

# Modeling and Simulation of Three-Phase Voltage Source Inverter Using a Model Predictive Current Control

Ali M. Almaktoof, A. K. Raji, and M. T. E. Kahn

**Abstract**—This paper focuses on a combination of three-phase Voltage Source Inverter (VSI) with a predictive current control to provide an optimized system for three-phase inverter that controls the load current. The present contribution presents a Finite Set-Model Predictive Control (FS-MPC) strategy for a two-level three-phase VSI with resistive- inductive load (RL-Load). In order to reduce the computational effort which gives rise to multiple possibilities has been determined. With different cases the evaluation of the system is done. Firstly, the system performance with long prediction horizon is carried out. Secondly, the dynamic response of the system with step change in the amplitude of the reference is investigated. Simulations are carried out using MATLAB/Simulink to test the effectiveness of an FS-MPC for the two-level VSI with RL-Load.

**Index Terms**—Finite Set-Model predictive control, voltage source inverter, RL-Load, prediction horizon.

## I. INTRODUCTION

Voltage source converters have been extensively studied in the last decades in most industrial sectors for many applications. By considering the increasing energy demands and power quality and efficiency; a control and power conversion using power electronics have become an important topic today.

Predictive control for power electronics has been presented since 1980's [1]. Several advantages make the predictive control suitable for the control of power converters, for instance; easy to understand and implement and can be applied to different kinds of voltage source converters. It requires a high amount of calculations, compared to classic control methods, but the fast microprocessors available today have made it possible to implement predictive control for VSI converters, and model predictive control (MPC) have distinct advantages when compared to the traditional PWM methods [2], [3].

MPC for power converters and drives is to take advantage of the inherent discrete nature of power converters. Since power converters have a finite number of switching states, the MPC optimization problem can be simplified and reduced to the prediction of the system behavior only for those possible switching states. Then, each prediction is used to evaluate a cost function (also known as quality or decision function), and consequently the switching state with minimum cost is selected, generated and applied in the next switching instant. This

control method is known as a finite state model predictive control (FS-MPC) since the possible control actions (switching states) are finite and this control strategy is used in this paper. It has been successfully applied to a wide range of power converter and drive applications [2], in a three-phase inverter [4]–[7] and a matrix converter [8] and flux and torque control of an induction machine [9]. An example of different controlled variables using a single cost function is presented in [10], where the current is controlled while, at the same time, minimizing the switching frequency and balancing the dc-link voltages in an inverter. In all these works the switching states are changed at equidistant time instants.

In this paper a combination of three-phase VSI with a predictive current control to provide an optimized system for three-phase inverter that controls the load current. The powerful and robustness of the proposed control method are evaluated through simulations results.

Section two presents the power converter model that is used in this paper. Firstly the time-continuous model is presented and then discretized. The control scheme is developed in section three that is used to control the power converter model in section two. Matlab/Simulink modeling and simulation work is presented in the penultimate section. Conclusion is presented in the last section of the paper.

## II. POWER CONVERTER MODEL

### A. Voltage Source Inverter Layout

A two-level VSI three-phase power converter is the least complicated multiple levels VSI because it presents only two voltage levels. It has been selected for a clear analysis of a predictive control strategy with RL-Load. The topology of the inverter considered in this paper is depicted in Fig.1. The circuit is operated by switching  $S_1$ ,  $S_2$ ,  $S_3$ ,  $S_4$ ,  $S_5$  and  $S_6$ . The inverter uses two pairs of complementary controlled switches in each inverter phase or leg, ( $S_1$ ,  $S_2$ ), ( $S_3$ ,  $S_4$ ) and ( $S_5$ ,  $S_6$ ) as shown in Fig. 1. Considering that the two switches in each inverter phase or leg operate in a complementary pair in order to avoid short circuiting the DC source.

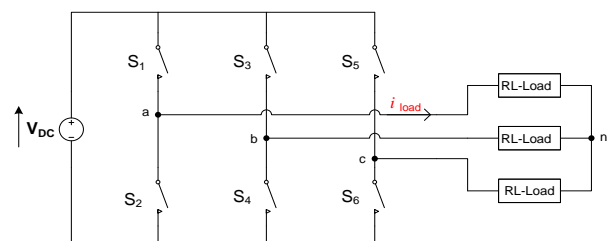


Fig. 1. Two-level voltage source inverter circuit topology.

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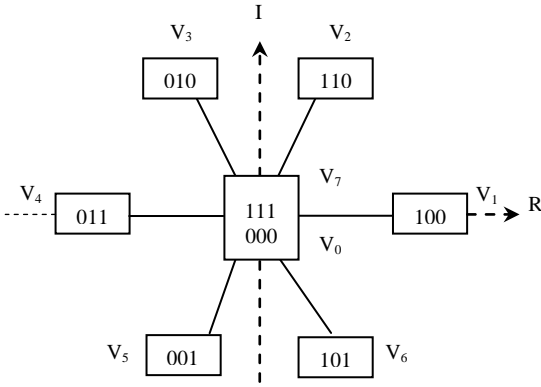
The state of the switches is determined according to:

$$\text{Phase/leg } a = \begin{cases} 1 & \text{if } S_1 \text{ ON and } S_2 \text{ OFF} \\ 0 & \text{if } S_1 \text{ OFF and } S_2 \text{ ON} \end{cases}$$

$$\text{Phase/leg } b = \begin{cases} 1 & \text{if } S_3 \text{ ON and } S_4 \text{ OFF} \\ 0 & \text{if } S_3 \text{ OFF and } S_4 \text{ ON} \end{cases}$$

$$\text{Phase/leg } c = \begin{cases} 1 & \text{if } S_5 \text{ ON and } S_6 \text{ OFF} \\ 0 & \text{if } S_5 \text{ OFF and } S_6 \text{ ON} \end{cases}$$

This leads to eight different switching possibilities and consequently, eight voltage vectors are obtained that is voltages  $V_{DC}$  and  $-V_{DC}$  can be switched. As shown in Fig. 2 the voltage vectors which are generated by the inverter resulted in only seven different voltage vectors because  $V_0$  and  $V_7$  produce the same zero voltage vector ( $V_0 = V_7$ ), that means a three-phase two-level voltage source converter can deliver only 7 different voltage vectors, although there are 8 different switching combinations, as it can be seen in Fig. 2. The switching states that define the value of the output voltages are determined according to:



$$\begin{aligned} v_{aN} &= S_a V_{DC} \\ v_{bN} &= S_b V_{DC} \\ v_{cN} &= S_c V_{DC} \end{aligned}$$

Fig. 2. Voltage vectors generated by 2-level VSI.

### B. Load Model

The differential equation of the load current is applied to obtain the continuous-time state-space equations of the load for each phase:

$$V_{DC}(t) = R \cdot i(t) + L \frac{di}{dt} \quad (1)$$

Using the Clarke transformation, the equations can be expressed in the stationary  $\alpha\beta$  frame.

Clarke transformation is defined as following,

$$V_\alpha = 2/3 (V_a - 0.5 V_b - 0.5 V_c) \quad (2)$$

$$V_\beta = 2/3 (0.5 \sqrt{3} V_b - 0.5 \sqrt{3} V_c) \quad (3)$$

Applying Clarke transformation on the load current, the equations can be expressed in the stationary  $\alpha\beta$  frame as in (4). Then, the continuous-time state-space equation of the load results to:

$$\begin{pmatrix} \dot{i}_\alpha \\ \dot{i}_\beta \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} + \begin{pmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{pmatrix} \begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} \quad (4)$$

A discrete-time equation for the future load current is obtained by using Euler-forward equation as in (5) in order to obtain a discrete-time system representation. The derivation of the state variables is approximated as follows:

$$\dot{x} \approx \frac{x(k+1) - x(k)}{T_s} \quad (5)$$

$T_s$  is the sampling time and  $k$  is the current sampling instant. The state variable is denoted with  $x$ . Then, the discrete-time load model can be to:

$$\begin{pmatrix} i_\alpha(k+1) \\ i_\beta(k+1) \end{pmatrix} = \begin{pmatrix} 1 - T_s \frac{R}{L} & 0 \\ 0 & 1 - T_s \frac{R}{L} \end{pmatrix} \begin{pmatrix} i_\alpha(k) \\ i_\beta(k) \end{pmatrix} + \begin{pmatrix} \frac{T_s}{L} & 0 \\ 0 & \frac{T_s}{L} \end{pmatrix} \begin{pmatrix} v_\alpha(k) \\ v_\beta(k) \end{pmatrix} \quad (6)$$

Equation (6) is used to predict the load current for each switching possibility. The cost function  $g$  is evaluated for each of the seven possible voltage vectors generated by this inverter to calculate the future value of the load current. The voltage vector that minimizes the cost function is selected and applied during the next sampling instant.

## III. CONTROL STRATEGY

### A. Finite Set-Model Predictive Control

An FS-MPC does not need use a modulator. FS-MPC has been used as a current controller [11], [12] for two- [2]-[4], three- [13] and four- [14], [15], level inverters. Fig. 3 shows VSI converter under FS-MPCC, where:  $i_{ref}$  represents the reference current for the predictive current control,  $i(k)$  is the  $m$  measurements taken at time  $k$  and  $i_{(k+1)}$  are the predicted values of the  $m$  states for  $n$  possible switching states at time  $k+1$ . The error between the reference and predicted values is obtained to minimize the cost function and the switching state that minimizes the cost function is chosen. The chosen state's switching signals,  $S$ , are then applied to the converter.

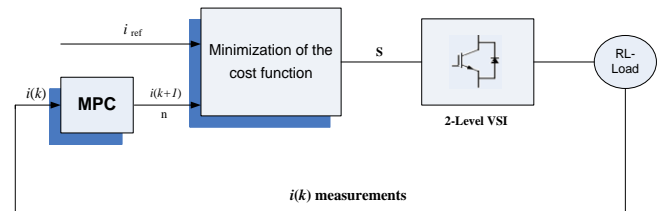


Fig. 3. FS-MPC block diagram.

In order to reduce the computational effort which gives rise to multiple possibilities (8 different switching possibilities for one prediction step) the best one of the 7 voltage vectors is determined; after that the best switching

state which delivers this voltage vector is determined. In order to determine the best one of the 7 voltage vectors that should be applied in the next sampling cycle  $k+1$ , the 1-norm cost function has to be minimized, for the current control of a 2-level VSI, a simple cost function can be defined in absolute value term with one prediction step and  $n$  prediction steps respectively as:

$$g = |i_{ref\alpha}(k+1) - i_{\alpha}(k+1)| + |i_{ref\beta}(k+1) - i_{\beta}(k+1)| \quad (7)$$

$$g = \sum_{n=1}^N |i_{ref\alpha}(k+n) - i_{\alpha}(k+n)| + |i_{ref\beta}(k+n) - i_{\beta}(k+n)| \quad (8)$$

In order to simplify the calculations, it can be assumed that the current reference values is constant in equation (9) with the prediction horizon for small sampling time  $T_S$  as in equation (10). This approximation is considered in this paper.

$$i_{ref}(k+n) \approx i_{ref}(k) \quad (9)$$

For more accurate approximation the reference current values  $i_{ref}(k+1)$  for  $\alpha$ - $\beta$  axis required by (7) have to be predicted from the present and previous values of the current reference using a second-order extrapolation given by

$$i_{ref}(k+1) = 3i_{ref}(k) - 3i_{ref}(k-1) + i_{ref}(k-2) \quad (10)$$

Equation (10) has been obtained from the quadratic Lagrange extrapolation formula [3], [16].

In general, the control algorithm as shown in Fig. 3 can be summarized to the following steps [17]:

- 1) Measure the load currents.
- 2) Predict the load currents for the next sampling instant for all the possible switching states.
- 3) Evaluate the cost function for each prediction.
- 4) Optimal switching state is selected which minimizes the cost function.
- 5) Apply the new switching state.

In the current control case, the cost function is minimized which obtained from the error between the reference current and predicted current for produce the switching state and applied.

### B. Prediction Step

From  $i(k+1)$  on the controller can be seen in Fig. 3 can use any possible output to bring the controlled currents that closer to their reference. In the next step  $i(k+2)$ , the prediction step, the controller thus calculates the measured currents at  $k+2$  for all possible switch states at  $k+1$ . With long prediction horizon ( $n$  steps) the output current with RL-Load can be expressed as

$$\begin{pmatrix} i_{\alpha}(k+n) \\ i_{\beta}(k+n) \end{pmatrix} = \begin{pmatrix} 1 - T_S \frac{R}{L} & 0 \\ 0 & 1 - T_S \frac{R}{L} \end{pmatrix} \begin{pmatrix} i_{\alpha}(k+n-1) \\ i_{\beta}(k+n-1) \end{pmatrix} +$$

$$\begin{pmatrix} \frac{T_S}{L} & 0 \\ 0 & \frac{T_S}{L} \end{pmatrix} \begin{pmatrix} v_{\alpha}(k+n-1) \\ v_{\beta}(k+n-1) \end{pmatrix} \quad (11)$$

When an inverter is controlled directly it gives rise to multiple possibilities. In this case the inverter leads to 8 different switching possibilities and consequently, eight voltage vectors are obtained for one prediction step, with long prediction horizon the calculation effort rises, for two prediction steps 64 possibilities, for three prediction steps 512 possibilities. With long prediction horizon the possibilities of a VSI have been evaluated for RL-Load using MATLAB/Simulink. Fig. 4 shows number of possible switching states with long prediction steps for three-phase two-level VSI.

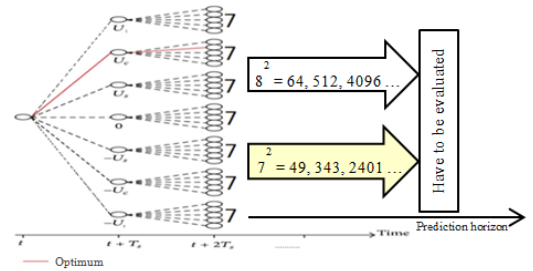


Fig. 4. Number of possible switching states with long prediction steps.

## IV. SIMULATION RESULTS

FS-MPC strategy for three-phase two-level VSI has been simulated with MATLAB/Simulink, in order to evaluate the performance of the proposed control algorithm and check the performance and robustness of the proposed predictive control method. A sinusoidal reference current was applied to the system and the amplitude of the reference current was set to 4 A and frequency of 50 Hz per phase, an RL-Load is connected to the output of the VSI as shown in Fig. 4. Table I. Shows the parameters used for the simulations.

TABLE I: PARAMETERS USED FOR THE SIMULATIONS

Parameter	Value
Load resistor, R	10 $\Omega$
Load inductor, L	10 mH
AC Filter, L	10 mH
DC link voltage, $V_{DC}$	100 V
Reference amplitude current, $i_{ref}$	4 A
Sampling time, $T_S$	25 $\mu s$ , 75 $\mu s$

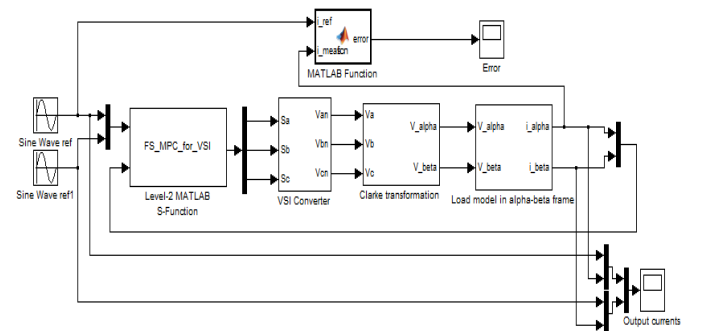


Fig. 4. Modeling an FS-MPC of VSI using MATLAB /simulink.

C. With long Prediction Horizon

The robustness of the proposed control method was tested with four prediction steps, it can be seen in Fig. 5 how the output currents are tracking their references with four prediction steps, it can be seen that the control algorithm shows excellent tracking behaviour.

The error between the reference and actual current for different values of prediction horizon has been evaluated to check the influence of the prediction horizon as shown in Fig. 6.

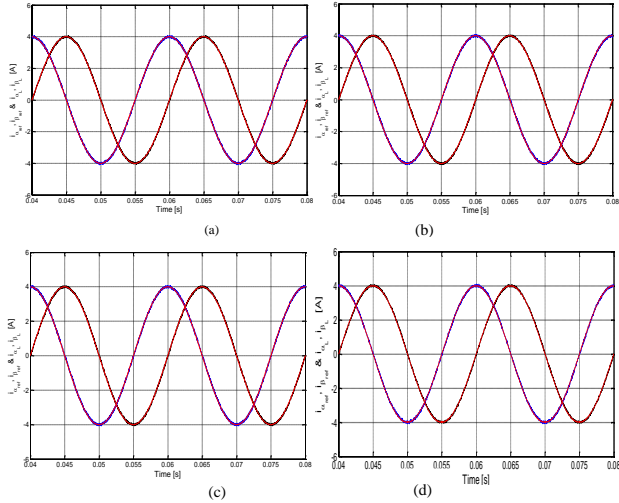


Fig. 5. Simulations results: the load current with RL-Load for different values of prediction horizon for a sampling time TS = 25 μs: a) n = 1. b) n = 2. c) n = 3. d) n = 4.

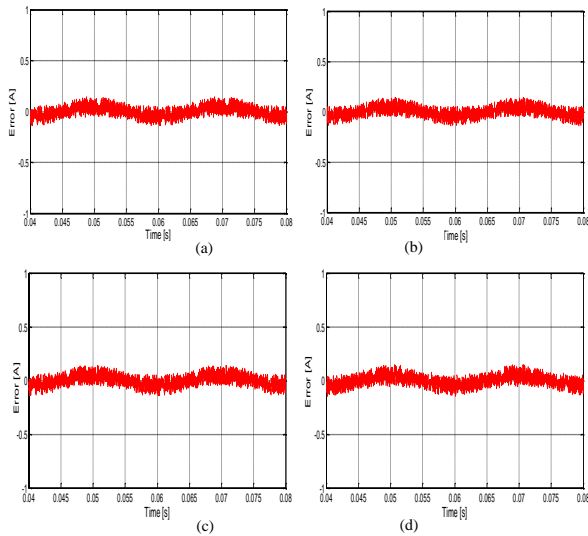


Fig. 6. Simulations results: Error between the reference and load current for different values of prediction horizon for a sampling time TS = 25 μs: a) n = 1. b) n = 2. c) n = 3. d) n = 4.

D. With Step Change

**With sinusoidal reference steps:** The second simulation shows the control result for sinusoidal reference values. The result for step changes in the amplitude of the references  $i_\alpha$  and  $i_\beta$  were changed from 4 A to 2 A and 4 A to 3 A at 0.042 s and 0.048 s respectively are shown in Fig. 7 (a), it can be observed in Fig. 7 (b) for the same test that during the step change of the currents  $i_\alpha$  and  $i_\beta$  the load voltage  $v_\alpha$  is kept at its maximum value until the reference current  $i_\alpha$  is achieved. This simulation clearly demonstrates the ability of

the proposed control algorithm to track sinusoidal reference currents. It can be observed from this simulation that the predictive control method has fast dynamic response with inherent decoupling between  $i_\alpha$  and  $i_\beta$ . It is again, the algorithm shows excellent tracking behavior.

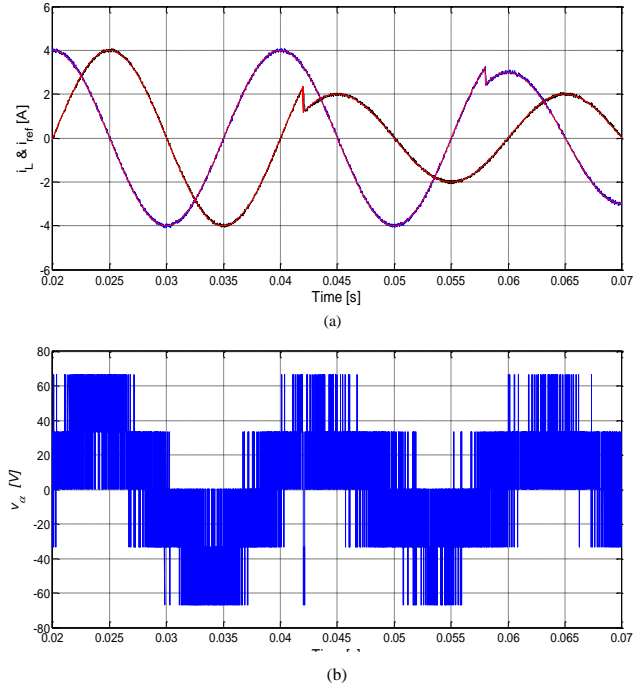


Fig. 7. Simulations results: Sinusoidal reference steps: (a) Load current with two step changes. (b) Load voltage  $v_\alpha$  changes during the reference steps.

**With constant reference steps:** in this simulation the control algorithm was tested with constant reference steps.

The simulation shows the control result for constant reference steps values, when a step change in the amplitude of the reference  $i_\alpha$  and  $i_\beta$  were changed from 0 A to 4 A and 0 A to -3 A respectively at 0.02 s as shown in Fig. 8. It can be seen in Fig. 8 how the load currents reach to their reference with fast dynamic response.

This simulation clearly demonstrates that the proposed control algorithm is able to track the currents to their reference values. The remaining current ripple in steady state results from the finite switching and controller frequency.

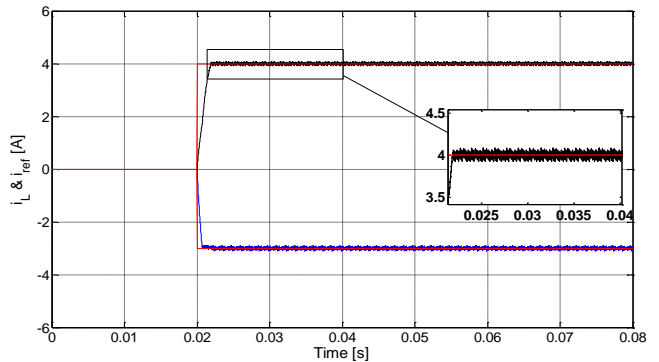


Fig. 8. Simulations results: Constant reference steps for load current.

V. CONCLUSIONS

In this paper the FS-MPC for two-level voltage source



inverters has been presented. The proposed control does not need to use modulator. The control algorithm has been evaluated with three different cases through simulation results. First of all, the robustness of the proposed control method with four prediction steps has been assessed; the assessment has been done by checking the load current and the error between the reference and actual current for four prediction steps. It has been noticed that the control algorithm provides very good current tracking behaviour. Secondly, with step change in the amplitude of the reference, the simulation results shows that the predictive control method has fast dynamic response with inherent decoupling between  $i_\alpha$  and  $i_\beta$ . Simulation results show that FS-MPC strategy gives very good performance under these conditions.

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