Predictive Current Control Strategy for Voltage Source Inverter

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***Abstract*—While the classical control techniques for three-phase two-level three-leg inverters are based on pulse width modulation or 3-D space vector modulation, this paper presents a Finite Control Set Model Predictive Control (FCS-MPC) strategy for a two-level three-leg voltage source inverter with resistive- inductive load. The Model Predictive Control method chooses a switching state that minimizes the error between the output currents and their references. Firstly the performance of the proposed predictive control method is compared with pulse width modulation control. Secondly the performance of controller is analyzed with various conditions is carried out. The proposed controller offers excellent reference tracking with less current harmonic distortion for all conditions. The proposed system's performance is investigated using a MATLAB simulation model.**

***Keywords*— Model predictive control (MPC), voltage source inverter, Current control, Pulsewidth modulation (PWM)**

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. Nowadays, MPC control scheme has been applied for current control of Active-Front-End Rectifier[10],[11], Distributed Generation Systems[12], Active Filters and Power Conditioning[5],[13],[14], Non-Conventional Renewable Energy[15],[16], uninterruptible power supplies (UPS)[4], drives[17],[18] and power factor correction [9]. This control scheme predicts the future load current behavior for each valid switching state of the converter, in terms of the measured load current and predicted load voltages.

The predictions are evaluated with a cost function that minimizes the error between the predicted currents and their references at the end of each sampling period.This has been applied for the controlling of power converters due to the advantages, like fast dynamic response, easy inclusion of nonlinearities and constraints of the system, and the flexibility to include other system requirements in the controller [2],[7].The classical current control techniques for a three leg two level VSI use PI controller and a modulation stage (PWM or SVM) to generate the gating signals. In the FCS-MPC takes the advantages of direct application of the control action to the converter without using modulator stage. Compared with the Classic Linear PI-PWM the MPC offers manyadvantages such as good reference tracking and minimum output distortion [1],[2],[5],[6].In this paper, the powerful and robustness of the proposed control method are evaluated through simulations results. This paper is organized as follows. In Section II, the mathematical model of the converter-load system is presented, followed by the explanation of the proposed control strategy in Section III. In Section IV, simulation results are presented. Finally in Section V appropriate conclusions are drawn.

II. POWER CONVERTER MODEL

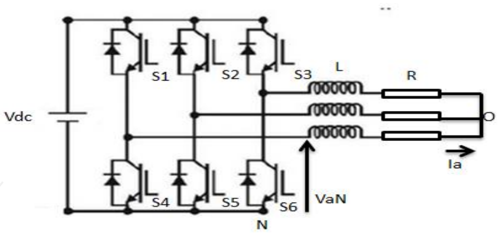

Fig. 1. Voltage source inverter power circuit.

A. Voltage Source Inverter Model

The power circuit of the converter considered in this work is shown in Fig. 1. It has been selected for a clear analysis of a predictive control strategy with RL-Load. It is a three leg two level inverter operated by switching S1, S2 ,S3, S4, S5and S6.The inverter consisting of two pairs of complementary controlled switches in each leg(S1, S4), (S2, S5) and (S3, S6). The switching states of converter are determined by the gating signals Sa, Sb, and Sc 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 it can be expressed in vectorial form by

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

where $a = e^{-j2\pi/3}$

The output voltages space vectors generated by the inverter are defined by

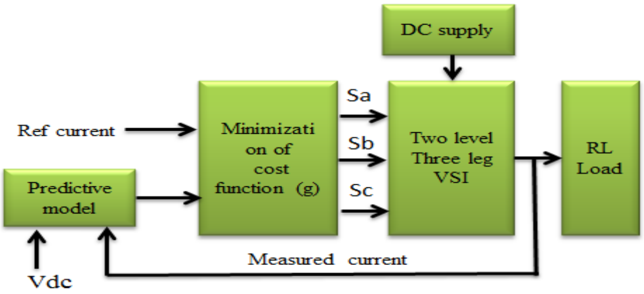

Fig.3.Model predictive current control block diagram.

$$v=\frac{2}{3}(V_aN+V_bN+V_cN) \qquad (5)$$

where V_aN , aV_bN and a^2V_cN are the phase to neutral voltages of the inverter . Then the load voltage vector V can be related to the switching state vector S by

$$v=V_{dc}S \qquad (6)$$

Then $$v=\frac{2}{3}V_{dc}(S_a+aS_b+a^2S_c) \qquad (7)$$

(or)

$$v_i=\frac{2}{3}V_{dc}(S_i[1\ \ a\ \ a^2]) \qquad (8)$$

where v_i is the voltage vector generated by the switching states S_i with i = 0,.....7.

By evaluating each of the switching states in (8), eight voltage vectors $(v_0 - v_7)$ can be generated by the inverter resulted in only seven different voltage vectors because v_0 and v_7 produce the same zero voltage vector , 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.

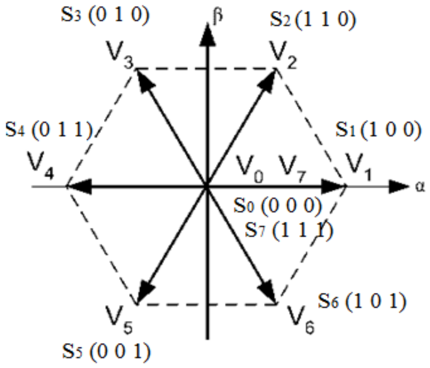

Fig. 2. Voltage vectors generated by the inverter.

B. *Load Model*

In a balanced three-phase load, the current can be defined as a space vector by

$$i=\frac{2}{3}(i_a+ai_b+a^2i_c) \qquad (9)$$

The load current dynamics can be expressed by vector equation

$$v=Ri+L\frac{di}{dt} \qquad (10)$$

where R is the load resistance L is the load inductance, v is the voltage generated by the inverter.

III. MODEL PREDICTIVE CURRENT CONTROL

A. *The Control Strategy*

The proposed predictive current control scheme is shown in Fig. 3.It uses the system model to predict the future behavior of the variables to be controlled. The quality function or cost function or error between the reference and predicted values is calculated. The switching state that minimizes g is selected and applied during the next sampling period.

It consisting of five main steps as follows[5]:

1) Measurements:The predictive model requires supply voltage and load currents at instant of k. In this system supply voltage is known and constant, when we go for other applications, supply voltage measurement is needed example APF. For this reason one voltage sensor and three current sensors is needed.

2) References calculation:Based upon on the application the current references are generated. In this system a simple modelling and control the inverter. So that the references are user defined. By changing the reference it can be used for any applications.

*3) Extrapolation:*For sufficiently small sampling time, example T_S is less than 20µs no extrapolation is needed. In that case take approximation as

$$i_0^*(k+1)=i_0^*(k) \qquad (11)$$

When sampling time T_S is greater than 20µs the following fourth-order extrapolation can be used:

$$i_0^*(k+1)=4i_0^*(k)-6i_0^*(k-1)+4i_0^*(k-2)-i_0^*(k-3) \qquad (12)$$

4) PredictiveModel: A discrete-time form of the load current for a sampling time T_S can be used to predict the future value of load current by using measurement of load current and supply voltage at the sampling instant k.

Approximating the derivative $\frac{di}{dt}$ by

$$\frac{di}{dt}=\frac{i(k)-i(k-1)}{T_S} \qquad (13)$$

Substituting equation (13) in equation (10) the following expression as

$$v = Ri + L\frac{i(k) - i(k-1)}{Ts} \tag{14}$$

Then the load current at instant k as

$$i(k) = \frac{1}{RT_S + L}[Li(k-1) + T_S v(k)] \tag{15}$$

Shifting the discrete-time one step forward in the future load current can be determined by

$$i(k+1) = \frac{1}{RT_S + L}[Li(k) + T_S v(k+1)] \tag{16}$$

where R and L are the load resistance and inductance, respectively is the sampling time, i(k) is the measured load current, and v(k+1) is the inverter predicted voltage is the decision variable to be calculated by the controller.

*5) Cost function or quality function optimization:*The error between the reference current and the measured load current at the next sampling instant can be expressed as follows

$$g = \left| i^*(k+1) - i(k+1) \right| \tag{17}$$

where, $i^*(k+1)$ is the reference current vector and $i(k+1)$ is predictive load current vector. Furthermore, (17) can be expressed in stationary frame as follows

$$g = \left| i_\alpha{}^*(k+1) - i_\alpha(k+1) \right| + \left| i_\beta{}^*(k+1) - i_\beta(k+1) \right| \tag{18}$$

where $i_\alpha(k+1)$ and $i_\beta(k+1)$ are the real and imaginary parts of the predicted current vector and $i_\alpha{}^*(k+1)$, $i_\beta{}^*(k+1)$ are the real and imaginary parts of the reference current vector respectively. In this work, the absolute error is used for computational simplicity. Other quality functions such as error squared could also to be used that can be expressed as follows

$$g = (i_\alpha{}^*(k+1) - i_\alpha(k+1))^2 + (i_\beta{}^*(k+1) - i_\beta(k+1))^2 \tag{19}$$

Finally the corresponding switching state is given to the inverter.

B. *MPC Algorithm*

In general, the control algorithm can be summarized to the following steps [6].

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 thecost function.
5) Apply the new switching state.

The optimal voltage vector is selected which minimizes the cost function and the switching state associated to the selected voltage vector is set to the gating signals.

IV. SIMULATION RESULTS

In this simulation two types of cases are considered. In the first case the Inverter controlled by the two different current control methods have been carried out, and in second case using Model Predictive Current Control method the simulations are carried out during non-sinusoidal reference and input frequency variation in order to assess the performance of the proposed predictive method.The Simulations are carried out using MATLAB/Simulink. The fig 4 and 5 denoting the matlab simulink model of the PI-PWM and MPC controller based voltage source inverter

A. *Comparison with PI-PWM Control*

A comparison of the proposed predictive current control with Classic Linear PI-PWMcontrol is presented in Figs. 6 and 7. Here, the amplitude of reference current i_α is reduced from 13 A to 5.2 A at instant 0.015 (s),while keeping the amplitude $i_\beta$current fixed. This is done to assess the decoupling capability of the current control loop. PI with PWM current control, shown in Fig. 6(a), presents slower dynamic response and some noticeable coupling effects between $i_\alpha$andi_β.In the response of the proposed predictive current control, for the same test, is shown in Fig.7(a).Its dynamic response is as fast than linear PI-PWM and no coupling effects between i_α and i_β.In Fig. 6(b) and Fig. 7(b) denoting the corresponding load voltages.

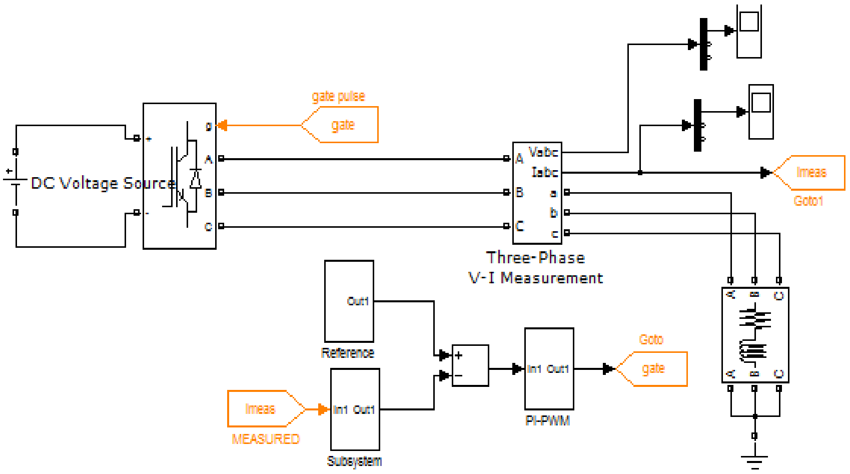

Fig . 4. Inverter controlled by PI-PWM controller- Simulink diagram.

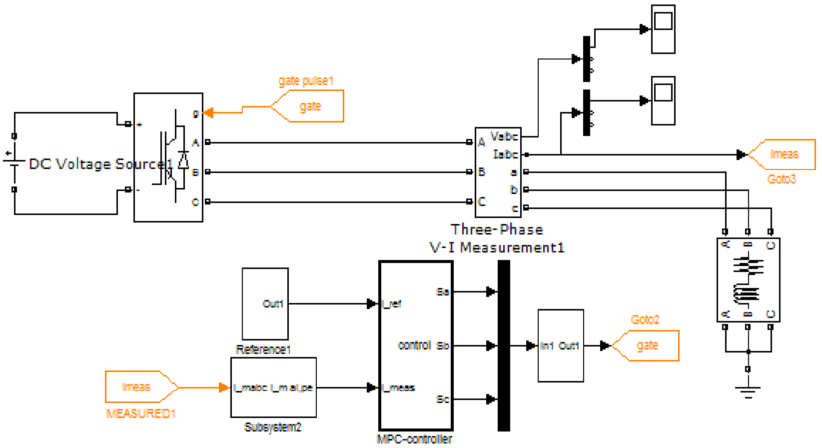

Fig. 5.Inverter controlled by MPC controller- Simulink diagram.

Table.1 Simulation Parameters

Variables	*Values*
Supply voltage	100V
Resistance	0.5 ohm
Inductance	10mH
PWM carrier frequency	2kHz
Sampling time	20e-6
Reference current	13 A

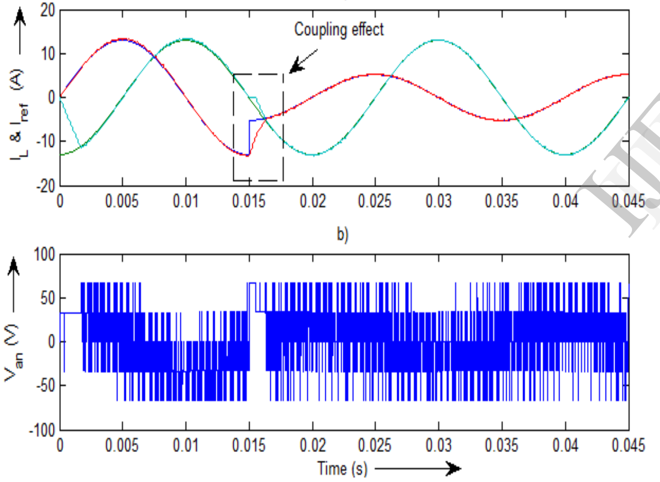

Fig. 6.Classic Linear PI-PWM step on i_α . a) Ref, Load (i_α and i_β) currents. b) load voltage.

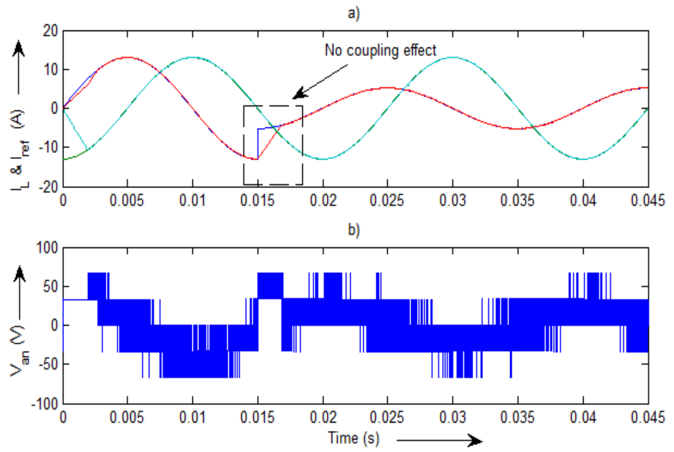

Fig. 7. MPC step on i_α . a) Ref, Load (i_α and i_β.) currents. b) load voltage.

B. *Performance of MPC for Various Conditions*

1) Analysis with input frequency variations

In this analysis the Reference frequency F = (50-20-70)Hz , Ref current (Ia,Ib,Ic) =13A and load Ra = Rb = Rc = 0.5ohm ; La = Lb = Lc = 10mH;

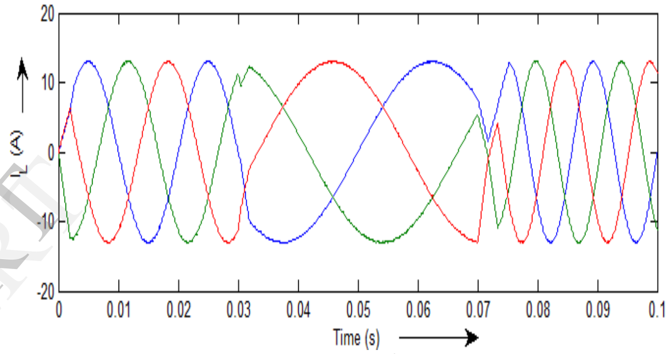

Fig.8 Simulation result with input frequency variations

In the fig.8 shows that good reference tracking with frequency variations and fast response is observed.

2) Analysis with Non sinusoidal reference

In this the seventh harmonic reference with amplitude and frequency are 10 A at 50 Hz, respectively. The loads are the same as of the input frequency variations earlier.

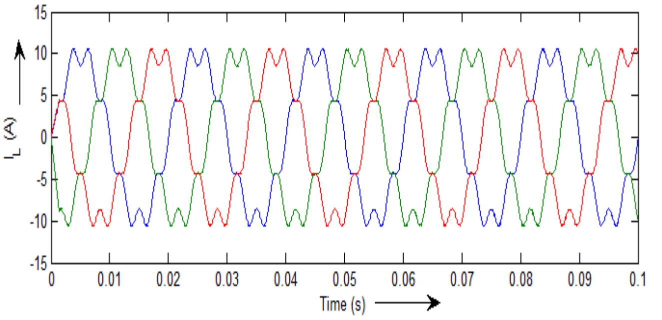

Fig .9 .Simulation results with seventh harmonic injected sinusoidal reference currents for Ts= 20μs

The results is indicated in Fig.9 where a good tracking of the load current to its reference is observed, which demonstrates that this control strategy can be applied effectively in a two-level three-leg converter operating as an active filter.

V. CONCLUSION

In this paper the FS-MPC for two-level voltage source inverters were studied. The control technique does not need to use modulator. The control algorithm has been evaluated with two different cases through simulation results. It has been noticed that the control algorithm provides very good current tracking behavior. First of all, when the 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 $i\beta$. Secondly, the simulation results show the good performances of the current tracking ability in various conditions such as input frequency variations and non-sinusoidal references.

Finally the Simulation results show that FS-MPC strategy gives very good performance under these conditions. In further research on predictive control is to analyze the performance of various condition such as load variations and sampling frequency variations.

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