A Novel Predictive Approach to Direct Power Control of a Grid Connected Multilevel Converter

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Abstract

In this paper a novel approach for direct power control (DPC) of a grid connected 3-level voltage source inverter (VSI) is presented.

This method is based on a decision strategy, which selects the best appropriate converter voltage vector for the next sampling period in order to precisely track the active and reactive power references.

To predict the VSI voltage vector, a discrete model of the system is derived. Using the discrete model, the voltage vector which minimizes a specific quality function will be selected. Due to a large number of voltage vectors available in the output of a 3-level converter and in order to reduce the computation time, a classification of available voltage vectors based on the grid voltage status has been done.

The performance of the proposed predictive control method is compared with classical solution (VOC) via extensive simulations. The results show that the predictive method effectively controls the active and reactive powers and performs very well compared to the VOC.

This predictive method improves the transient response and keeps the steady-state harmonic spectrum in an acceptable level.

Keywords: Direct power control, multilevel DC/AC power converters, predictive control

I. Introduction

During last two decades, generation of electrical energy by renewable energy, mostly wind energy, has been increasingly developed because of various reasons such as environmental, economical, etc. [1]. Generally, the output voltage of this generation systems is a DC signal and for connecting them to the grid, a DC/AC converter must be applied.

With increasing amount of power delivered from renewable resources, the necessity of directly connecting of them to the medium voltage grid is Important, however the main problem is the voltage limitations of power switches. A suitable solution for this problem is to use a multilevel converter, inasmuch we can reach a higher voltage level at the output of the converter, with the same power switches, without reaching their voltage limitations. Another advantage of multilevel inverter is decreased THD of current and so; smoother current signals can be obtained [2].

This converter must provide a specific target of active and reactive powers to the mains; therefore an appropriate control scheme must be applied. Control methods that are used for this purpose are classified as two main groups such as indirect power control and direct power control (DPC) [1].

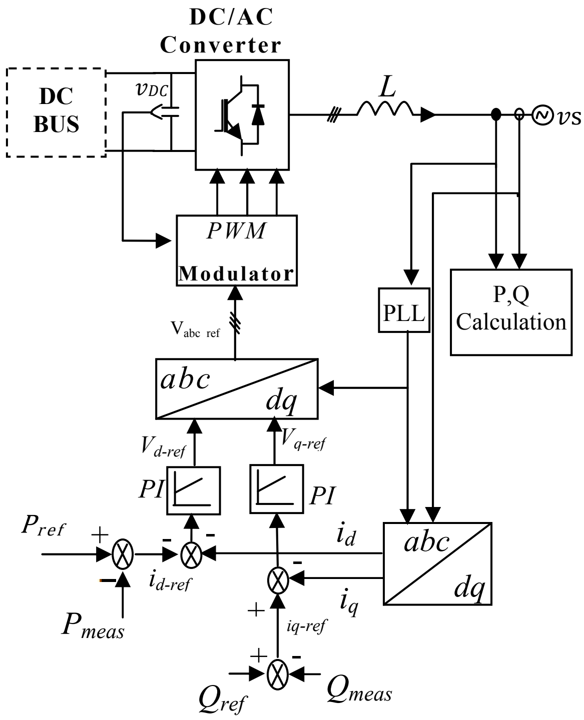

Fig. 1 Block diagram of VOC

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Voltage oriented control (VOC) is the most popular and effectively used strategy among the various indirect control strategies to control the grid-side converters. The main characteristic of this method is the presence of a modulator that computes the turn off/on time of each switch (See Fig.1) [9].
As it shows in Fig.1, in VOC there are two internal PI controllers. Setting the parameters of these controllers increases the complexity of this method. On the other hand, in direct power control techniques, switching state will be chosen by establishing a direct relation between the state of the converter's switches and the behavior of the active and reactive powers [1]. Thus there is no need to have a modulator (See Fig. 2).

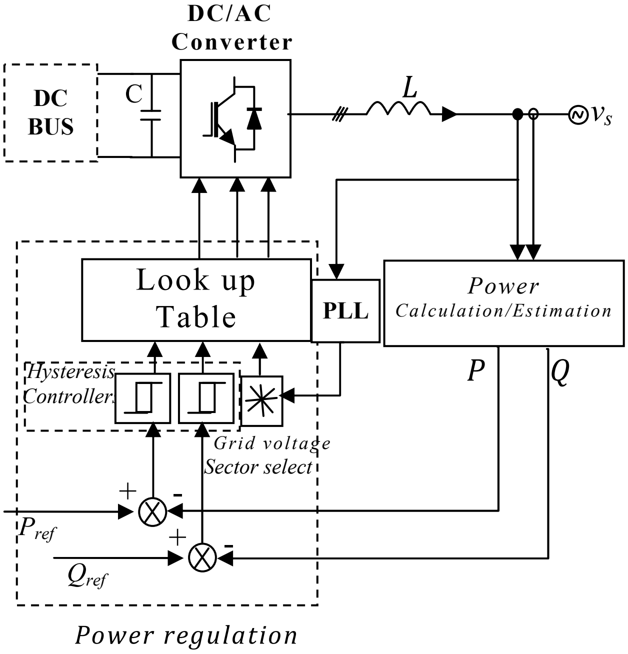

Fig. 2 Block diagram of DPC

Unlike VOC there are no internal current control loops and coordinate transformation, avoiding coupling effects between transformed variables.
One of the most important disadvantages of VOC is the necessity of having a large ratio between the switching and grid frequency to model the converter as an ideal continuous voltage source. Besides, in VOC we must have a coordinate transformation between abc and dq0 frame, that leads to coupling effects between transformed variables and more complex algorithm. On the other hand, the most important advantages of DPC are simple algorithm and good transient and dynamic behavior. The implementation of DPC is very simple and as it said, there is no need to a modulator and internal loops and there are no coupling effects.
This paper focuses on a predictive approach to direct power control of a grid connected three-level VSI. For this, after describing this approach for a two-level VSI, we extend it to obtain a general solution for three-level converters. A detailed explanation of the method is presented, including the models used for active and reactive power prediction and the quality function used for switching state selection. Simulation results comparing the performance of the proposed strategy with the well-known voltage oriented control (VOC) strategy are presented which confirms the superiority of the presented technique.

II. Proposed Method for Control of Three Phase VSI

In this section a discrete model of system will be developed. Based on this model, a simple predicting strategy will be described for a three phase grid-connected two-level VSI. Finally based on the described model for two-level VSI, a general solution will be proposed for a three phase grid-connected three-level VSI.

A. Discrete model of system

Instantaneous active and reactive power behavior of grid side can be defined as:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{1}$$

where $v_{\alpha-\beta}$ and $i_{\alpha-\beta}$ are the line voltage and current in the stationary coordinates, respectively. On the other hand, the following equation shows the per-phase dynamic behavior of a VSI with an inductive filter (Fig. 3):

$$v_K = Ri + L\frac{di}{dt} + v \tag{2}$$

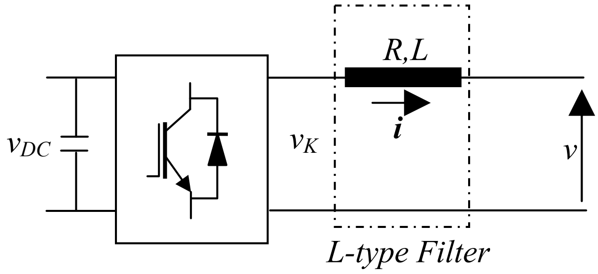

Fig. 3 Single-phase model of a line-connected VSI.

In this equation v_K is the converter voltage vector, v is the line voltage vector, and i is the line current vector.
From (2) we consider that by selecting appropriate converter voltage vector, instantaneous line current can be controlled and it is the key note, inasmuch by controlling the line current, active and reactive powers can be controlled [7].
Neglecting the resistance of the inductor (R) and rearranging (2), the line current change is provided by the following expression.

$$\frac{di}{dt} = \frac{1}{L}(v_K - v) \tag{3}$$

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With a sufficiently large sampling frequency ($1/T_S$), next control period current will be:

$$i(k+1) = i(k) + \Delta i(k) \tag{4}$$

Where $\Delta i(k) = \frac{T_S}{L}(v_K - v)$. From (1), we can estimate the active power for the next control cycle ($k+1$) as.

$$p(k+1) = v_\alpha(k+1) i_\alpha(k+1) + v_\beta(k+1) i_\beta(k+1) \tag{5}$$

The sampling frequency is high enough so, the change in system voltage can be neglected and (5) becomes:

$$p(k+1) = p(k) + v_\alpha(k)\Delta i_\alpha(k) + v_\beta(k)\Delta i_\beta(k) \tag{6}$$

And so on for the reactive power we can define it as:

$$q(k+1) = q(k) + v_\alpha(k)\Delta i_\beta(k) - v_\beta(k)\Delta i_\alpha(k) \tag{7}$$

Thus the changes of active and reactive powers during the ($k+1$)th and (k)th control period are defined as:

$$\Delta p(k) = v_\alpha(k)\Delta i_\alpha(k) + v_\beta(k)\Delta i_\beta(k) \tag{8}$$

$$\Delta q(k) = v_\alpha(k)\Delta i_\beta(k) - v_\beta(k)\Delta i_\alpha(k) \tag{9}$$

B. Proposed method for two-level VSI

Fig.4 shows a three phase tow level VSI. In this topology, there are 8 possible voltage vectors (6 active vectors and 2 zero vectors) that can be presented in the $\alpha\beta$ frame as shown in Fig. 5.

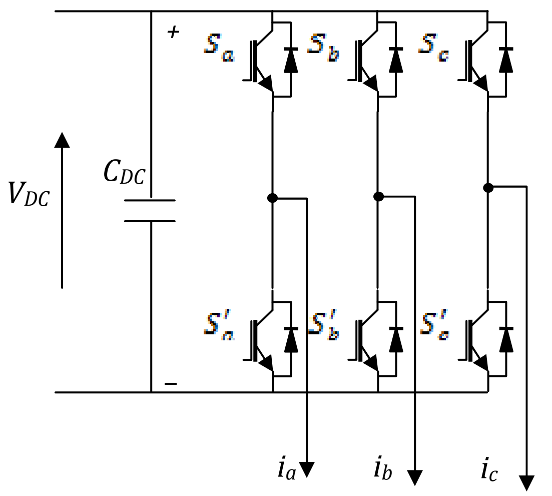

Fig. 5 Two-level VSI

Each of these voltage vectors can be obtained in the output of the inverter by switching on some specific switches.

As said, by choosing different voltage vectors, we can control the line current; therefore from equation (8) and (9), seven different values can be obtained for the next active and reactive powers, according to seven different voltage vectors. Hence, the best appropriate voltage vector must be selected to have minimum deviation from reference values for active and reactive powers. For this purpose the cost function σ is defined as:

$$\sigma = k_p(P_{ref} - p(k+1))^2 + k_q(Q_{ref} - q(k+1))^2 \tag{10}$$

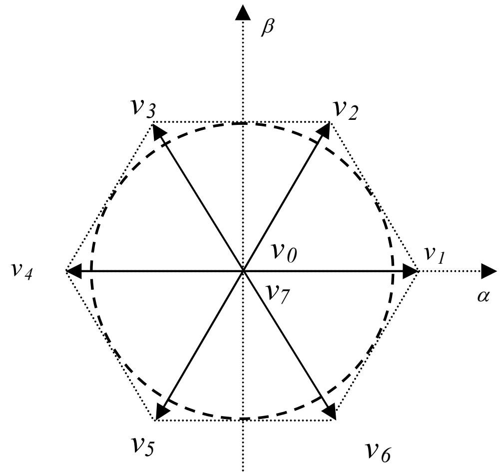

Fig. 5 Voltage vectors in a two-level VSI

The constants k_p and k_q can be selected to control the relative ripple of the active and reactive powers. In each control period, the vector which minimizes this quality function is the best appropriate switching state.

C. Proposed method for three-level VSI

On account of the topology of neutral point clamped (NPC) three-level VSI, (Fig. 6) there are 19 different voltage vectors available at the output of a three-level VSI (18 active vectors and one on-active vector) that can be presented in the $\alpha\beta$ frame as shown in Fig. 7.

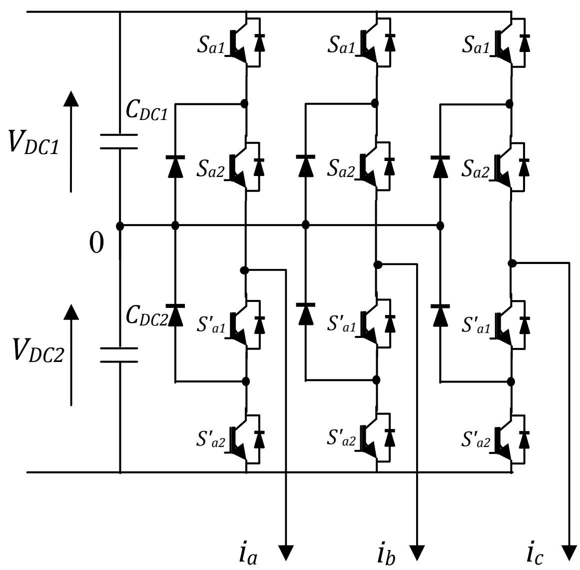

Fig. 6 Two-level VSI

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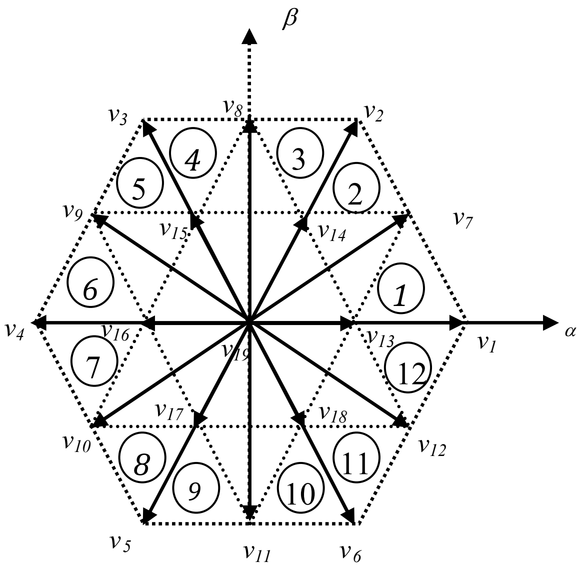

Fig. 7 Voltage vectors in a three-level VSI

If we use the same method as two-level VSI, because of numerous available voltage vectors the computational time for selecting next switching state will be very large and available processors may not be able to accomplish the control task within a small sampling period. Therefore in the proposed method, available voltage vectors are classified into 12 classes in order to reduce the number of voltage vectors that must be involved in the equation (10). For this, as shown in Fig. 5, the $\alpha\beta$ plan is divided into 12 equal sectors. From previous equations we see that:

$$q(k+1) = q(k) + \Delta q(k)$$

And:

$$\Delta q(k) = \frac{T_S}{L}(v_\alpha v_{K\beta} - v_\beta v_{K\alpha}) \qquad (11)$$

So if $q(k)$ is less than q_{ref}, $\Delta q(k)$ must be a positive value to track q_{ref} and vice versa. Therefore available voltage vectors must be classified into two groups, those who make (11) positive and the others who make it negative. For example, if in the sampling moment, grid voltage is within sector 1, vectors $\{1,5,6,10,11,12,13,17,18\}$ make $\Delta q(k)$ a positive and vectors $\{2,3,4,7,8,9,14,15,16\}$ make $\Delta q(k)$ a negative. In the table 1 such a classification is presented (Vector numbers are according to Fig. 7). It should be noted that the vector number 19, which is a non-active vector, does not have any effect on the reactive power variations.

In each sampling cycle, by using a PLL angular position of grid voltage can be obtained so, after finding the sector in which the grid voltage lies, the nine voltage vectors will be selected according to the table 1. Among these voltage vectors plus the vector 19, the one which minimizes the quality function of (10) will be the best appropriate switching state and will be applied to the converter.

Table 1 Classification of available voltage vector

Sector	$\Delta q(k) > 0$	$\Delta q(k) < 0$
1	1,5,6,10,11,12,13,17,18	2,3,4,7,8,9,14,15,16
2	1,5,6,7,11,12,13,17,18	2,3,4,8,9,10,14,15,16
3	1,2,6,7,11,12,13,14,18	3,4,5,8,9,10,15,16,17
4	1,2,6,7,8,12,13,14,18	3,4,5,9,10,11,15,16,17
5	1,2,3,7,8,12,13,14,15	4,5,6,9,10,11,16,17,18
6	1,2,3,7,8,9,13,14,15	4,5,6,10,11,12,16 17,18
7	2,3,4,7,8,9,14,15,16	1,5,6,10,11,12,13 17,18
8	2,3,4,8,9,10,14,15,16	1,5,6,7,11,12,13,17,18
9	3,4,5,8,9,10,15,16,17	1,2,6,7,11,12,13,14,18
10	3,4,5,9,10,11,15,16,17	1,2,6,7,8,12,13,14,18
11	4,5,6,9,10,11,16,17,18	1,2,3,7,8,12,13,14,15
12	4,5,6,10,11,12,16,17,18	1,2,3,7,8,9,13,14,15

III. Simulations

In order to verify the effectiveness of the proposed control method, simulations have been carried out using MATLAB/SIMULINK. Performance of the predictive strategy is compared with the classical solution (VOC). Parameters of the simulated system are presented in table 2.

Table 2 parameters of system under study.

Per phase system voltage	400 V_{RMS}
System frequency	50 Hz
DC link voltage	1200 V
Filter inductance	20 mH
DC link capacitor	1 mF
Switching frequency	2.5kHz

In VOC case, the parameters of the PI controllers are optimized by genetic algorithms and are set to K_p=6 and K_i=503.

The initial active and reactive powers reference values are 25 kW and 0 Var respectively. At t = 0.08 s the reactive power reference value is stepped up to 5 kVar and at t = 0.15 s stepped down to 3 kVar. Also, the active power reference value is stepped up to 32 kW at t = 0.1 s and stepped down to 28 kW at t = 0.13 s.

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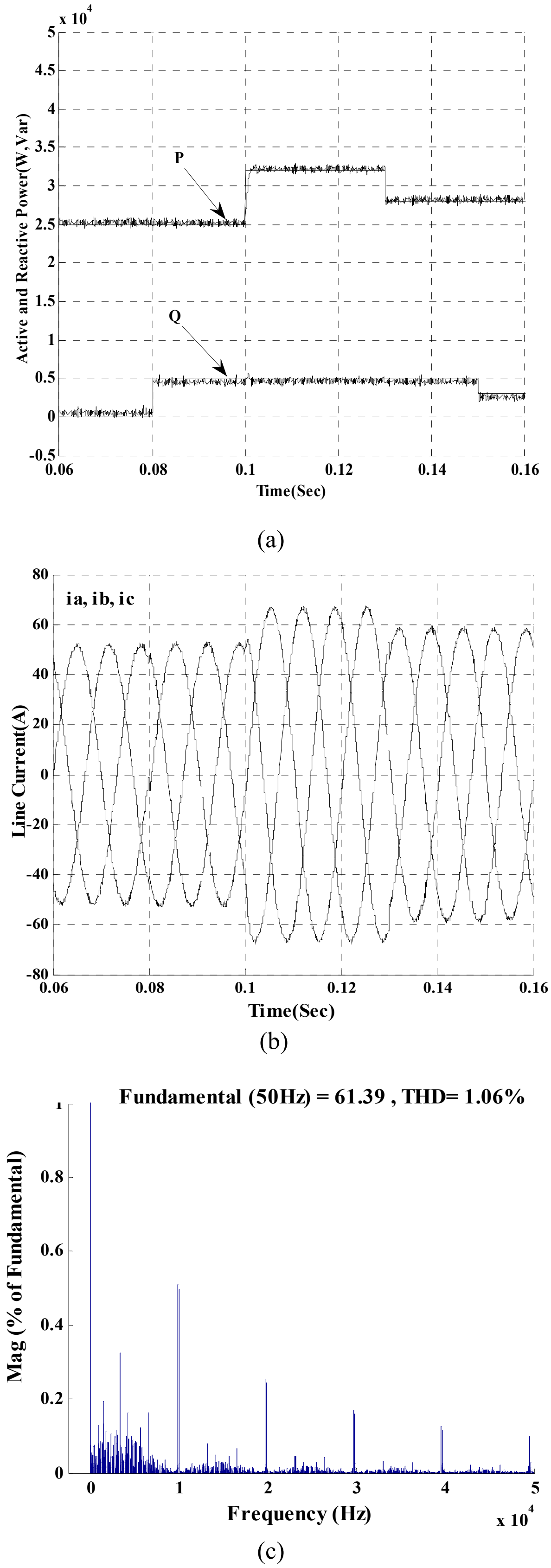

Fig. 8 Simulation results for proposed method
a) Active and Reactive power, injected to the grid.
b) Three phase line currents.
c) Harmonic spectrum of line current

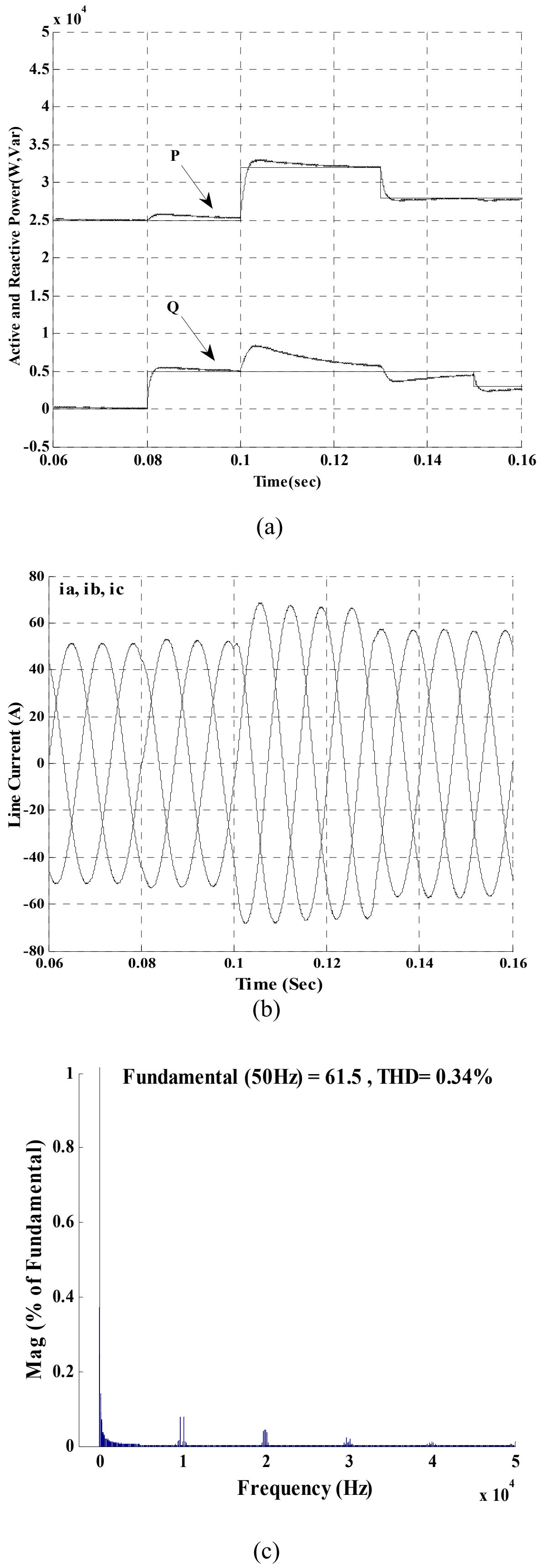

Fig. 9 Simulation results for VOC method
a) Active and Reactive power, injected to the grid.
b) Three phase line currents.
c) Harmonic spectrum of line current

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In Fig. 8a the active and reactive powers of the proposed method are shown. The dynamic response is very fast and almost assures decoupled control of active and reactive powers. Three phase line current waveforms are shown in Fig. 8b. Currents are quite sinusoidal (Total Harmonic Distortion, THD, of 1.06% (Fig. 8c))

The simulated waveforms for the VOC case are presented in Fig. 9. The dynamic response to the active and reactive power step changes is relatively slower than the predictive DPC case (Fig. 9a). Besides, active and reactive powers are not controlled separately and there are some coupling effects. Obviously, in the VOC case, line current waveforms are smoother (THD of 0.34% (Fig. 9c)).

I. Conclusions

In this paper a predictive approach for direct power control of a grid connected multilevel converter was presented. This strategy is based on the instantaneous power theory. A discrete model of the system is developed and based on this model a decision strategy to choose the best appropriate switching state is proposed. In order to reduce the computational efforts, a classification approach is proposed which makes the proposed control viable in industrial applications. Simulation results confirm the effectiveness of the proposed method in providing precise and fast power tracking and at the same time low mains current distortion. Besides, in the proposed method there is no coupling effect between controlled variables and the active and reactive powers are controlled separately. In addition to the transient and dynamic performance, one of the most important advantages of the proposed method is simplicity of algorithm and its implementation.

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