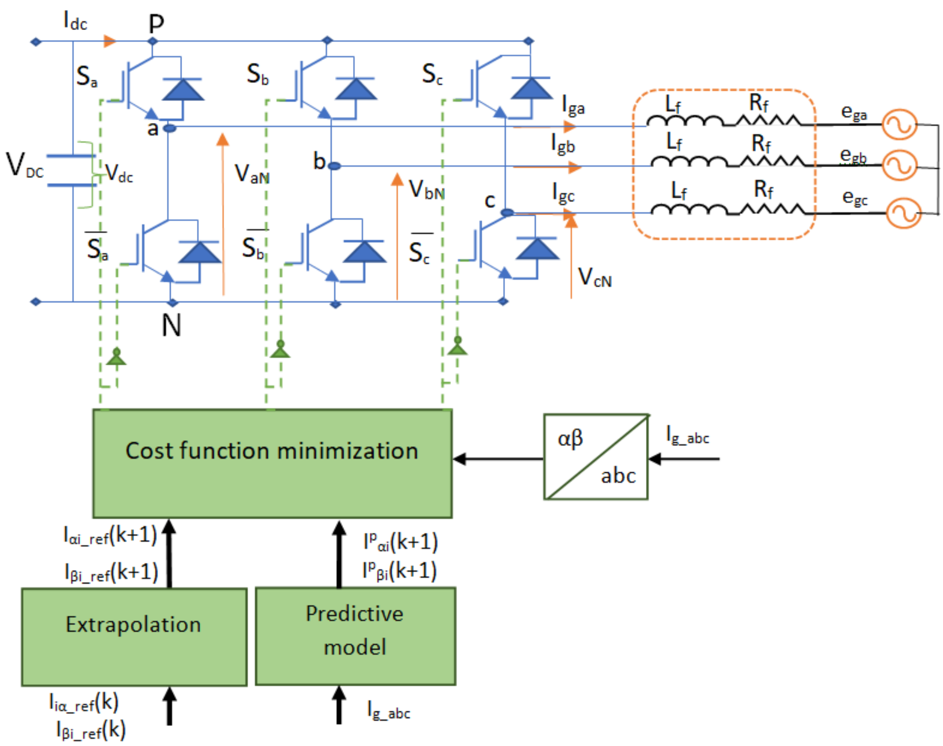


Fig. 3 Principle of FS-MPC

Prediction of future system behavior the phase-by-phase model of the injected current is given by the equation below (3):

$$R_f i + L_f \frac{di}{dt} + e = v$$
$$\frac{di}{dt} = -\frac{R_f}{L_f} i + \frac{1}{L_f}(v - e) \tag{3}$$

Where: e: the grid voltage, *v*: is the inverter output voltage, *i*: the current injected.

In order to predict the behavior of the variables evaluated by the cost function, a discreet time model of the system is necessary. The Euler preview technique is used to discretize the system model because of its brevity. It also provides acceptable precision, which is essential for better effectiveness. According to this technique, we have the discrete time form of the system as follows in (4) [16], [18]:

$$\frac{dx}{dt} \approx \frac{x(k+1) - x(k)}{T_s} \tag{4}$$

T_s: is the time of sampling.

$x(k)$ et $x(k+1)$: are the state variable value in the current state and in the next sampling time, respectively

By using Euler's method, equation (4) is discredited in order to obtain an expression which makes it possible to predict the future current at (k+1) for the eight possible switching states applied to the inverter, this expression s 'written in the following form (5):

$$i(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i(k) + \frac{T_s}{L_f}(v(k) - e(k)) \tag{5}$$

Quadratic optimization as a final step, the cost function is defined and expressed in orthogonal coordinates and measure the error between the reference and predicted currents and given by (6) [4]:

$$g = \left| i^*_{\alpha}(k+1) - i_{\alpha,P}(k+1) \right| + \left| i^*_{\beta}(k+1) - i_{\beta,P}(k+1) \right| \tag{6}$$

$I_{\alpha,P}(k+1)$ and $i_{\beta,P}(k+1)$: are the real and imaginary part of the predicted grid current.

$I_{\alpha}*(k+1)$ et $I_{\beta}*(k+1)$: are the real and imaginary part of the reference grid current.

The goal of optimizing the cost function is to select the cost value g as close to zero as possible. The optimal switching state which minimizes the cost function is chosen and then applied to the converter at the time of the next sampling instant.

FS-MPC algorithm

The control strategy can be summarized by the following steps and illustrated in Fig (4):

1. Build a model of the static converter and its possible switching states. The injected currents are measured and then undergo a transformation according to the d-q coordinates. The values of the reference currents are subsequently obtained from the output quantity of the DC bus regulation loop.
2. Build a model of the currents injected for the prediction. The system model is used to predict the injection current value in the sampling interval (k+1), for each of the eight voltage vectors.
3. Define the cost function. The cost function (g) minimizes the error between the reference and predicted current.
4. The voltage vector which minimizes the current error is selected and the signals corresponding to the switching states are applied.

Estimation of the references currents the reference estimates of the two controlled currents, iα and iβ, can be estimated from the currents using the outputs of a three-phase PLL. For this method, the references of the absorbed currents are given by equation (7), from which the three unit sinusoidal signals, sin(ωt), sin(ωt-2π / 3) and sin(ωt-4π / 3) are obtained through a 03-phase PLL. [17]

$$\begin{cases} i_a^*(t) = I_{\max}\sin(wt) \\ i_b^*(t) = I_{\max}\sin(wt - \frac{2\pi}{3}) \\ i_c^*(t) = I_{\max}\sin(wt - \frac{2\pi}{4}) \end{cases} \quad (7)$$

By applying the abc / αβ transformation, the references of the currents in the stationary frame αβ, are defined by the expressions below (8):

$$\begin{cases} i_\alpha^*(t) = \frac{\sqrt{3}}{\sqrt{2}} I_{\max}\sin(wt) \\ i_\beta^*(t) = \frac{\sqrt{3}}{\sqrt{2}} I_{\max}\cos(wt) \end{cases} \quad (8)$$

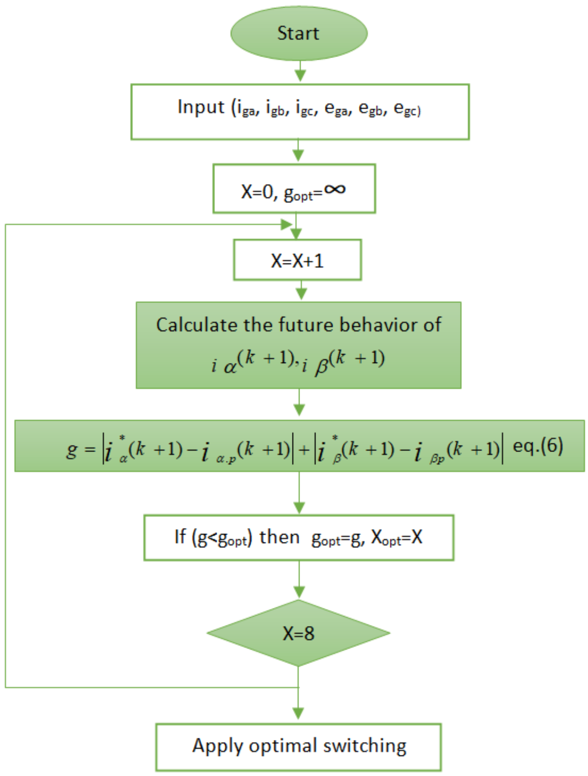


Fig. 4 Predictive control algorithm

4. SIMULATION RESULTS

The main parameters of three phase two level converter are given in Table 1. The use of simulation is a very important step in the study of photovoltaic systems, it makes it possible to modify system parameters such as sunshine and test the performance of control methods under different conditions. To perform a simulation, the functioning of the system components must be represented in the form of mathematical equations understandable by the simulation software. The simulation study of this first approach to predictive control of the three-phase inverter with two levels based on the selection of the optimal control vector is carried out through the Matlab/Simulink tool and the SimPower system library. The results are obtained in steady state and for a purely sine wave power supply. In this work, we present the different models used for the photovoltaic panel and the parts of a photovoltaic system connected to the network then we integrate the proposed control scheme in order to validate the proposed scheme

A control scheme test proposed for a photovoltaic system connected to the network was conducted under solar irradiation profile as in Figure(a)is considered and injected into the photovoltaic panel and the temperature is set at 25 ° C.

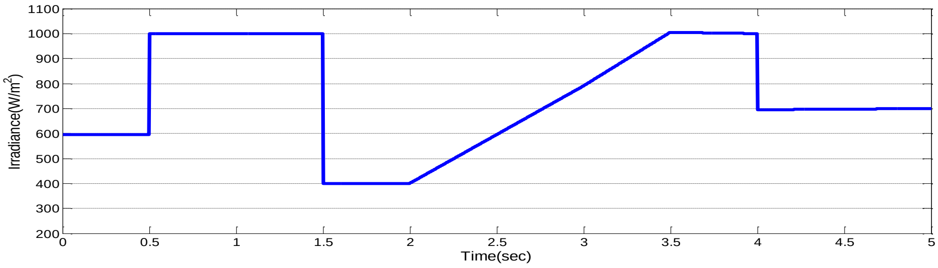
The aim of first study is to demonstrate the improvement achieved by applying the proposed control method based on MPC with the conventional P&O method in terms of MPPT, DC-link voltage control, Δ-β current control axes and grid current current quality. In the second study, the development platform is tested to evaluate the grid current THD%.

Figures (b) and (c) illustrate the simulation results of the evolution of the voltage and current, while the current is proprtionnel to thesolar irradiation.

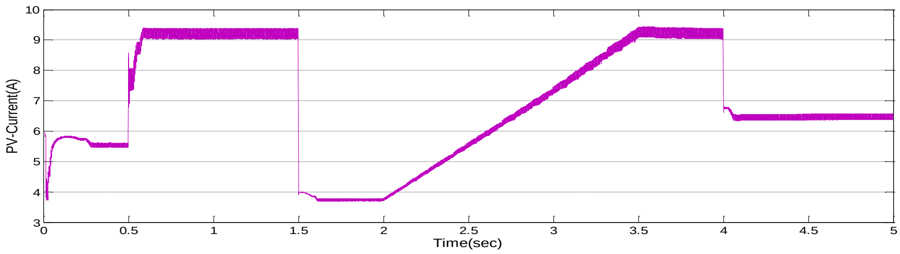
The Figure (d) shows output power of the photovoltaic panel obtained with the algorithm of the P&O method a sudden decrease and increase in solar irradiation from 600 to 1000w/m^2 at 0.5 sec, a large sudden decrease from 1000 to 400w/m^2 at 1.5 sec. The MPPT reaches the maximum power MPP rapidly. Moreover, Figure (e) shows the simulation result of the evolution of the DC bus voltage obtained for a reference voltage of 220V, the proposed control scheme tekes only mily seconds to track the reference voltage. The figures (f), (g),(h) present the grid current, figures (i),(j) and (k) illustrate the line and phase voltage with predictive control. The grid currents are increased or decrease rapidly due to the increase or decrease of solar irradiation, and kept the sinusoidal form with the grid current amplitude is proportion at to the irradiation.

Figures (l) and (m) illustrate the active and reactive power, it is clear that the developed control technique provides improved performance during the cases of irradiation with a perfect active and reactive power.

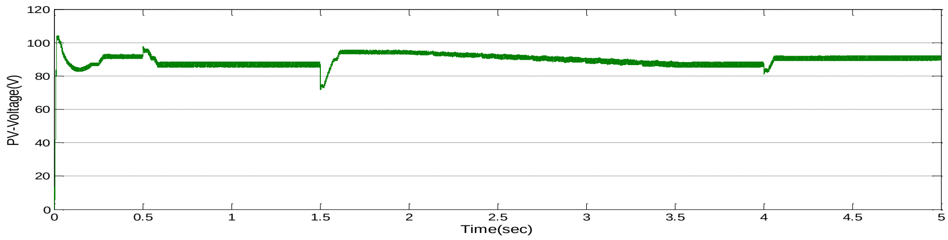
The harmonic content of the currents THD values obtained are shown in figure (k) using FFT analysis, a grid current THD% have been provided by the model predictive control. Finally, to prove the efficiency of the predictive technique, in the goal to shows the contribution of the control technique proposed. The criteria taken into account in the evaluation of the efficiency of these commands is the total distortion harmonic of the network currents (THD) as presented in figure (o) under different irradiation and the ripple of the active and reactive powers.



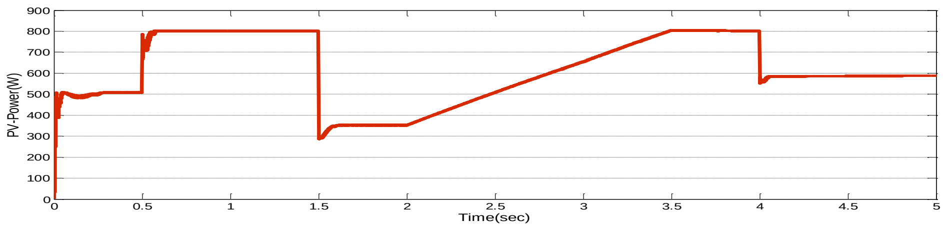
(a) Irradiations (W/m^2)



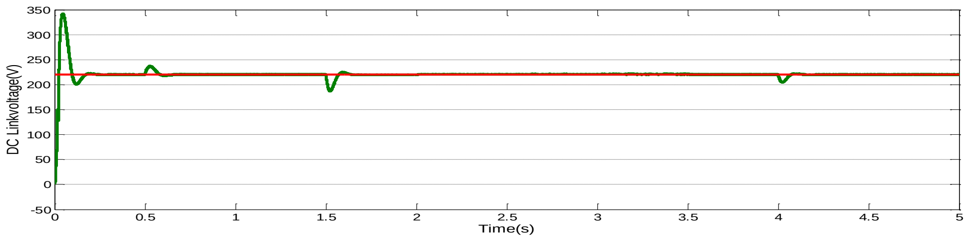
(b) Photovoltaic current (A)



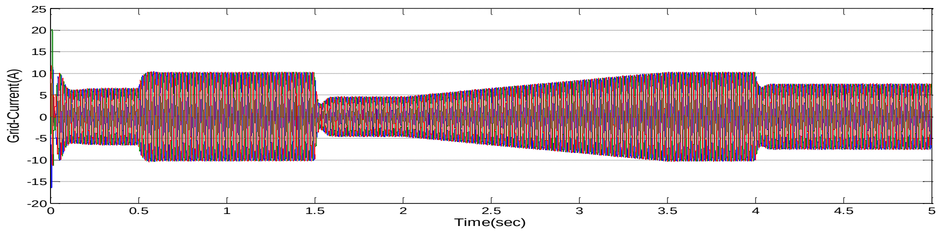
(c) Photovoltaic voltage (V)



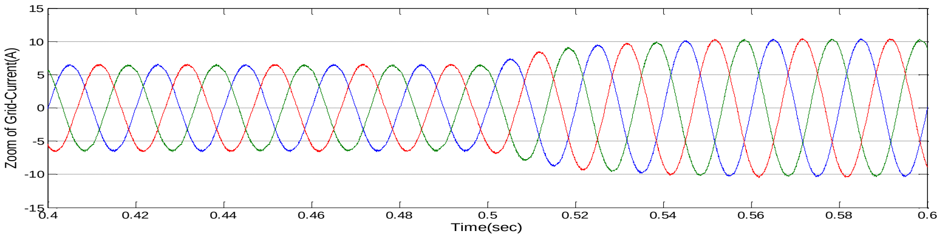
(d) PV Power (W)



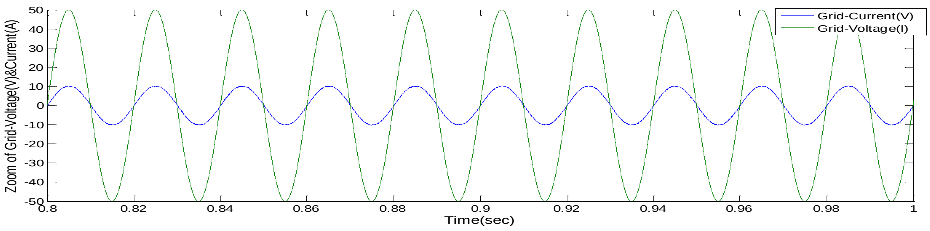
(e) DC Voltage (V)



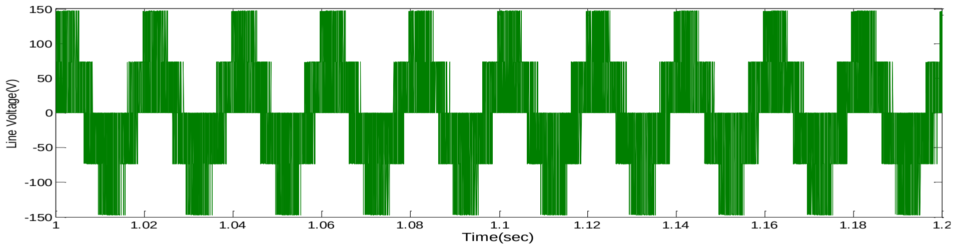
(f) Grid current (A)



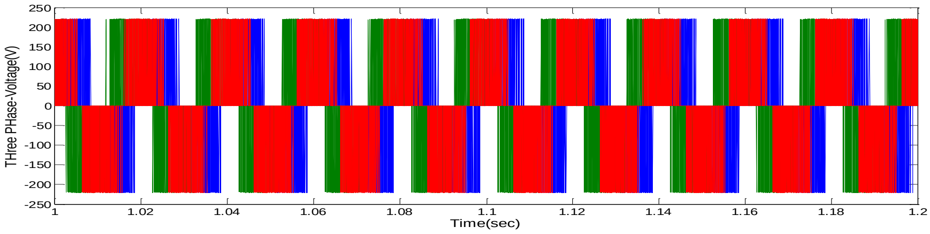
(g) Zoom of Grid current (A)



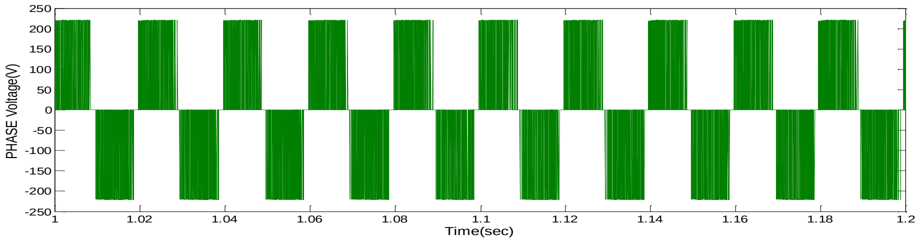
(h) Zoom of Grid Voltage (V) & current (A)



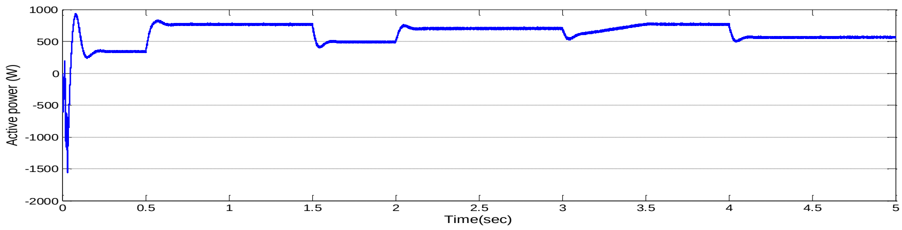
(i) Zoom of phase voltage (V)



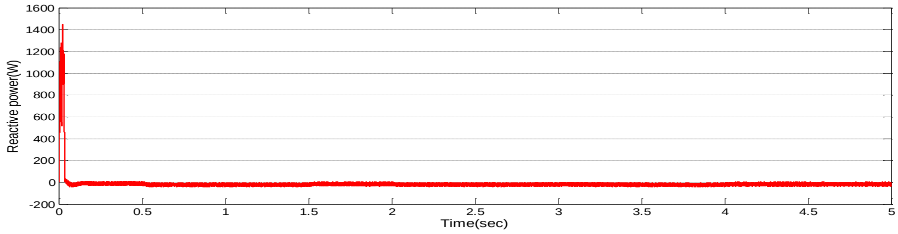
(j) Zoom of three line voltage (V)



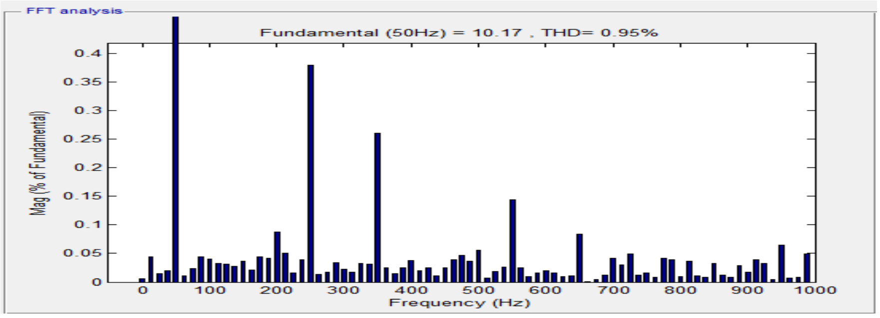
(k) Zoom of line voltage (V)



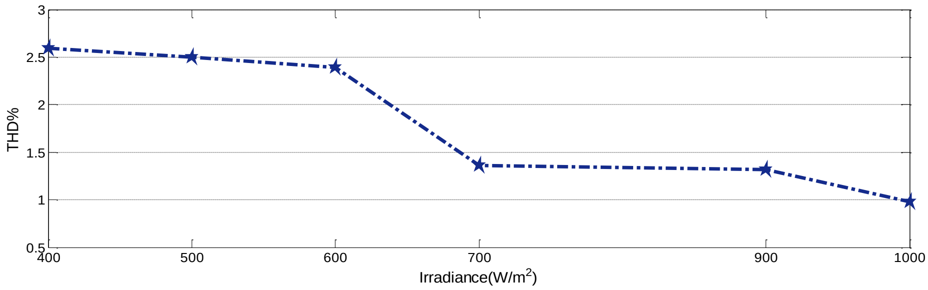
(l) Active power (W)



(m) Reactive power (VAR)



(n) Total harmonic distortion



(o) Total harmonic distortion

Fig. 6 Simulation results

We can note that the power of the photovoltaic panel faithfully follows the change in lighting, in a fast and stable manner with small oscillations around the optimal power points.

The PI regulator proposed for the conventional control of the DC-voltage has proven to be effective whatever the operating conditions. It tracks its reference despite the change in the lighting with good accuracy, precision and stability which proves efficiency of the proposed PI.

We can also note that the amplitude of current injected is proportional to the illumination, almost sinusoidal and in phase with the line voltage which means that the power factor is very close to the unit. In the grid level, the predictive command is used to regulate the current reference in order to inject the maximum active power into the electrical network as shown in figures (l) and (m). To prove the performance of the predictive method, the simulation results show that the predictive command proposed ensures current injection continuously.

We note that each injected current into the network obtained with the predictive algorithm perfectly follows its reference.

On another side, we have proposed the predictive control, synthesized at basis of an optimization principle for current control at the inverter level. The results obtained with these control laws have shown a good dynamic performance, great capacity for tracking references and high robustness against variations in metrological conditions.

Furthermore, Figure (n) shows the harmonic spectrum of one current grid phase analyzed by fast Fourier transform (FFT) of fundamental frequency. As shown in this figure, the total harmonic distortion is less than 3% in more distorted region of current which occurs 400W/m^2 sun irradiance.

Moreover, we note that the currents distortion rate for different instants obtained by the predictive algorithm is acceptable and improved when the illumination is increased.

5. CONCLUSION

This work presents FS-MPC technique for current control in a three-phase inverter built to resolve the disadvantages of traditional techniques. Active and reactive current are modeled as the reference control variables. In order to deal with these control goals, the cost functions are specified during each interval of sampling time. The control targets are accomplished on the basis of cost-function minimization. The DC-Bus voltage control is also controlled while the MPPT control is achieved by the P&O. The proposed PV system has been tested under various irradiation profiles. The results obtained indicate that the proposed system has a fast dynamic response, high performance of reference tracking with low oscillation, and fewer errors of steady state. The PV system transfers power to the utility grid with good efficiency when connected to the grid using an FS-MPC controller. An optimal power factor and a very low harmonic distortion rate (THD) percent were also achieved.

Table 1 System Parameters

	Parameters	Value		Parameters	Value
PV module	Short circuit current Isc	5 A	Filter	Inductor	10 mH
	Oppen circuit voltage	21.6V		Resistor	0.1Ω
			Grid	Grid frequency	50 Hz
Boost chopper	Input capacitor	330 μF		Grid voltage	50v
	DC link capacitor	330 mH	Simulation parameters	MPPT sampling time Tm	1e-3s
	Indictor	330 μF		Predictive sampling time Ts	1e^{-5} s

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