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Advanced Direct Power Control for Grid-connected Distribution Generation System Based on Fuzzy Logic and Artificial Neural Networks Techniques

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ABSTRACT

This paper proposes an improvement of the direct power control (DPC) scheme of a grid connected three phase voltage source inverter based on artificial neural networks (ANN) and fuzzy logic (FL) techniques for the renewable energy applications. This advanced control strategy is based on two intelligent operations, the first one is the replacement of the conventional switching table of a three phase voltage source inverter (VSI) by a selector based on artificial neural networks approach, and the second one is the replacement of the hysteresis comparators by fuzzy logic controllers for the instantaneous active and reactive power errors. These operations enable to reduce the power ripples, the harmonic disturbances and increase the response time period of the system. Finally, the simulation results were obtained by Matlab/Simulink environment, under a unity power factor (UPF). These results verify the transient performances, the validity and the efficiency of the proposed DPC scheme.

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1. INTRODUCTION

In recent years, the renewable energy sources have known a fast evolution, this leads the researchers to carry out investigations in a way to increase the reliability and the effectiveness of electromechanical conversion, electric conversion, and also to improve the energy quality supplied in order to guarantee the stability of their utility grid [1]-[2]. Among these, there is the photovoltaic (PV) system, which is considered as the most appropriate technology, the more successful and the most promising in the electricity production of renewable origin [3]. This source of decentralized energy generation presents the advantage of being abundant, inexhaustible, non-polluting for the environment, and provides lower-cost electricity and also higher power reliability compared to the centralized generation sources [4].

The connection of PV systems to the utility grid involves the use of the three phase voltage source inverter, with injection a sinusoidal current at low total harmonic distortion (THD) on the grid [5]. However, to guarantee the stability and the electrical grid quality, the operating conditions of this type of converter are imposed such as, the unity power factor operation, the control of the active and reactive power injected into grid. However, the use of voltage source inverters is very promising; it offers the choice of implementation of sophisticated control algorithms which allows functioning quickly with a low cost [6].

Various control strategies of voltage source inverter in grid connected photovoltaic systems have been presented in the literature. These control techniques are classified according to their principles for using the control loops of the powers and the currents in two categories: direct power control and voltage oriented control (VOC). The DPC strategy directly uses the instantaneous active and reactive power as control variables [7]; it is similar to the direct torque control (DTC) for induction motors [8]. This control method has two configurations: one used the voltage vector named voltage-based direct power control (V-DPC) and the other uses the virtual flux called virtual-flux-based direct power control (VF-DPC) [9]. However, the DPC has main advantages such as, a simple algorithm, no separate PWM block, no current regulation loops, and it has good dynamic performance. While VOC strategy allows orienting the current vector in the same orientation as the voltage vector of the grid, where the current control is performed in the d-q synchronous frame. This technique is similar to the vector control of the electric machines. The VOC can also use the virtual flux to estimate the grid voltages; this method is known under the name virtual flux oriented control (VFOC) [10]. Moreover, there are other types of controls that are used in the control of three phase voltage source inverter connected to the utility grid such as, non-linear control based on the sliding mode [11] and nonlinear control based on input-output feedback linearization [12].

In this paper, we propose a new structure of direct power control based on intelligent techniques for three phase VSI connected to the utility grid. This new DPC consists, on the one hand, to replace the conventional hysteresis regulators by fuzzy logic controllers. On the other hand, it allows replacing the predefined switching table by a selector based on the artificial neural networks approach. Moreover, this intelligent control constitutes a good solution to problems related to the conventional control. It allows ensuring a unity power factor, well control the active and reactive powers injected in utility grid at their references as well reduced considerably its fluctuations and also reduced the harmonic disturbances.

The paper is organized as follows: Section 2 presents the modeling of the three phase voltage source inverter in grid connected photovoltaic systems, the principle of the new DPC structure is exposed in section 3, section 4 is devoted to the fuzzy logic controllers design, the artificial neural networks selector are described in section 5, section 6 shows the simulation results of the overall system. Finally, a conclusion is given in section 7.

2. MODELING OF THREE PHASE VOLTAGE SOURCE INVERTER

Figure 1 shows the overall configuration of the proposed system. It is consists of a photovoltaic system connected to a three phase voltage source inverter, which in turn connected to a three phase inductance in order to transfer power to utility grid.

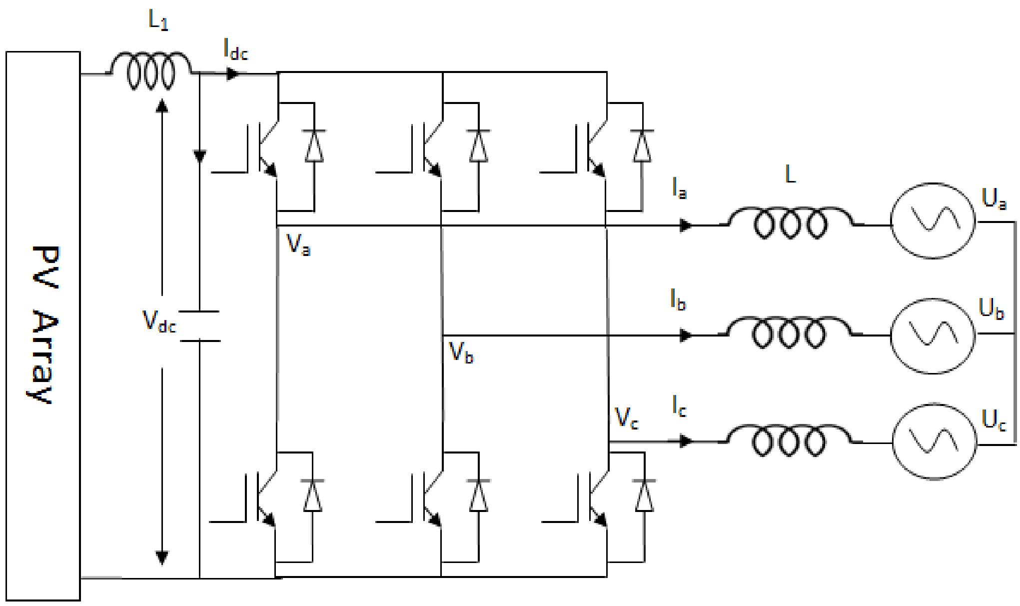

Figure 1. Functional diagram of the proposed system

Figure 2 shows the equivalent diagram of a grid connected three phase DC/AC converter in α-β coordinates system.

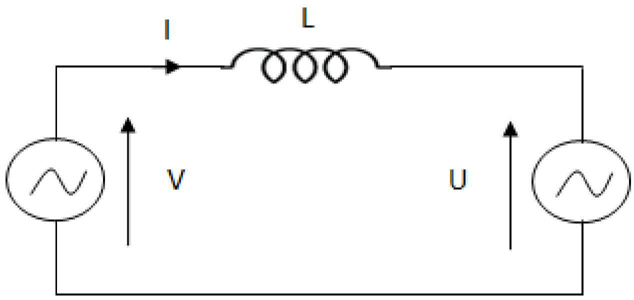

Figure 2. Equivalent diagram of a grid connected DC/AC converter

From the Figure 2, the mathematical model which governs this converter as ideal voltage source can be expressed in α-β coordinates as follow:

$$\begin{cases} V_\alpha = U_\alpha + L\dfrac{dI_\alpha}{dt} \\ V_\beta = U_\beta + L\dfrac{dI_\beta}{dt} \end{cases} \tag{1}$$

For this three phase system, the grid active and reactive power can be determined by several techniques [13] such as, the measurement of currents and grid voltages. In stationary α-β coordinates, the grid active and reactive power is expressed as follow:

$$\begin{cases} p = \dfrac{3}{2}(U_\alpha.I_\alpha + U_\beta.I_\beta) \\ q = \dfrac{3}{2}(U_\beta.I_\alpha - U_\alpha.I_\beta) \end{cases} \tag{2}$$

3. PRINCIPLES OF THE PROPOSED DPC STRATEGY

The DPC is the control structure that directly uses the instantaneous active and reactive power as control variables. The switching states of the switches of the three phase inverter are determined using a selector based on artificial neural networks approach, whose these inputs are the sector where is the position of the voltage vector of the grid and the digitized errors d_p, d_q, between the values of the instantaneous active and reactive power p, q, and their reference values p_{ref}, q_{ref} [14]. These errors are provided by fuzzy logic controllers.This control technique is similar to the direct torque control of induction machines whose the torque and the stator flux are the controlled quantities [8]. The simplified representation of the new DPC based on artificial neural networks approach and on fuzzy logic controllers for the three phase voltage source inverter is shown in Figure 3, in which (S_a, S_b, S_c) are the switching states of the VSI.

In order to obtain a unity power factor, the reference of reactive power is directly imposed equal to zero. While the DPC technique uses the angular position of the grid voltage vector to determine the sector of work, for that, the α-β plane is divided into twelve equal sectors, as shown in Figure 4. These sectors are determined numerically as follow:

$$(n-1)\frac{\pi}{6} \le \gamma_n \le n\frac{\pi}{6} \;;\; \text{n=1,2,…,12} \tag{3}$$

Where n is the sector number.

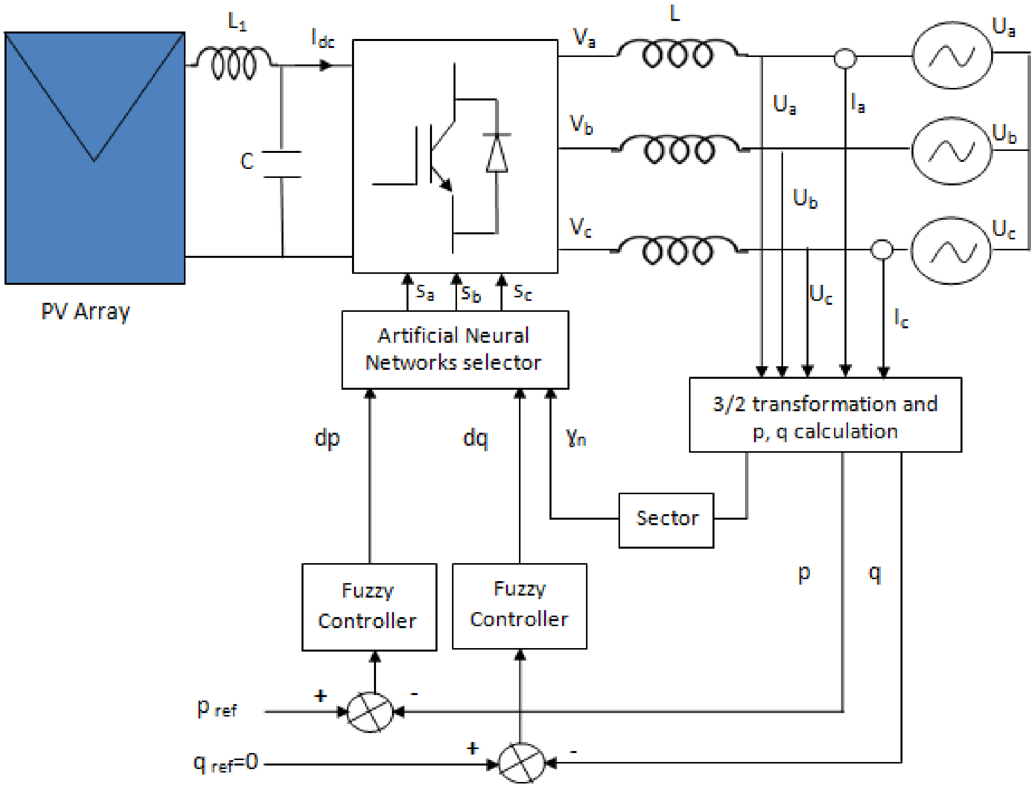

Figure 3. Block diagram of the proposed DPC strategy

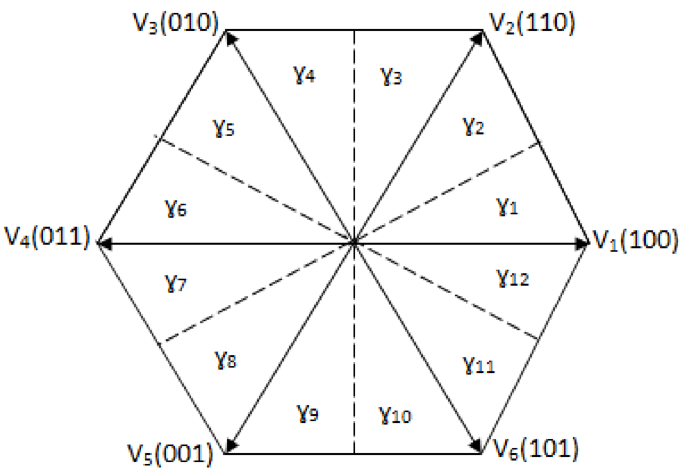

Figure 4. Sectors and voltage vectors of VSI

4. THE PROPOSED FUZZY LOGIC CONTROLLERS

The fuzzy logic control is a strategy used in artificial intelligence. It allows determining a very efficient control law compared to the traditional controller. While the fuzzy controller is based on three important steps: fuzzification, inference engine and defuzzification [15].

In this work, the fuzzy logic system has two inputs for the active power block and two inputs for the reactive power block. These inputs are the errors of active power e_p, reactive power e_q and their variations de_p, de_q; they are determined respectively by the following expressions:

$$\begin{cases} e_p(k) = p_{ref}(k) - p(k) \\ de_p(k) = e_p(k) - e_p(k-1) \end{cases} \tag{4}$$

And

$$\begin{cases} e_q(k) = q_{ref}(k) - q(k) \\ de_q(k) = e_q(k) - e_q(k-1) \end{cases} \tag{5}$$

4.1. Fuzzification

In order to perform the fuzzification of the errors of active and reactive powers, we have employed the trapezoidal membership functions. Thus, the two fuzzy sets chosen to accomplish this fuzzification are: N (Negative), P (Positive). The output variables are the two logic outputs d_p and d_q of two fuzzy controllers, the discourse universe of its output is divided into two fuzzy sets, its membership functions are forms of type singleton. The membership functions of the input and output variables are presented in Figures 5, 6 and 7.

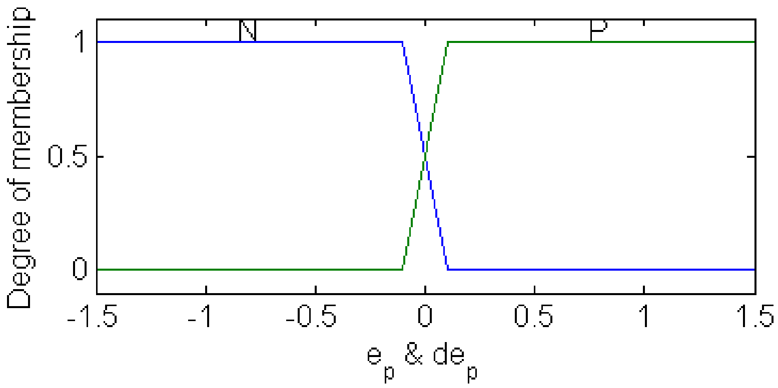

Figure 5. Membership functions for active power

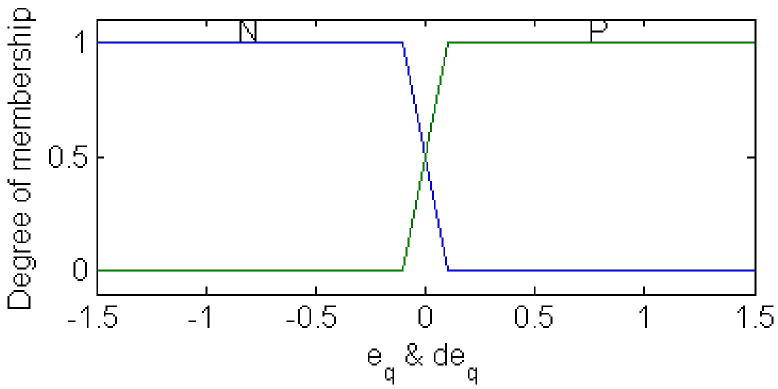

Figure 6. Membership functions for reactive power

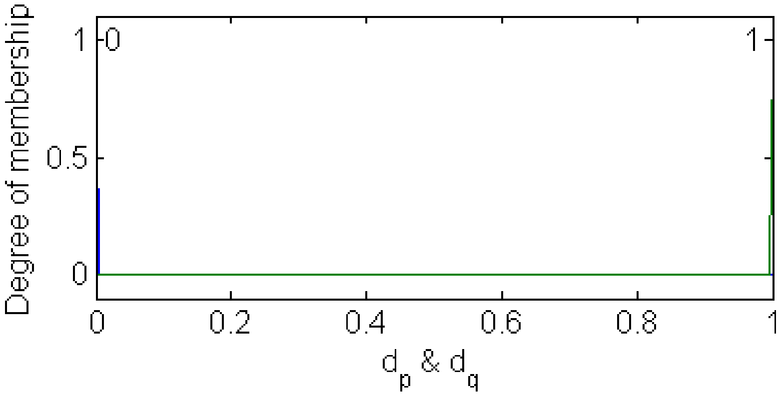

Figure 7. Membership functions for the output variable of the active and reactive power

4.2. Inference engine

The input linguistic variables e_p, de_p, e_q and de_q attack the inference engine where the whole linguistic rules are executed. The fuzzy sets of output are then determined using the fuzzy implication technique of Mamdani [16]. The Table 1 indicates the control linguistic rules of active and reactive power; these rules can be written in the following form:

IF (e_p IS N) AND (de_p IS P) THEN (d_p IS P)

IF (e_q IS N) AND (de_q IS P) THEN (d_q IS P)

Table 1. The control linguistic rules of active and reactive power

$de_{p,q}$ \ $e_{p,q}$	N	p
N	N	N
p	p	p

4.3. Defuzzification

This defuzzification block allows transforming linguistic variables from the two fuzzy controllers to real variables. To perform this task, several techniques have been proposed in the literature [17]. In our case, the center of gravity technique is used to perform this deffuzzification. The conventional switching table of the DPC is given in Table 2. It was built based on the outputs of two fuzzy controllers d_p, d_q and the sector position of work γ_n.

Table 2. Switching table of the DPC

d_p	d_q	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_{12}
1	0	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
1	1	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
0	0	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
0	1	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0

5. THE PROPOSED NEURAL NETWORKS SELECTOR

The development of neural networks is relatively recent. The origin of these latter comes from the modeling test of biological neuron [18]. They form a set of nonlinear functions allowing building by learning, a vast family of models and non-linear correctors [19]. The information in the neural networks spreads from one layer to another. We can distinguish three types of layers: an input layer, hidden layers and the output layer [20]. The neural networks are used in many areas include the classification, pattern recognition, the static or dynamic modeling of process and the control of industrial processes [21].

In this work, we proposed to change the conventional selector of the switching sequences of the three phase VSI by a neural networks selector, in order to reduce the ripples of active and reactive power. The inputs of the neural selector are the angular position of the voltage vector and the power errors provided by the fuzzy logic controllers. So, these outputs are the switching states of the VSI. Figure 8 shows the architecture of the neural networks used. While, the Table 3 shows the parameters of the neural networks used. Thus, this neural selector is generated by Matlab/ Simulink environment.

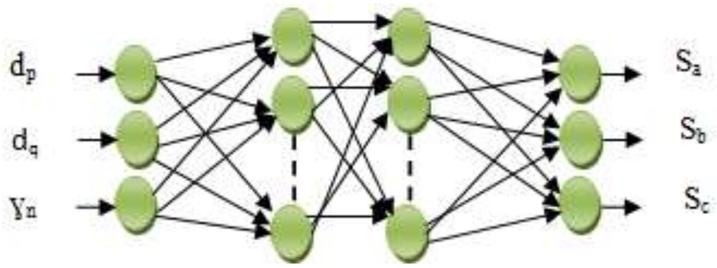

Figure 8. Architecture of ANN selector

Table 3. Parameters of the neural networks used

Number of neurons in the input layer	3 neurons
Number of neurons in the hidden layer	20 neurons
Number of neurons in the output layer	3 neurons
Number of epochs	1500
Mean square error	10^{-6}
Training algorithm of network	Backpropagation algorithm
Type of activation functions	Tansig and Purelin

6. SIMULATION RESULTS AND ANALYSIS

In order to show the performance of the new DPC strategy based on artificial neural networks approach and fuzzy logic controllers applied to a grid connected three phase DC/AC converter system, we present, in this section, the different results of numerical simulation. The system parameters are defined in the Table 4.

Table 4. Electrical parameters of system

Parameters of system	Value
Switching frequency	10 KHz
Line inductance L	0.01 H
DC-bus capacitor C	2400 µF
Grid phase voltage U	50 V
Grid frequency f	50 Hz
dc-bus voltage V_{dc}	113 V

The simulations are performed using Matlab/Simulink environment in steady and transient state. This simulation study was conducted for the purpose to present and explain the operating stability of the new DPC technique, and also to expose these dynamic performances. Figures 9-15 show the simulation results of the new DPC scheme in steady-state under a unity power factor operation. The simulation of the twelve sectors of the voltage vector in the α-β coordinate was shown in Figure 9. The Figure 10 shows the switching states S_a, S_b and S_c of the switches of the three phase VSI established by the ANN selector. The waveform of the DC-bus voltage V_{dc} is illustrated in Figure 11. The output phase voltage of the voltage source inverter is given in Figure 12. Figure 13 shows the waveform of the active and reactive power injected into utility grid. According to this figure, it was found that the DPC strategy based on fuzzy logic controllers, which do not require any exacte mathematical model of the studied system, and the ANN approach provide better control of active and reactive power and also a considerable minimization of the ripples of these powers during a fixed time period. Figure 14 illustrates the waveforms of the currents injected into the grid under a UPF, it may be noted that these currents have almost sinusoidal forms, which gives a reduced THD which is 0.17%. The current I_a and the voltage U_a injected into the grid are in phase which illustrates a UPF, as shown in Figure 15.

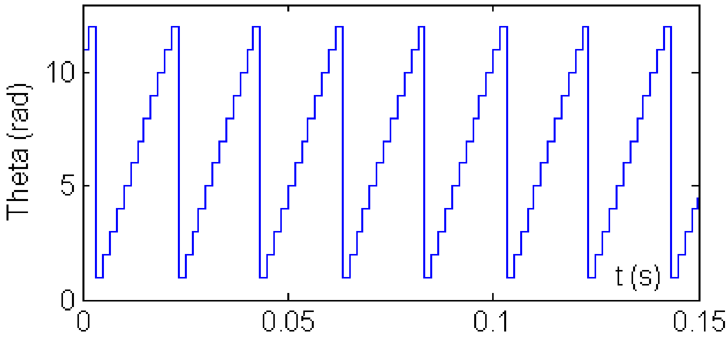

Figure 9. The twelve sectors of the voltage vector

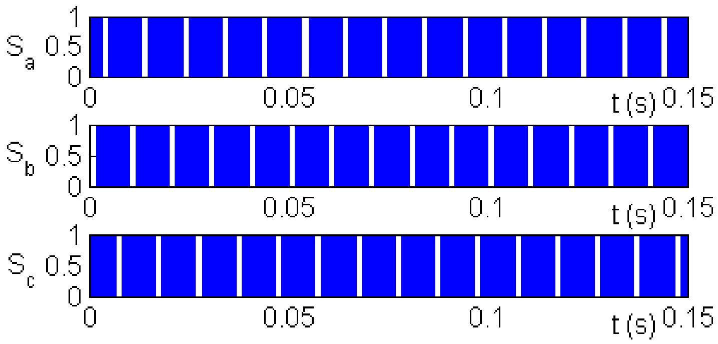

Figure 10. The switching states S_a, S_b and S_c of the VSI

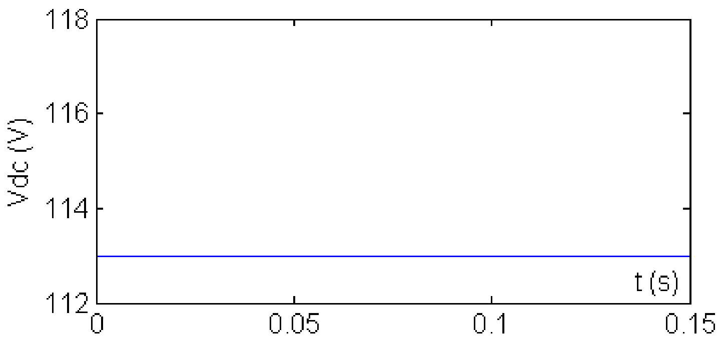

Figure 11. DC bus voltage waveform

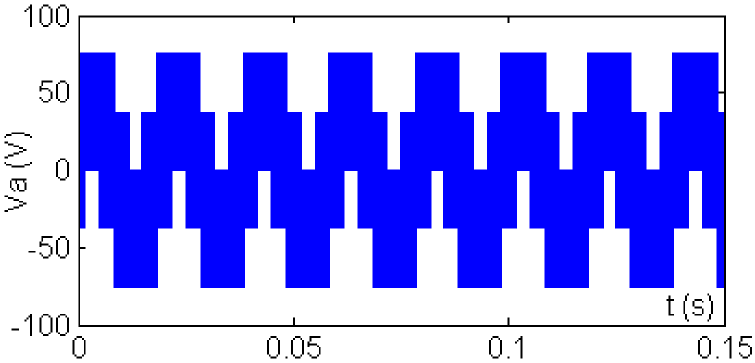

Figure 12. Waveform of the output voltage of the VSI

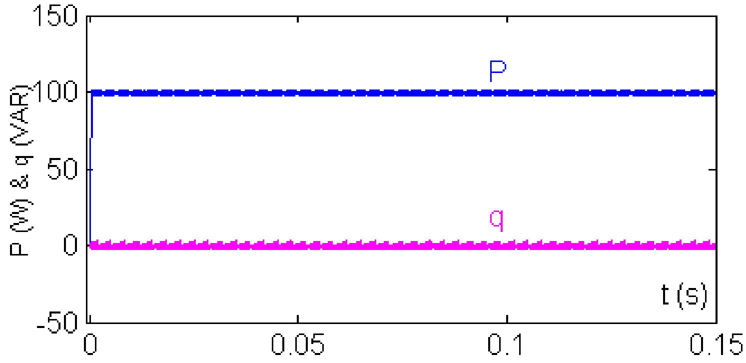

Figure 13. Waveform of the injected active and reactive power into grid

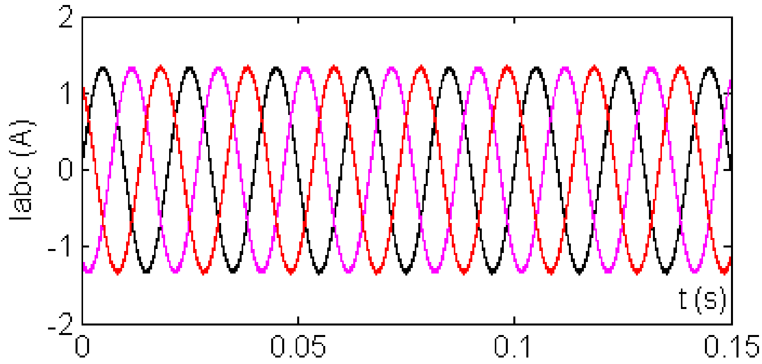

Figure 14. The current waveform I_a, I_b and I_c

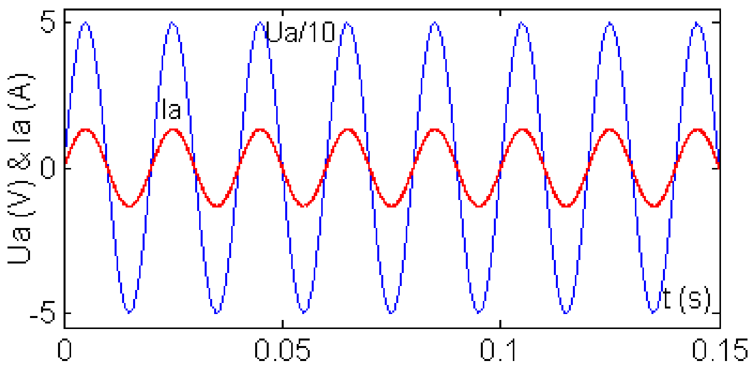

Figure 15. Phase grid voltage and grid currents at UPF

The waveforms of Figures 16-18 present the simulations results of the new DPC scheme in transient state under a UPF, for a step change of the reference active power of p_{ref} = 0 W to p_{ref} = 100 W at t = 0.075 s. The Figure 16 represents the waveforms of active and reactive power transferred into utility grid, we can note here that the active power has a good tracking of its reference without affecting the reactive power (UPF), which illustrates a decoupled control of this powers. The currents injected into utility grid responds well to the variation of the reference active power, he establishes quickly after a transition phase as shown in Figure 17. The current I_a and the voltage U_a are in phase (UPF) as shown in Figure 18.

It is evident from the simulation results that the DPC scheme based on artificial neural networks approach and fuzzy logic controller for grid connected voltage source inverter, in steady and transient state, give better responses in terms of overshoot, fast response and static error. Furthermore, they present an improvement of the robustness, excellent dynamic performance of active and reactive power control, as well as a significant mitigation of current ripples which seems sinusoidal, which gives a reduced THD.

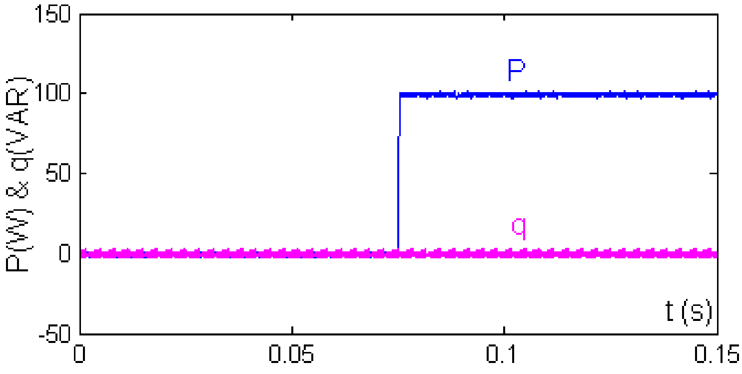

Figure 16. The waveform of the injected active and reactive power in the grid with active power step

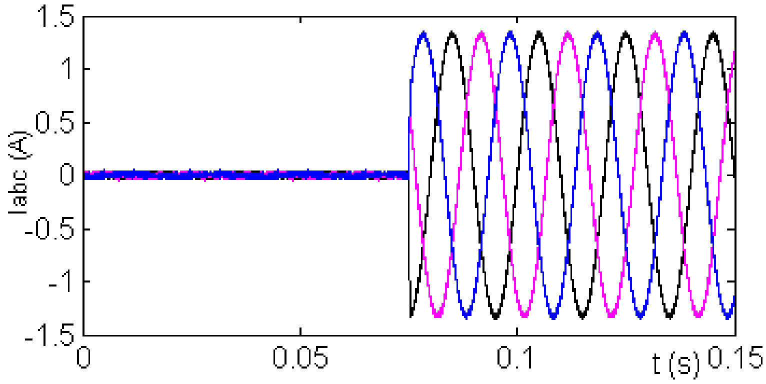

Figure 17. The waveform of the currents with active power step

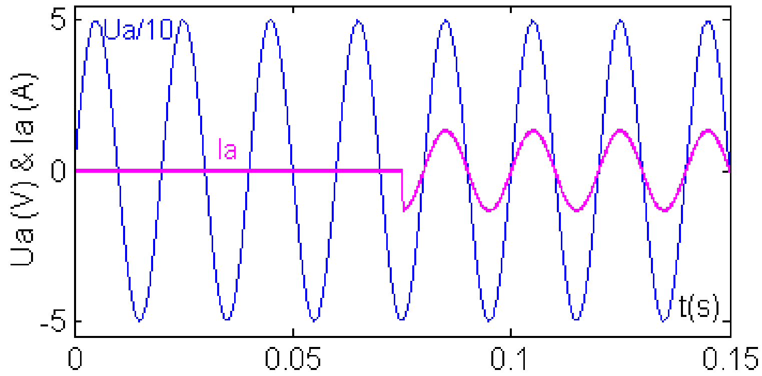

Figure 18. Phase grid voltage and grid currents (UPF) with active power step

7. CONCLUSION

In this paper, we have introduced an improved DPC strategy for three phase voltage source inverter in grid connected photovoltaic systems based on intelligent techniques. This technique of control is simulated using the Matlab/Simulink environment. The main objectives of the proposed control are to reduce the ripples of the active and reactive power, maintain these powers at the required level as well as it guarantees sinusoidal currents with low THD. The simulation results obtained have attested good static, dynamic performances and excellent robustness of this advanced control scheme in steady and transient state.

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