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***Abstract*—The total harmonic distortion (THD) plays a major role in determining the quality of the inverter output waveform. The use of an inverter with an output LC filter allows for generation of sinusoidal voltages with low harmonic distortion. Several control schemes have been proposed for the control of three-phase inverter. This paper presents a new and simple control scheme using predictive control. The controller uses a discrete-time model of the system to predict the behavior of the output voltage for all possible switching states generated by the inverter. Then, a cost function is used as a criterion for selecting the switching state that will be applied during the next sampling interval. A simple estimation of the load-current can be calculated from filter-current and output voltage. Therefore, there is no need of internal current-control loops and no modulators; the gate-drive signals are generated directly by the control. The simulation results under linear and nonlinear loads are presented, using Matlab/Simulink tools, verifying the feasibility and good performance of the proposed control scheme. Finally, the effect of error in system parameters values are presented.**

***Index Terms*—Power conversion, predictive control, uninterruptible power systems.**

I. INTRODUCTION

The use of a three-phase inverter has become very popular in the recent decades for a wide range of applications. The control of a three-phase inverter is one of the most important and classical subjects in power electronics and has been extensively studied in the last decades [1]. The control of inverters with output LC filter has a special importance in applications where a high quality voltage is needed, such applications include distributed generation and uninterruptible power supplies (UPSs). It is desired, especially for UPS systems, to achieve a good output voltage regulation with any load, typically a nonlinear load [2]. Therefore, low total harmonic distortion (THD) in the output voltage of UPS inverter under various loads and fast dynamic response are the main requirement for high-performance UPS.

The inclusion of a LC filter at the output of the inverter makes more difficult the controller design and controller parameters adjustment [2]. Several control schemes have been proposed for this converter, including nonlinear methods (like hysteresis control), linear methods (like proportional-integral controllers using pulse-width modulation (PWM)) [1], [3], [4], deadbeat control [6]–[8], multiloop feedback control [9]–[11] and repetitive-based controllers [12]. Some tuning strategies have been presented including H-infinity control design [13]. In most of these schemes the output voltage and one of two currents are used by a cascaded control considering outer and inner control loops, with linear or nonlinear controllers and a modulator is needed to generate the drive signals for the inverter switches [2].

Predictive control had found recent application in power converters due to its fast dynamic response [5]. It can be applied to a variety of systems, constraints and nonlinearities can be easily included, multivariable case can be considered, and the resulting controller is easy to implement. It requires a high amount of calculations, compared to a classic control scheme; however, the fast microprocessors available today make possible the implementation of predictive control. The main characteristic of predictive control is the use of the model of the system for the prediction of the future behavior of the controlled variables. This information is used by the controller in order to obtain the optimal actuation, according to a predefined optimization criterion. Several control algorithms have been presented under the name of predictive control like hysteresis-based predictive control, trajectory-based predictive control, deadbeat control, model predictive control (MPC) and MPC with finite control set, as presented in [2], [5]. The difference between these algorithms of controllers is that deadbeat control and MPC with continuous control set need a modulator, in order to generate the required voltage. This will result in having a fixed switching frequency. The other controllers directly generate the switching signals for the converter, do not need a modulator, and present a variable switching frequency. A well-known type of predictive controller is the deadbeat controller. It has been applied for current control in three-phase inverters [14], [15], active filters [16], [17], power factor preregulators [18], uninterruptible power supplies [8], [19], and dc-dc converters [29]. One of disadvantage of these deadbeat control schemes is that nonlinearities and constraints of the system variables are difficult to incorporate. Another approach is the model predictive control (MPC), also known as receding-horizon control; it uses a model of the system to predict the behavior of the variables until a certain horizon of time, and a cost function is used as criterion to select the optimal future actions [5], [20]–[23]. MPC is a very flexible control scheme that allows the easy inclusion of system constraints and nonlinearities in the design stage of the controller [2], [5]. In MPC, different formulations of the cost function are possible, considering different norms and including several variables and weighting factors [5]. It is also possible to consider different prediction horizons, as shown in [24]. The inputs of the system can be considered continuous, by using a modulator to apply the optimal voltages, as presented in [20] and [25]. In order to simplify the implementation of MPC, the converter can be modeled as a system with a finite number of switching states, and only one time step horizon can be considered for the optimization, as presented for a three-phase inverter in [1] and [26], an active front-end rectifier in [27], and a multilevel inverter in [28]. This way, all possible switching states can be evaluated online; then, the one that minimizes the cost function is selected.

This paper proposes a new and simple MPC scheme for a three-phase inverter with output LC filter. The controller uses a model of the system to predict, on each sampling interval, the behavior of the output voltage for each possible switching state. Then, a cost function is used as a criterion for selecting the switching state that will be applied during the next sampling interval. There is no need of internal current-control loops and no modulators; the gate-drive signals are generated directly by the control.

II. CONVERTER MODEL

The power circuit of three-phase inverter with output LC filter considered in this paper is shown in Fig. 1. The converter and filter models are presented here, and the load is assumed unknown. The switching states of the converter are determined by the gating signals S_a, S_b, and S_c as follows:

$$S_a = \begin{cases} 1, & \text{if } S_1 \text{ on and } S_4 \text{ off} \\ 0, & \text{if } S_1 \text{ off and } S_4 \text{ on} \end{cases} \tag{1}$$

$$S_b = \begin{cases} 1, & \text{if } S_2 \text{ on and } S_5 \text{ off} \\ 0, & \text{if } S_2 \text{ off and } S_5 \text{ on} \end{cases} \tag{2}$$

$$S_c = \begin{cases} 1, & \text{if } S_3 \text{ on and } S_6 \text{ off} \\ 0, & \text{if } S_3 \text{ off and } S_6 \text{ on} \end{cases} \tag{3}$$

and can be expressed in vectorial form by

$$\mathrm{S} = \frac{2}{3}(S_a + \mathrm{a}S_b + \mathrm{a}^2 S_c) \tag{4}$$

where $\mathrm{a} = e^{j(2\pi/3)}$.

The output-voltage space vectors generated by the inverter are defined by

$$\mathrm{v}_i = \frac{2}{3}(\boldsymbol{v}_{aN} + \mathrm{a}\boldsymbol{v}_{bN} + \mathrm{a}^2\boldsymbol{v}_{cN}) \tag{5}$$

where $\boldsymbol{v}_{aN}$, $\boldsymbol{v}_{bN}$, and $\boldsymbol{v}_{cN}$ are the phase voltages of the inverter, with respect to the negative terminal of the dc-link N (see Fig. 1). Then, the load voltage vector v_i can be related to the switching state vector S by

$$\mathrm{v}_i = V_{dc}\mathrm{S} \tag{6}$$

where V_{dc} is the dc-link voltage.

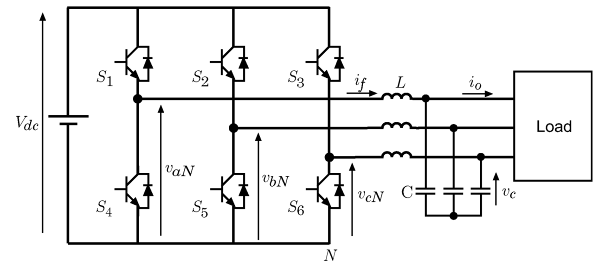


Fig. 1. Three-phase inverter with output LC filter.

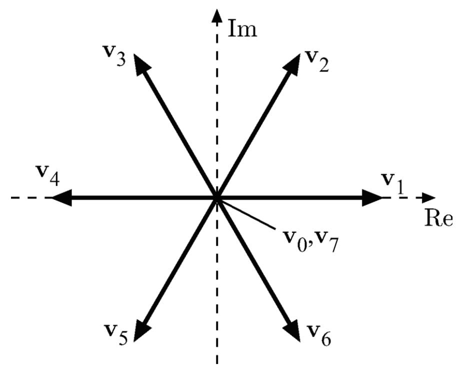


Fig. 2. Possible voltage vectors generated by the inverter.

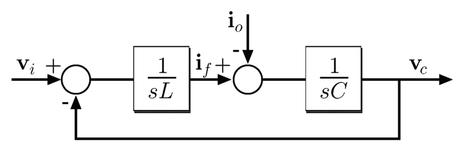


Fig. 3. LC filter model.

Table I
POSSIBLE SWITCHING STATES AND VOLTAGE VECTORS FOR A THREE-PHASE INVERTER

S_a	S_b	S_c	v_i
0	0	0	$\mathrm{v}_0 = 0$
1	0	0	$\mathrm{v}_1 = \frac{2}{3}V_{dc}$
1	1	0	$\mathrm{v}_2 = \frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	0	$\mathrm{v}_3 = -\frac{V_{dc}}{3} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	1	$\mathrm{v}_4 = \frac{-2}{3}V_{dc}$
0	0	1	$\mathrm{v}_5 = -\frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3}V_{dc}$
1	0	1	$\mathrm{v}_6 = \frac{V_{dc}}{3} - j\frac{\sqrt{3}}{3}V_{dc}$
1	1	1	$\mathrm{v}_7 = 0$

Considering all the possible combinations of the gating signals S_a, S_b, and S_c, eight switching states and consequently eight voltage vectors are obtained, as shown in Table I, using (6). Here, variables S_a, S_b, and S_c represent the switching states of the a, b, and c legs of the inverter. Note that $\mathrm{v}_0 = \mathrm{v}_7$, resulting in only seven different voltage vectors, as shown in Fig. 2.

In this paper, the inverter is considered as a nonlinear discrete system with only seven different voltage vectors as possible outputs. Nevertheless, using modulation techniques like pulsewidth modulation, the inverter can be modeled as a continuous system.

Using vectorial notation, the filter current i_f, the output voltage v_c, and the output current i_o can be expressed as space vectors and are defined as

$$\mathrm{i}_f = \frac{2}{3}(\boldsymbol{i}_{fa} + \mathrm{a}\boldsymbol{i}_{fb} + \mathrm{a}^2\boldsymbol{i}_{fc}) \tag{7}$$

$$\mathrm{v}_c = \frac{2}{3}(\boldsymbol{v}_{ca} + \mathrm{a}\boldsymbol{v}_{cb} + \mathrm{a}^2\boldsymbol{v}_{cc}) \tag{8}$$

$$\mathrm{i}_o = \frac{2}{3}(\boldsymbol{i}_{oa} + \mathrm{a}\boldsymbol{i}_{ob} + \mathrm{a}^2\boldsymbol{i}_{oc}) \tag{9}$$

The LC filter is modeled as shown in the block diagram in Fig. 3. This model can be described by two equations, one that describes the inductance dynamics and the other describing the capacitor dynamics.

The equation of the filter inductance expressed in vectorial form is

$$L\frac{d\mathrm{i}_f}{dt} = \mathrm{v}_i - \mathrm{v}_c \tag{10}$$

where L is the filter inductance.

The dynamic behavior of the output voltage can be expressed by the following:

$$C\frac{d\mathbf{v}_c}{dt} = \mathrm{i}_f - \mathrm{i}_o \tag{11}$$

where C is the filter capacitance.

These equations can be rewritten as a state-space system as

$$\frac{d\mathrm{x}}{dt} = A\mathrm{x} + B\mathrm{v}_i + B_d\mathrm{i}_o \tag{12}$$

where

$$\mathrm{x} = \begin{bmatrix}\mathrm{i}_f \\ \mathrm{v}_c\end{bmatrix}, \mathrm{A} = \begin{bmatrix}0 & \frac{-1}{L} \\ \frac{1}{C} & 0\end{bmatrix}, \mathrm{B} = \begin{bmatrix}\frac{1}{L} \\ 0\end{bmatrix}, \text{and } \mathrm{B}_d = \begin{bmatrix}0 \\ \frac{-1}{C}\end{bmatrix}.$$

Variables i_f and v_c are measured, while v_i can be calculated using (6), and i_o is considered as an unknown disturbance. In this paper, the value of V_{dc} is assumed fixed and known.

The output of the system is the output voltage v_c and written as a state equation

$$\mathrm{v}_c = \begin{bmatrix}0 & 1\end{bmatrix}\mathrm{x} \tag{13}$$

A. Discrete-Time Model of the Filter

A discrete-time model of the filter is obtained from (12) for a sampling time T_s and is expressed as:

$$\mathrm{x}(k+1) = A_q\mathrm{x}(k) + B_q\mathrm{v}_i(k) + B_{dq}\mathrm{i}_o(k) \tag{14}$$

where

$$A_q = e^{AT_s}, B_q = \int_0^{T_s} e^{A\tau}Bd\tau, \text{and } B_{dq} = \int_0^{T_s} e^{A\tau}B_d d\tau.$$

These equations are used as the predictive model in the proposed predictive controller.

In order to predict the output voltage using (14), the output current i_o is needed, but usually, this current is not measured, and the load is unknown. A simple estimation of the load current can be calculated from filter-current and output-voltage measurements using the following equation obtained from (11):

$$\mathrm{i}_o(k-1) = \mathrm{i}_f(k-1) - \frac{C}{T_s}\big(\mathrm{v}_c(k) - \mathrm{v}_c(k-1)\big) \tag{15}$$

It will be preferred to use an observer for load-current estimation, enhancing the behavior of the proposed controller without increasing the number of current sensors, but it is not the subject of this paper.

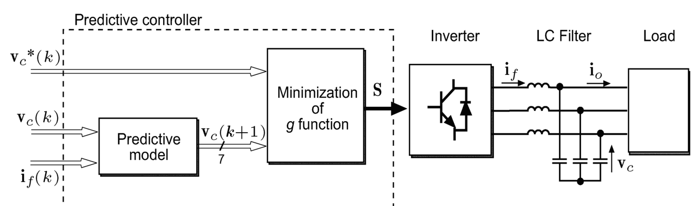


Fig. 4. Block diagram of the predictive controller.

III. PROPOSED PREDICTIVE CONTROLLER

The use of MPC to control the power converter is proposed in this paper. It is suitable to control this kind of system due to its fast dynamic response. It can be applied to a variety of systems, constraints and nonlinearities can be easily included, multivariable case can be considered, and the resulting controller is easy to implement. The desired behavior of the system is formulated as a cost function to be minimized. This paper takes into account an important restriction of the inverter, it can generate only seven different output-voltage vectors, and takes advantage of this restriction, making it possible to solve online the optimization problem of MPC. In these control schemes, an open-loop model is used for prediction and selection of the optimal actuations, but the use of a receding horizon provides the feedback to the control. This means that only the first element of the optimal actuation sequence is applied, and all the optimization is calculated again each sampling time.

The block diagram of the proposed predictive control for a three-phase inverter with output LC filter is shown in Fig. 4. Here, measurements of the output voltage $\mathrm{v}_c(k)$ and the filter

Table II
SYSTEM PARAMETERS

Parameter	Value
DC link voltage V_{dc}	520 [V]
Filter capacitor C	40 [μF]
Filter inductance L	2.4 [mH]
Sampling time T_s	33 [μs]

current $\mathrm{i}_f(k)$ are used to predict, using (14), the value of the output voltage at the next sampling instant $\mathrm{v}_c(k+1)$ for all the possible voltage vectors that the inverter generates, as shown in Table I.

In order to obtain the prediction $\mathrm{v}_c(k+1)$ from (14), an estimate of the (unmeasured) output current $\mathrm{i}_o(k)$ is required using the simple derivative approximation in (15). To choose the *optimal* voltage vector v_i to be applied by the inverter, the seven predictions obtained for $\mathrm{v}_c(k+1)$ are compared using a cost function g. The voltage vector v_i that minimizes this function is then chosen and its corresponding switching state that minimizes the cost function is applied at the next sampling instant, as shown in Table I.

In this paper, we choose a cost function g expressed in orthogonal coordinates and defines the desired behavior of the system: To minimize the error in the output voltage

$$g = (\boldsymbol{v}_{c\alpha}^* - \boldsymbol{v}_{c\alpha})^2 + (\boldsymbol{v}_{c\beta}^* - \boldsymbol{v}_{c\beta})^2 \qquad (16)$$

where $\boldsymbol{v}_{c\alpha}^*$ and $\boldsymbol{v}_{c\beta}^*$ are the real and imaginary parts of the output-voltage reference vector v_c^*, while $\boldsymbol{v}_{c\alpha}$ and $\boldsymbol{v}_{c\beta}$ are the real and imaginary parts of the predicted output-voltage vector $\mathrm{v}_c(k+1)$.

This cost function has been chosen in order to obtain the lowest voltage error. However, additional constraints can be considered in this function, such as current limitation, switching frequency reduction, and spectrum shaping.

This control strategy can be summarized in the following steps.

- Define a cost function g.
- Build a model of the converter and its possible switching states.
- Build a model of the load for prediction.

IV. SIMULATION RESULTS

Simulation of the system shown in Fig. 1 were carried out for resistive and nonlinear loads, using Matlab/Simulink tools, to verify the proposed control strategy for a three-phase inverter. The parameters of the system are shown in Table II.

The behavior of the proposed predictive controller in steady-state operation for a resistive load of 3-Ω is shown in Fig. 5. Also, the steady-state operation for a resistive load of 20-Ω is shown in Fig. 6. The amplitude of the reference voltage is set to 200 V, and the frequency is 50 Hz. It is shown in the figures that the output voltages are sinusoidal with low distortion. Also, due to the resistive load, the load current is proportional to the output voltage.

The effect of changing the value of resistive load, e.g. $R = 3\Omega, R = 6\Omega,$ and $R = 10\Omega$, with different values of output

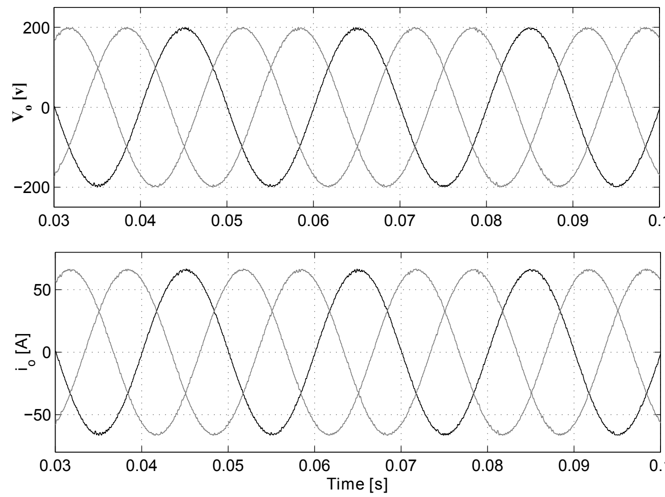


Fig. 5. Simulation results: output voltages and currents in steady state for a reference amplitude of 200 V with 3-Ω load. Voltage THD: 0.71%

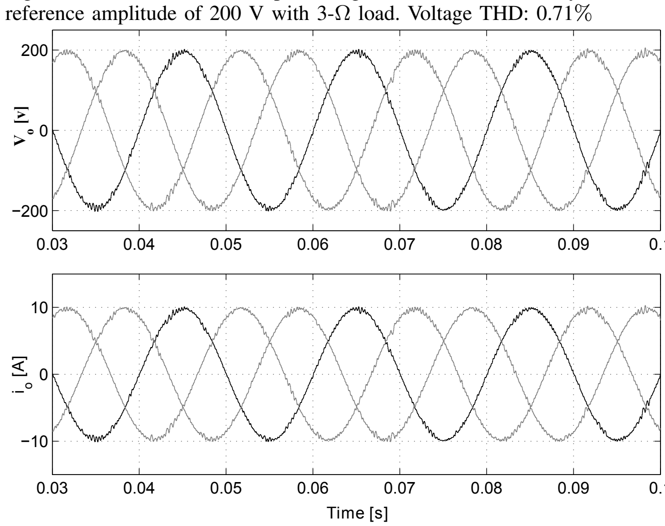


Fig. 6. Simulation results: output voltages and currents in steady state for a reference amplitude of 200 V with 20-Ω load. Voltage THD: 1.71%

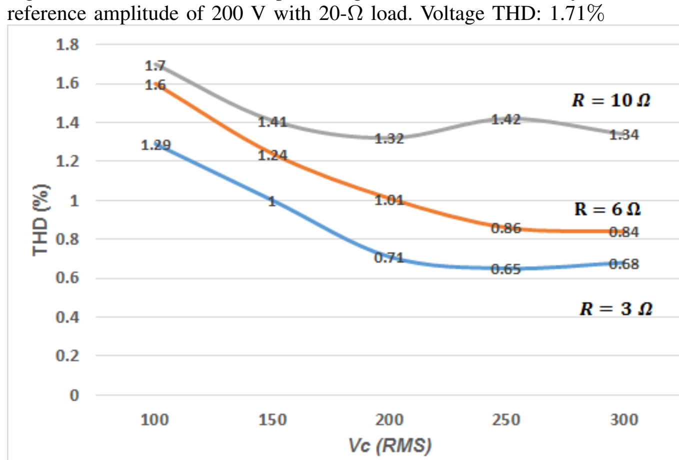
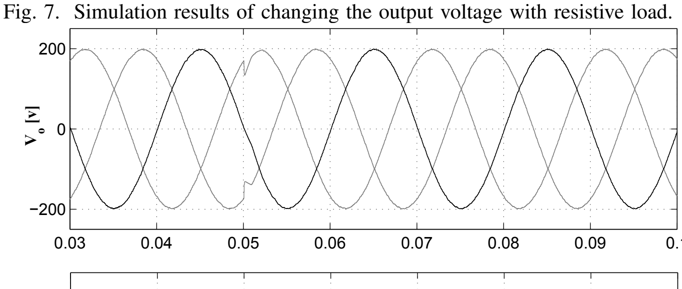


Fig. 7. Simulation results of changing the output voltage with resistive load.



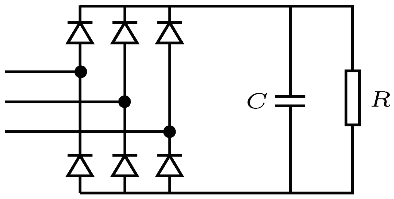


Fig. 9. Diode-bridge rectifier used as nonlinear load.

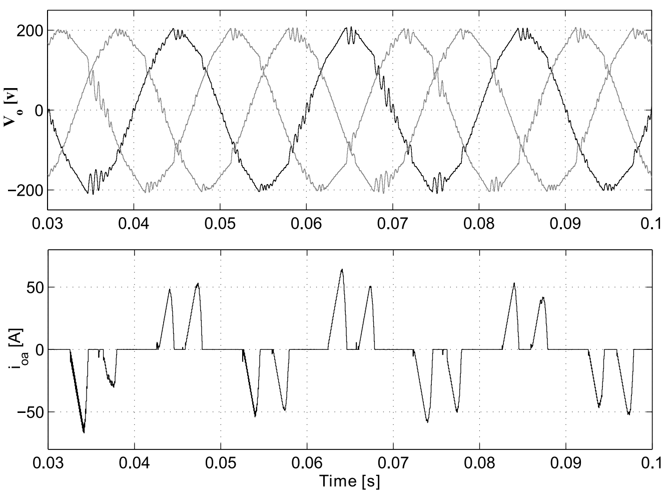


Fig. 10. Simulation results: output voltages and currents in steady state for a nonlinear load and a reference amplitude of 200 V. Voltage THD: 4.70%

voltage is shown in Fig. 7. It is shown in the figure that the output voltage is inversely proportional to THD. It means that, the increase of output voltage value, between 200 and 300 V, and the decrease of resistive load, $R = 3\Omega$, leads to improve the performance of the proposed predictive controller.

The transient behavior of the system for a load step from no load to full load is shown in Fig. 8. Assume that a 3-Ω load is connected at time of 0.05 s. It can be seen in this result that the output voltage of phase "A" is not affected by this change in the load. But, the output voltage of two other phases is affected by this change in the load for about 0.7 msec. Note that the controller quickly compensates the voltage drop caused by the transient with low distortion.

The diode-bridge rectifier, with values $R = 20\Omega$ and $C = 3000\mu F$, shown in Fig. 9 was used as nonlinear load. The behavior of the proposed predictive controller in steady-state operation for a nonlinear load is shown in Fig. 10. Here, the output voltage presents a small distortion, but it is still sinusoidal despite the highly distorted load currents. A noticeable unbalance in the load currents is present in this result due to unbalanced voltages when a nonlinear load is connected. This result could be improved by using a higher sampling frequency, $T_s = 10\ \mu s$, as shown in Fig. 11. But in the hardware implementation, this solution may be difficult to implement due to hardware restrictions. It is possible to improve the system performance, without changing the value of sampling frequency, by increasing the filter capacitance

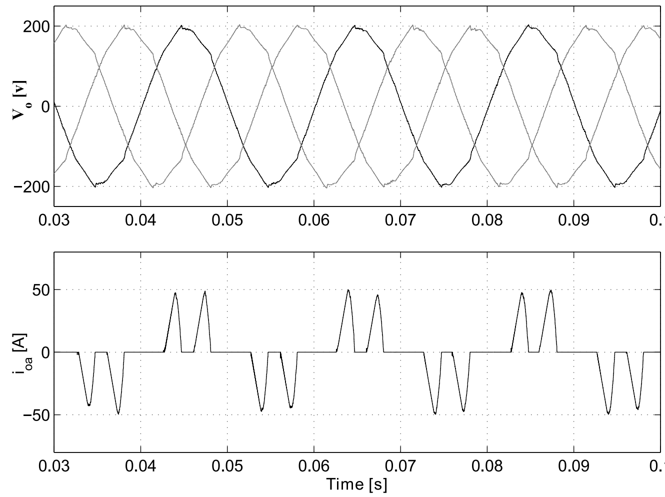


Fig. 11. Simulation results: output voltages and currents in steady state for a nonlinear load, a reference amplitude of 200 V and a sampling time of $T_s = 10\ \mu s$. Voltage THD: 2.18%

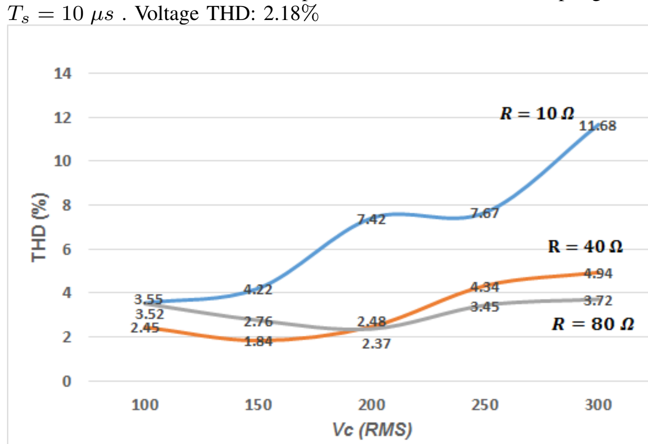


Fig. 12. Simulation results of changing the output voltage with resistance of a nonlinear load.

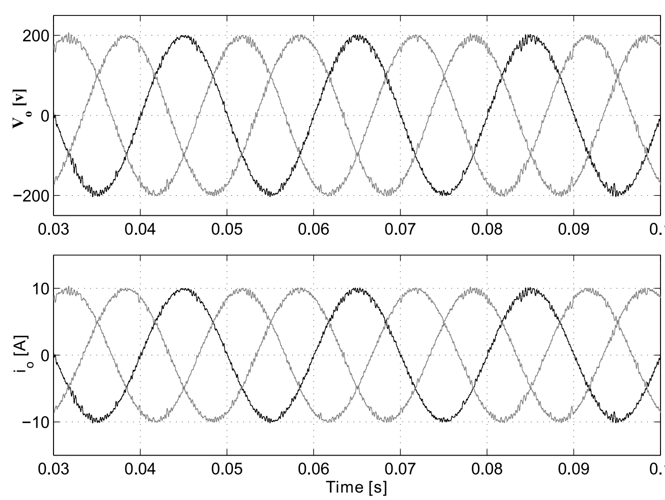


Fig. 13. Simulation results: output voltages and currents in steady state for a reference amplitude of 200 V with 20-Ω load when an error in the capacitor value of the model is -50% of the real value. Voltage THD: 2.60%

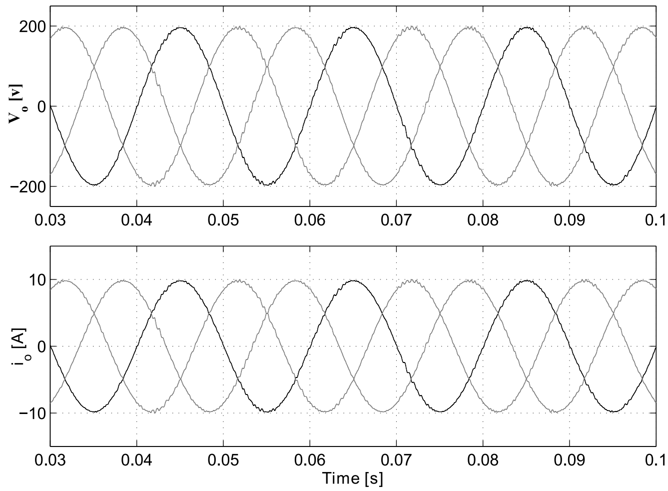


Fig. 14. Simulation results: output voltages and currents in steady state for a reference amplitude of 200 V with 20-Ω load when an error in the capacitor value of the model is +150% of the real value. Voltage THD: 1.01%

value. The effect of changing the value of resistance, e.g. $R = 10\Omega, R = 40\Omega,$ and $R = 80\Omega$, of a nonlinear load with different values of output voltage is shown in Fig. 12. It is shown that, the THD increases with increasing the output voltage and decreasing the resistance of a nonlinear load. It means that, the increase of output voltage value, between 150 and 200V, and the increase of resistance leads to improve the performance of the controller. The best performance of controller occurs at $\mathbf{v}_c = 150$V and $R = 40\Omega$ because the THD equal to 1.84%.

Considering that the performance of the predictive controller highly depends on the parameters of the model used for prediction, some tests considering errors in the parameter values are presented. An error in the capacitor value, -50% and +150% of the real value, was introduced in the predictive model. When the converter is connected to a resistive load, the error in the model have little effect, as shown in Fig. 13 and Fig. 14. However, when connected to a nonlinear load, distortion in the output voltage is noticeable but the performance of controller still good, as shown in Fig. 15 and Fig. 16.

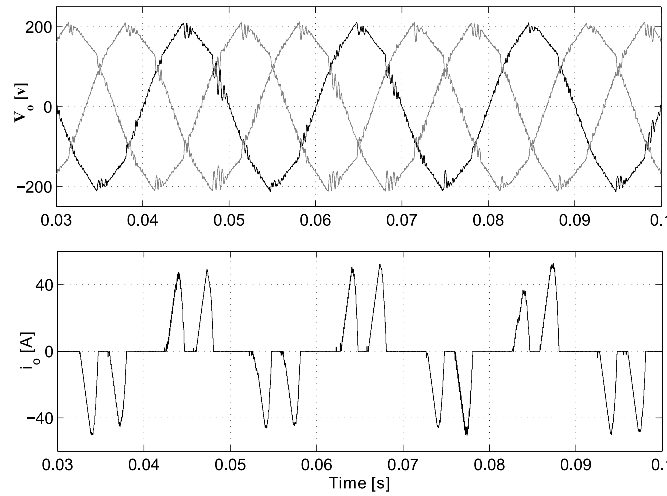


Fig. 15. Simulation results: output voltages and currents in steady state for a nonlinear load and a reference amplitude of 200 V when an error in the capacitor value of the model is -50% of the real value. Voltage THD: 4.44%

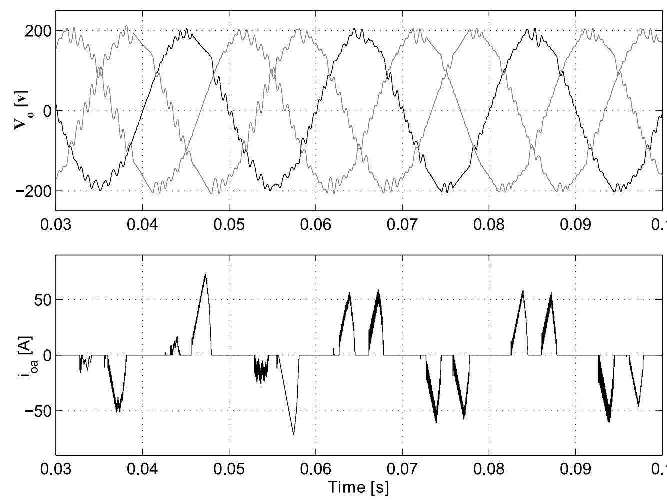


Fig. 16. Simulation results: output voltages and currents in steady state for a nonlinear load and a reference amplitude of 200 V when an error in the capacitor value of the model is +150% of the real value. Voltage THD: 4.98%

V. CONCLUSION

In this paper, a new and simple control scheme was presented for a three-phase inverter with output LC filter. Results show that the proposed scheme achieves a good voltage regulation with linear loads as well as with nonlinear loads.

The proposed controller has no parameters to adjust; it needs a model of the system for calculating predictions of the controlled variables. The gate-drive signals are generated directly by the controller, so a modulator is not needed.

The output voltage is directly controlled, without using a cascaded control structure, with an inner current-control loop. This allows for a fast dynamic response of the voltage control.

The effect of error in system parameters values has been studied by means of simulation, achieving a good voltage regulation, with linear loads and nonlinear loads, even with errors of -50% and +150% in the capacitor value.

Predictive control presents a different approach for the control of power converters taking into account the discrete nature of the converters and the microprocessors used for the control. This method is applicable for systems with different frequencies and can be applied without major changes to any type of converter and variables to be controlled.

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