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An Improved Model Predictive Control of an Inverter with LC Filter

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***Abstract*—In this paper, a new control method based on model predictive controller (MPC) is proposed to control a three phase inverter with LC filter. The proposed method is very similar to conventional MPC in algorithm and simulation and only adds one calculation step for selection of the optimum voltage vector which minimizes the cost function. Simulation results show the superiority of this method for linear and nonlinear load in comparison with the conventional one.**

Keywords—model predictive control; voltage source inverter; total harmonic distortion; active vector.

I. INTRODUCTION

As inverters are one of the most extensively used devices in power electronic converters family, their control is a classic subject in this field. The control of inverters with an output LC filter has a special importance in applications where a high quality voltage is needed. In the inverter-based systems, it is desired to achieve a good output-voltage regulation with any kind of load, being very important that the functionality of the system does not deteriorate under nonlinear loads, such as diode rectifiers.

Variety of control methods have been proposed such as PI controller with pulse width modulator, hysteresis control, deadbeat control etc. Most of these control schemes need a modulator to apply the gate signals for switches and they include inner and outer control loops. The switching frequency is also kept constant due to a modulator block [1].

In recently years, one popular topic is predictive control [2] [3] that takes the advantage of the inherent features of the inverter, since there are only eight possible switching states by turning on and off the gates for each switch. Among those, two switching states are called zero vector and the other six states are called active vectors.

The MPC techniques applied to power electronics have been classified into two main categories [4]: Continuous Control Set MPC and Finite Control Set MPC (FCS-MPC). In the first group, a modulator generates the switching states starting from the continuous output of the predictive controller. On the other hand, the FCS-MPC approach takes advantage of the limited number of switching states of the power converter for solving the optimization problem.

The idea of choosing the optimal switching state based on the prediction and minimization was introduced in [5] with a general R-L type load considered. A more general treatment of this approach is to evaluate the prediction of all possible switching states against a pre-defined cost function that may consist of the difference between the prediction and reference vector, the number of switches per cycle, power losses, constraints and etc. As a result, the switching state that minimizes the cost function is selected as the best voltage vector to apply to the inverter. This minimization approach with the aid of cost function is termed as FCS-MPC in some literatures [4].

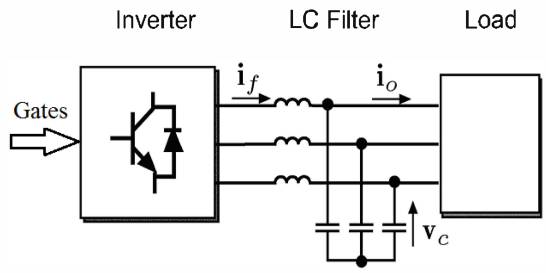

Fig. 1. Inverter with LC filter.

A discrete model is used to predict the behavior of the system for every period. The switching action that minimizes a predefined cost function is finally selected to be applied in the next sampling instant. The main advantage of FCS-MPC lies in the direct application of the control action to the converter, without requiring a modulation stage. This control method is studied for unbalanced load, nonlinear load [6] and UPS applications [7].

In [8], an interpolated switching state is explained. So, there are total twelve active vectors available for the evaluation of the cost function. The interpolated six virtual vectors are achieved by the modulation of the nearest two physical switching vectors. Similar to the conventional FCS-MPC, the optimal switching state is selected by minimiz-ing the distance between one-step predictions with the desired reference. Also A Simplified FCS-MPC to reduce the number of cost function calculations is described in [9]. In [10] is discussed a new method to solve the optimization problem in implicit MPC that has a computational complexity less than that of explicit MPC.

The proposed approach in this paper is adding an extra one active vector to improve the control of inverter. This new one is a half amplitude vector of one of the six main active vectors. The implementation of the proposed algorithm is based on the minimizing the cost function between eight main vectors and one half vector. Similar to the conventional FCS-MPC, the optimal switching state is selected by minimizing the distance between one-step predictions with the desired reference. As well as, a comparison between the proposed method and conventional MPC is presented with linear and nonlinear load.

II. INVERTER AND SYSTEM MODEL

The 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.

A. Inverter Model

The main components of an inverter are the six switches which locate at the upper and lower legs of the inverter, respectively. For each leg of the inverter, only one switch will be turned on at any time to prevent the short circuit occurring. Thus, there are total eight combinations produced by turning on and off the six switches and they could be represented by the state of their upper switch. The switching states of the converter are determined by the gating signals.

The output voltage space vectors generated by the inverter are defined by switches state. So, it can be written as

$$v_i = \frac{2}{3}\left(v_{aN} + a v_{bN} + a^2 v_{cN}\right) \tag{1}$$

where $a = e^{j(2\pi/3)}$ and v_{aN}, v_{bN}, and v_{cN} are the phase voltages of the inverter, with respect to the negative terminal of the dc-link N. Then, the load voltage vector v_i can be related to the switching state vector and the dc-link voltage (V_{dc}).

Considering all the possible combinations of the gating signals, eight switching states and, consequently, Fig. 2 shows possible voltage vectors generated by the inverter. Note that $v_0 = v_7$, resulting in only seven different voltage vectors.

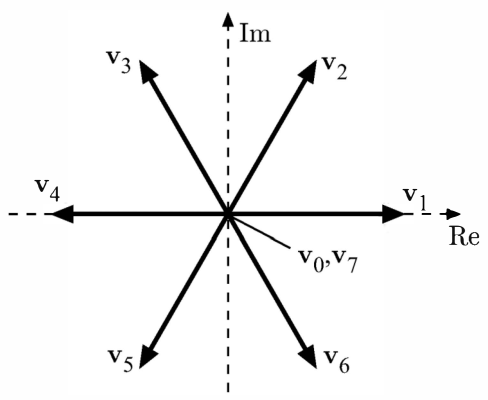

Fig. 2. Eight possible voltage vectors generated by the inverter.

B. LC Filter Model

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. The v_i is the inverter output voltage.

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 dynamic behavior of the output voltage can be expressed by the following equations.

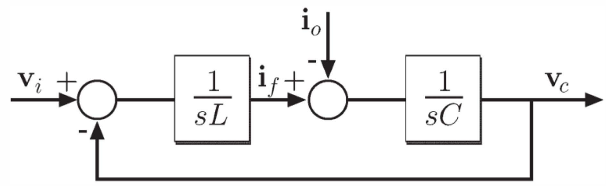

Fig. 3. LC filter model.

The equation of the filter inductance expressed in vectorial form is:

$$L\frac{di_f}{dt} = v_i - v_c \tag{2}$$

where L is the filter inductance.

The equation of the filter capacitance expressed in vectorial form is:

$$C\frac{dv_c}{dt} = i_f - i_o \tag{3}$$

where C is the filter capacitance.

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

$$\frac{dx}{dt} = Ax + Bv_i + B_d i_o \tag{4}$$

where

$$x = \begin{bmatrix} i_f \\ v_c \end{bmatrix}, \quad A = \begin{bmatrix} 0 & -1/L \\ 1/C & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}, \quad B_d = \begin{bmatrix} 0 \\ -1/C \end{bmatrix} \tag{5}$$

Variables i_f, v_c and i_o are measured, while v_i can be calculated using (1). 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.

These equations are used as the predictive model in the proposed predictive controller. The output voltage is obtained from

$$v_c = \begin{bmatrix} 0 & 1 \end{bmatrix} x \tag{6}$$

To implementation these equations, it is necessary to modify a discrete model. A discrete-time model of the filter is obtained from (4) for a sampling time T_s and is expressed as

$$x(k+1) = A_q x(k) + B_q v_i(k) + B_{dq} i_o(k) \tag{7}$$

where

$$\begin{aligned} A_q &= e^{AT_s} \\ B_q &= \int_0^{T_s} e^{A\tau} B \, d\tau \\ B_{dq} &= \int_0^{T_s} e^{A\tau} B_d \, d\tau \end{aligned} \tag{8}$$

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

III. THE PROPOSED MODEL PREDICTIVE CONTROLLER

A. Conventional Method

The conventional FCS-MPC adopts only six active switching vectors and thus it inevitably leads to poor approximation of the optimal input. This is mainly due to the absence of modulation in FCS-MPC.

MPC presents several advantages that make it suitable to control this kind of system: concepts are easy to understand, constraints and nonlinearities of the system can be easily included, and the desired behavior of the system is formulated as a cost function to be minimized. This study 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.

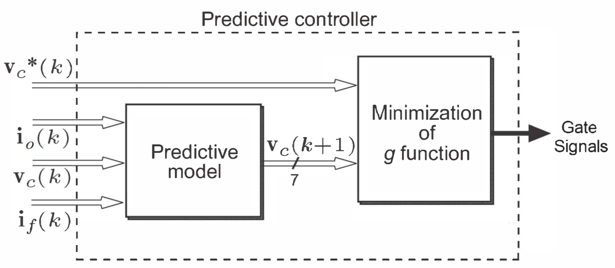

Fig. 4. Block diagram of the model predictive controller.

The block diagram of the model predictive control for a three phase inverter with output LC filter is shown in Fig. 4. Here, measurements of the output current $i_o(k)$, the output voltage $v_c(k)$ and the filter current $i_f(k)$ are used to predict, using (7), the value of the output voltage at the next sampling instant $v_c(k+1)$ for all the possible voltage vectors that the inverter generates.

To choose the optimal voltage vector v_i to be applied by the inverter, the seven predictions obtained for $v_c(k+1)$ are compared using a cost function g . The voltage vector v_i that minimizes this function is then chosen and applied at the next sampling instant.

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.

$$g = \left(v_{c\alpha}^* - v_{c\alpha}\right)^2 + \left(v_{c\beta}^* - v_{c\beta}\right)^2 \tag{9}$$

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

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.

B. Proposed Method

We propose a new method to improve the tracking the reference by adding only one vector and one step calculation. When the reference voltage is smaller than the DC link voltage, note that applying the active vectors may not suitable, because use of any active vector within T_s period keep out the output voltage from reference. We propose to add a half vector to the six main vector. Therefore, if a vector with half amplitude is applied to the inverter, tracking the reference voltage will be more accurate. Fig. 5. shows the main vector and half vectors.

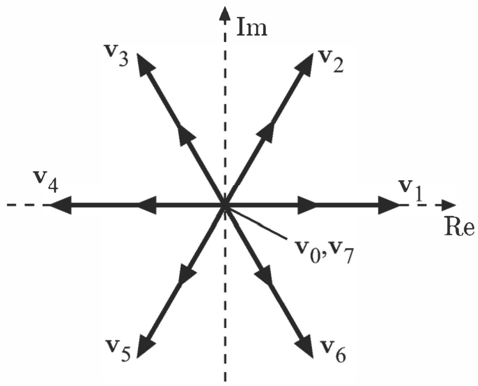

Fig. 5. Main vectors vs half vectros.

Suitable active vector is determined according to the cost function like previous. The main vector and the half vector are checked by the cost function again and the best is chosen. Thus, by adding only one step for calculation, the better voltage vector can be selected. If the half vector was the best, it is needed to apply two vectors in one sample time. To achieve a vector with half amplitude, we use $T_s/2$ for active vector and $T_s/2$ for zero vector.

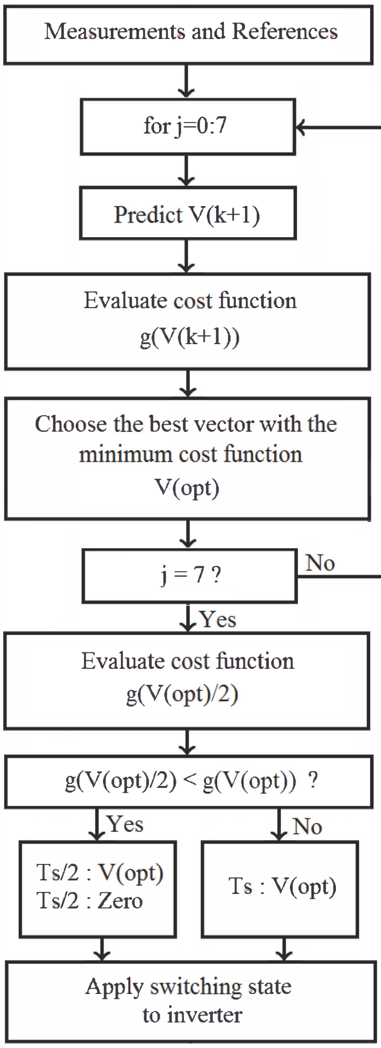

Fig. 6. Algorithm of proposed MPC with half vectors.

C. Performance of Proposed Method

In conventional control method, decreasing the sampling time could affect the output voltage quality and voltage THD. Also in MPC, adding some vector to the main vectors, could improve the output voltage. But in the proposed control method this decrement in THD is possible by adding only one vector with half magnitude and one step for calculation.

The method is useful when the reference waveform is smaller than the source voltage dc inverter. Although for all amount of amplitude, this half vector may be selected for best vector.

D. Algorithm

For implementation the proposed method, consider six active vectors with zero vector and calculate the cost function.

In the first, six main vectors are evaluated by the cost function and the best vector of these is specified. Then the half amplitude vector of this is checked by the cost function again and the cost of the half vector is compared with the main vector. Finally, the main or the half vector is chosen to apply to the inverter. The block diagram of the proposed method is shown in Fig. 6.

IV. SIMULATION RESULTS

The PSIM software has been used to simulate and analyze the converter and proposed method. Different scenarios are considered to show the feasibility of new method to control the inverter feeding several loads. The entire parameters are shown in Table I.

TABLE I. PARAMETERS

Parameter	Value
DC link voltage	100 V
Output frequency	50 Hz
Filter Capacitor C	40 µF
Filter inductance L	2.4 mH
Sample time Ts	50 µs

In the next parts, it is applied a reference signal to simulate the system. The amplitude of output voltage is set to 30 V. The sample time is assumed to 50µs. This T_s guarantees the digital processor to calculate the equations and cost function in each period. The simulations are verified the performance of conventional and proposed MPC. The total harmonic distortion of output voltage is calculated for both methods. In these simulations, the output voltage THD is compared each other to qualify the proposed method.

A. Linear Load

In the most employment of inverter, it is needed that output voltage to trace the reference signal. In this part of simulation, consider a sinusoidal waveform and control the inverter with both conventional and proposed method of MPC. The reference signal is a three phase sinusoidal voltage with amplitude of 30V. The Resistance of the linear load is 40 ohms that connected to the inverter through an LC filter. The output voltages and currents and the filter current of conventional MPC are shown in Fig. 8. Total harmonic distortion of this waveform is 3.57%. The proposed method of MPC are shown in Fig. 9 with THD=2.57%. The comparison between two figures shows that by proposed MPC the THD is improved.

B. Nonlinear Load

Several non-linear loads such as power supplies, electronic ballasts, and etc. are used in many domestic and office applications. These loads impose high current harmonic distortions which can affect load voltages. According to international standards such as IEC62040-3 for UPSs, the most sever condition for the nonlinear load is a full bridge diode rectifier followed by a capacitive filter which is depicted in Fig. 7. It is mentioned in this standard the THD value of the load must not exceed 8%.

A three phase diode bridge with a resistor R = 10 Ω and a capacitor C = 470 μF is chosen as a nonlinear load. The result of this simulation shows high value of THD. This result could be improved by using a higher sampling frequency, but this solution is difficult to implement due to hardware restrictions. Alternative solution to improve the quality of the control for nonlinear loads is the proposed MPC.

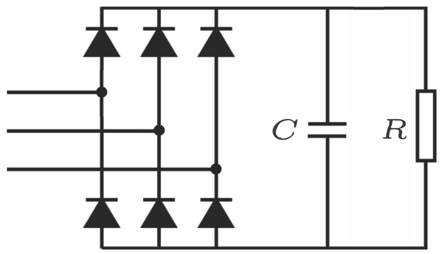

Fig. 7. Diode-bridge rectifier used as nonlinear load.

The simulation results of conventional MPC and the proposed method are shown in Fig. 10. and Fig. 11. respectively. The THD of the first conditions is 5.37%. But the last, has the THD about 4.63%. The proposed MPC is more effective when the modulation index is low.

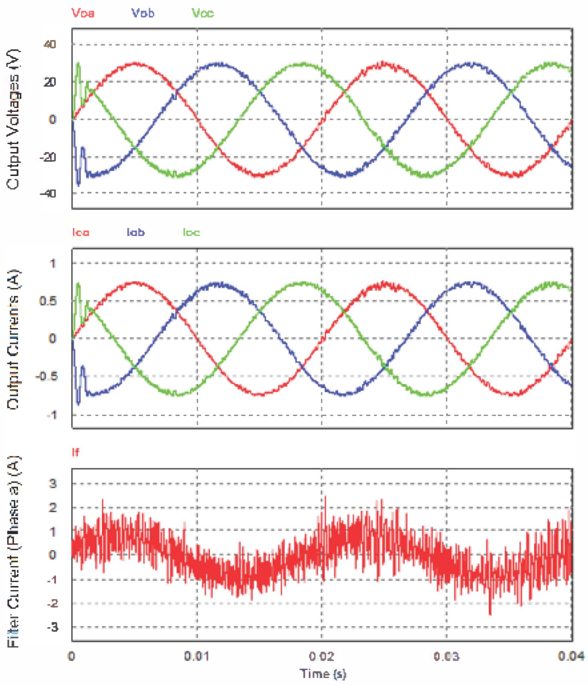

Fig. 8. Conventional MPC, THD = 3.57%.

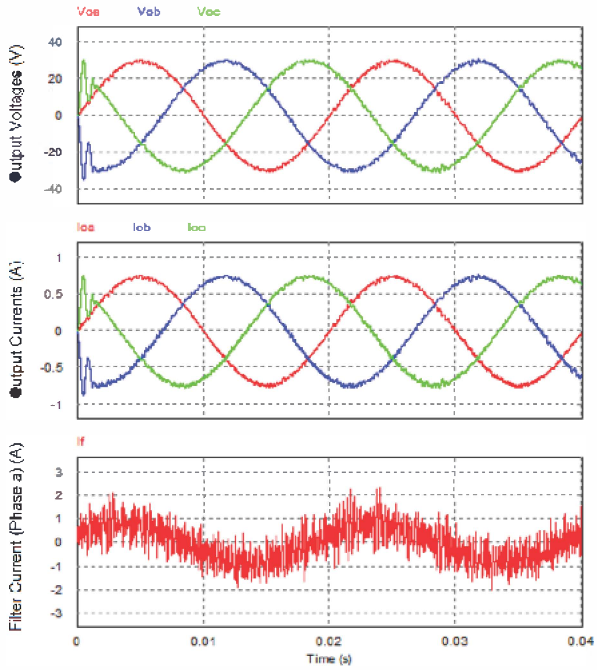

Fig. 9. Proposed MPC, THD = 2.57%.

All simulation results illustrate the qualification of the proposed control method that voltage THD factor is better than conventional MPC in all cases. It is noticeable that the THD of the both conventional and proposed MPC can meet the standard. But the proposed technique has smaller THD and improved output waveform.

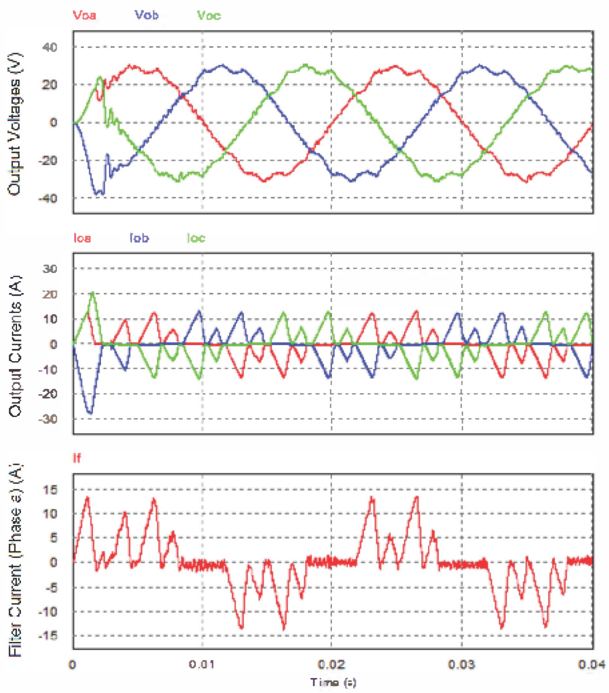

Fig. 10. Conventional MPC under nonlinear load, THD = 5.37%.

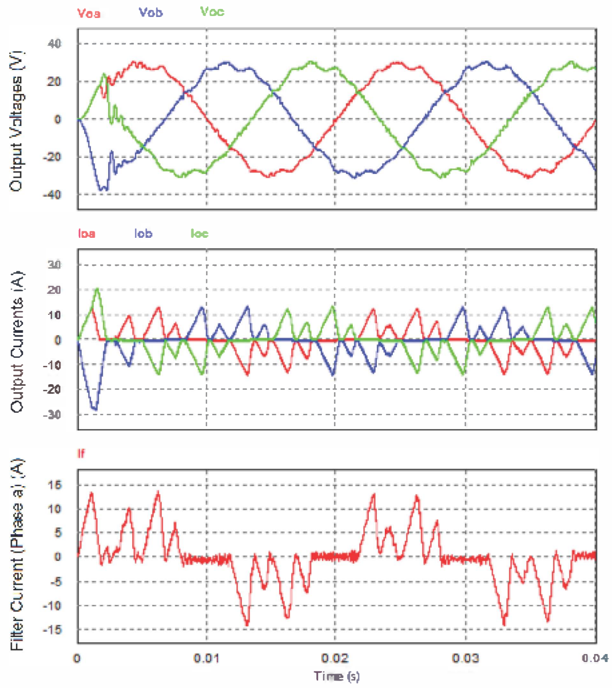

Fig. 11. Proposed MPC under nonlinear load, THD = 4.63%.

V. CONCLUSION

In this paper, a new control method based on model predictive controller is proposed to control a three phase inverter with LC filter. The proposed controller is very similar to conventional MPC in algorithm and simulation. Firstly, in this method the conventional MPC is exerted and the best vector that has the minimum cost is selected. Then calculates the cost of half amplitude of selected vector and compares with the main vector. The vector with minimum cost between them applies to the inverter. This method needs no more calculation for digital signal processor to implementation, because only one step of calculation is added. The simulation results illustrate the proposed method improves the output waveform and reduces the output voltage THD. Also this method is suitable for linear and nonlinear loads.

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