

## Modular Approach to Implement Model Predictive Control on Three Phase Voltage Source Inverter

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### ABSTRACT

A modular abstraction is presented to implement model predictive control (MPC) on a three phase two level voltage source inverter to control its output current. Traditional ways of coded implementation do not provide insights into the complex nature of MPC; hence a more intuitive, logical and flexible approach for hardware implementation is conceptualized in the form of signal flow graphs (SFGs) for estimation, prediction and optimization. Simulation results show good performance of the approach and easier code generation for real time implementation. RL load is assumed for the inverter and the importance of choosing load inductance and sampling time ratio is emphasized for better control performance.

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## 1. INTRODUCTION

Three phase two level voltage source inverters are widely used in power electronics applications especially in drive control [1], [2]. Controlling output current of such inverter topologies is also widely researched topic. Model predictive control (MPC) is emerging as the most promising digital control method in the field of power electronics and drive applications. It has extensively been studied for induction and synchronous motor drives, front end rectifiers, multilevel inverters, and DC-DC converters [3], [4]. MPC demand higher computational costs and its applications will rapidly increase in the field of power electronics with the advent of high speed microprocessors and digital signal processors. MPC provide numerous benefits over traditional control methods such as easier handling of system constraints, parameter variations and easier incorporation of control tasks in the optimization cost function [5]–[7]. Most of the control strategies treat converters to be linearized systems ignoring their highly nonlinear nature. MPC takes this factor into account.

A model based predictive control for VSI is presented and discussed in detail in [1]. A space vector (SV) representation is used to model and analyze the system. An RL load and a simple back EMF model is used to investigate the performance of the controller. Controller consists of three stages of implementation i.e. estimation of back EMF, prediction of future currents, and optimization of a cost function involving current error. The estimation and prediction is based on Euler's forward approximation formula and prediction horizon of 1 is assumed.

Most of the controller applications are implemented in the form of C codes, making the working and troubleshooting of the controller obscure and difficult. Instead of directly implementing the control scheme in the form of codes, a signal flow graph representation and automatic code generation of the controller is

suggested here for easier modifications, understanding and implementation. A module based SFG will make it also possible to adopt model referencing for incorporating prediction horizon greater than 1 by simply repeating the appropriate modules. Tustin discretization rule is adopted for better results and a prediction horizon equal to 2 is used. Moreover the role of a special resistance L/Ts is elaborated with simulation results as a gain factor.

In the first section, mathematical model of inverter and load is presented. In section II, detailed discussion on the proposed MPC approach is given, followed by simulation results and conclusion in section III and IV respectively.

**2. INVERTER AND LOAD MODEL**

The inverter and load model is adopted from [8]. The circuit diagram of the system is shown in Figure 1.

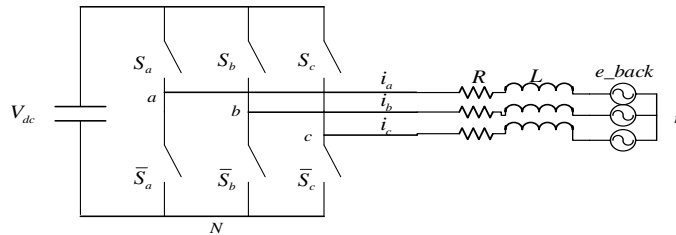


Figure 1. Three phase voltage source inverter with RL load

A dc source feeds the inverter with a constant supply voltage  $V_{dc}$ . Switches of the inverter are operated in bipolar fashion i.e. no two switches in the same leg are turned ON or OFF simultaneously. Therefore the lower switches are represented with a complimentary symbol. Inverter is driving a three phase RL load with a sinusoidal back EMF  $e\_back$ . A space vector representation will be assumed throughout the discussion. Space vector for three phase quantities  $x, y$  and  $z$  is defined as:

$$sv \{x, y, z\} = \frac{2}{3} \left( x + ye^{j\frac{2\pi}{3}} + ze^{j\frac{4\pi}{3}} \right) \tag{1}$$

The inverter voltage space vector can be defined as:

$$sv \{v_{aN}, v_{bN}, v_{cN}\} = \frac{2}{3} \left( v_{aN} + v_{bN}e^{j\frac{2\pi}{3}} + v_{cN}e^{j\frac{4\pi}{3}} \right) \tag{2}$$

Where

$$\begin{aligned} v_{aN} &= S_a V_{dc} \\ v_{bN} &= S_b V_{dc} \\ v_{cN} &= S_c V_{dc} \end{aligned} \tag{3}$$

Based on (2) and (3) a table (Table 1) of inverter voltage vectors can be generated for each possible switching state. Note that  $v_0 = v_7 = 0$  lie on the origin. Voltage vectors are shown in Figure 2.

The load equation in the form of space vectors can be written as [9]:

$$v = iR + L \frac{di}{dt} + e\_back \tag{4}$$

Following vectors are assumed in (4):

$$\begin{aligned}
 v &= sv \{v_{aN}, v_{bN}, v_{cN}\} \\
 i &= sv \{i_a, i_b, i_c\} \\
 e\_back &= sv \{e\_back_a, e\_back_b, e\_back_c\}
 \end{aligned}
 \tag{5}$$

**3. MODULAR MPC CONTROLLER**

The block diagram of the traditional way to implement MPC for current control is shown in Figure 3.

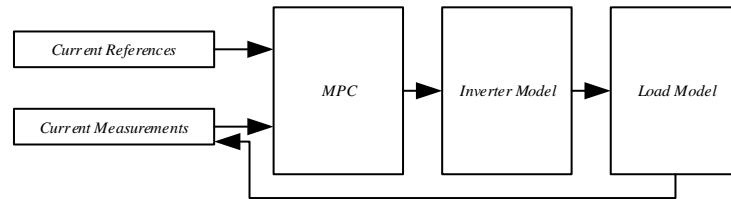


Figure 2. Traditional implementation of MPC

Table 1. Inverter\_Switching States and Resulting Voltage Vectors

$k$	$S_a$	$S_b$	$S_c$	$v_k$
0	0	0	0	0
1	1	0	0	$\frac{2}{3}V_{dc} \angle 0^\circ$
2	1	1	0	$\frac{2}{3}V_{dc} \angle 60^\circ$
3	0	1	0	$\frac{2}{3}V_{dc} \angle 120^\circ$
4	0	1	1	$\frac{2}{3}V_{dc} \angle 180^\circ$
5	0	0	1	$\frac{2}{3}V_{dc} \angle 240^\circ$
6	1	0	1	$\frac{2}{3}V_{dc} \angle 300^\circ$
7	1	1	1	0

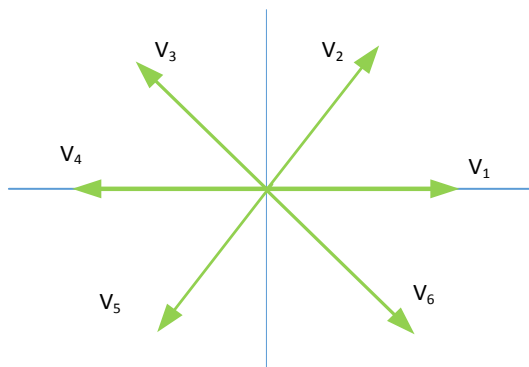


Figure 3. Voltage vectors

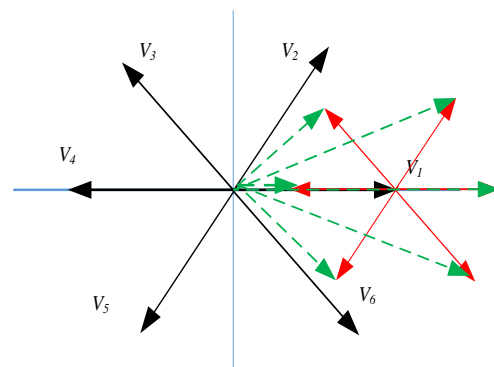


Figure 3. Voltage Vector addition for prediction horizon N=2

For predicting currents, we can discretize (4) using Euler's forward rule  $\frac{dy(t)}{dt} \approx \frac{y(k+1) - y(k)}{T_s}$  to get the following approximation [10]:

$$i(k+1|k) = \left(1 - \frac{R}{R_o}\right) i(k) + R_o (v(k) - e\_back(k)) \quad (6)$$

Where  $i(k+1|k)$  is the predicted value of current, one sampling step into the future  $k+1$  and the prediction is made at time instant  $k$ .  $R_o = \frac{L}{T_s}$  is a special ratio and can be changed by changing the sampling time  $T_s$  [11]. Note that  $v(k)$  can take 7 values depending upon the switching combination applied to the inverter. We will assume all the possible switching states to predict 7 values of the current and choose the best switching state which produces minimum current error.

For better performance, we will assume prediction horizon equal to 2. Therefore, at time instant  $k+2$  the current can be predicted to be:

$$i(k+2|k) = \left(1 - \frac{R}{R_o}\right) i(k+1|k) + R_o (v(k+1) - e\_back(k+1)) \quad (7)$$

Since back EMF is slow varying, therefore we can safely assume  $e\_back(k+1) \approx e\_back(k)$ .

Putting (6) into (7) with  $c_1 = \left(1 - \frac{R}{R_o}\right)$  and  $c_2 = R_o$  and simplifying:

$$i(k+2|k) = c_1 i(k) + c_2 \left(\underline{c_1 v(k) + v(k+1)}\right) - (c_1 c_2 + c_2) e\_back(k) \quad (8)$$

The underlined part in (8) is significant since it represents the voltage vector addition to predict current two instants into the future. Each vector from  $v_0$  to  $v_6$  is added to the scaled version of entire vector space. Ignoring  $v_0$  addition, we can anticipate 36 sums. This situation is shown for  $v_1$  addition in fig. 4. Note that  $c_1$  is less than 1, therefore the added vectors are smaller in lengths. In the same way we can get all the sums and evaluate (8) for different vectors. Number of sums can further be reduced by considering the fact that  $R_o$  is larger than  $R$  which will give  $c_1 \approx 1$ .

For better estimation of back EMF, we will use Tustin's Bilinear Transformation [12] i.e.  $s = \frac{2}{T_s} \left( \frac{1 - z^{-1}}{1 + z^{-1}} \right)$ . Applying Laplace transform on (4) will result in:

$$V = RI + sLI + E\_back \quad (9)$$

After discretization:

$$E\_back = (1 - z^{-1})V - (R + 2R_o)I - (R - 2R_o)z^{-1}I + z^{-1}E\_back \quad (10)$$

$z^{-1}$  represents unit delay and the system is assumed relaxed. Based on equation (6) and equation (10) the implementation block diagrams are shown in Figure 5 and Figure 6. These block diagrams can be separately implemented for real and imaginary parts of the system or multiplexed as a vector.

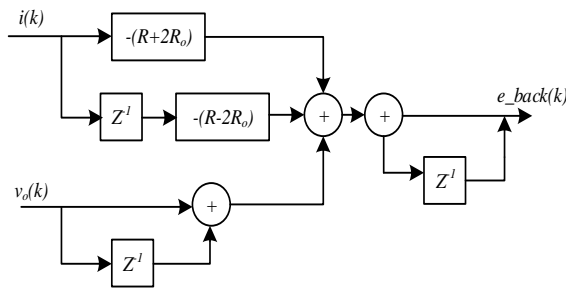


Figure 4. Back EMF estimation module

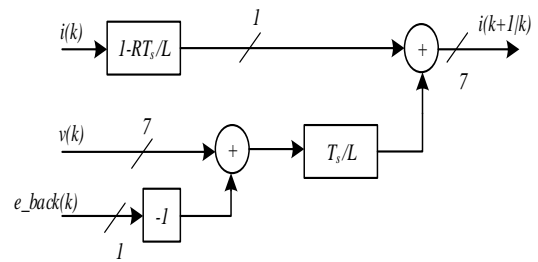


Figure 5. Current Prediction

We can repeat the prediction module twice to get the predictions  $i(k+2|k)$  and the process can be extended to further predictions easily. However, the number of computations will increase  $N^2$  times. There are various techniques available to reduce these calculations.

After prediction and estimation, we have to choose the best switching state to be applied at the next sampling interval based on the following cost function.

$$g = \sum_{N=1}^2 \left\| i_{ref,\alpha}(k+N) - i_{\alpha}(k+N|k) \right\| + \left\| i_{ref,\beta}(k+N) - i_{\beta}(k+N|k) \right\| \tag{11}$$

Here, the currents are referred to the stationary  $\alpha\beta$  frame. Assuming that we choose  $N = 1$ , from fig. 6, we see that there are 7 predictions for current at time instant  $k+1$ , hence 7 values of cost function in (11) can be obtained by the implementation shown in Figure 7. The diagram uses basic building blocks available in most simulation software for code generation. After the calculation of 7 error values between future reference current and 7 predicted currents, their absolute value is computed. Next block finds the minimum absolute error ( $g_{opt}$ ). To find the voltage vector which produces this minimum error, we compare  $g_{opt}$  with all the other values. Only one comparison produces 1 which is multiplied with the index values to determine optimal state  $state_{opt}$  to be applied at next sampling interval. For prediction horizon greater than 1, this module can easily be replicated as required. The overall implementation block diagram is shown in Figure 8.

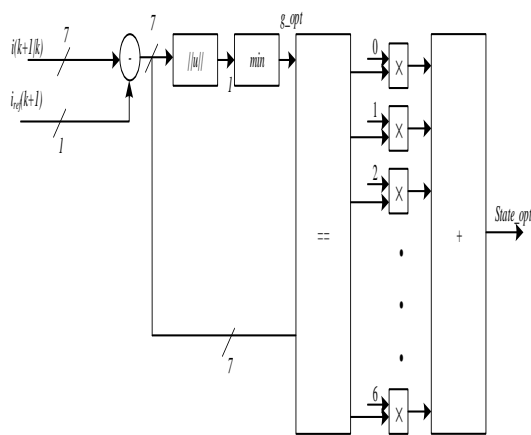


Figure 6. Selection of optimal switching states

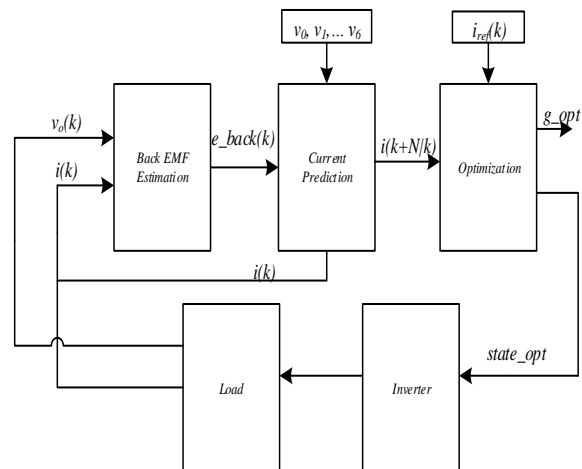


Figure 7. Implementation Block Diagram

**4. SIMULATION RESULTS**

The proposed modular approach is implemented in Matlab/Simulink for  $L = 10\text{ mH}$ ,  $R = 8\Omega$ . Peak amplitude of back EMF is assumed to be 120V and frequency of 50 Hz while DC source of 450V is considered. Figure 9 shows the simulation results of output currents for a sinusoidal reference of amplitude 12A and frequency 50 Hz, for two different values of sampling time i.e.  $100\mu\text{s}$  and  $20\mu\text{s}$ . Since decreasing the value of sampling time will require a higher switching frequency, it will significantly increase the quality of the output currents at the same time giving a boost to the computational demands. Practically, it becomes computationally heavier to use smaller values of sampling time. Therefore a compromise is made while choosing the sampling time for less distorted current waveforms.

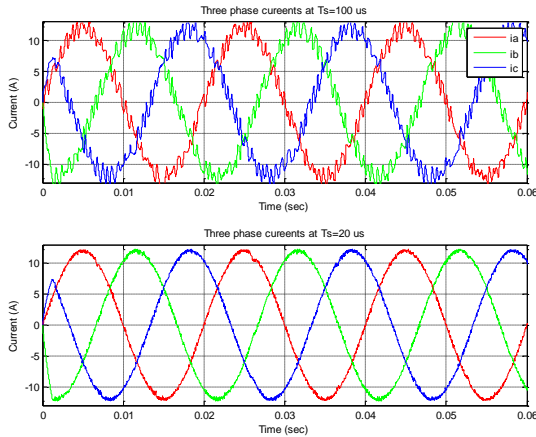


Figure 8. Effect of sampling time on output current

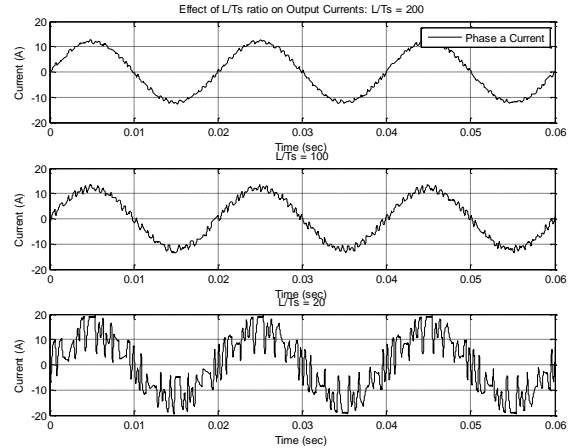


Figure 9. Effect of L/Ts ratio on output currents

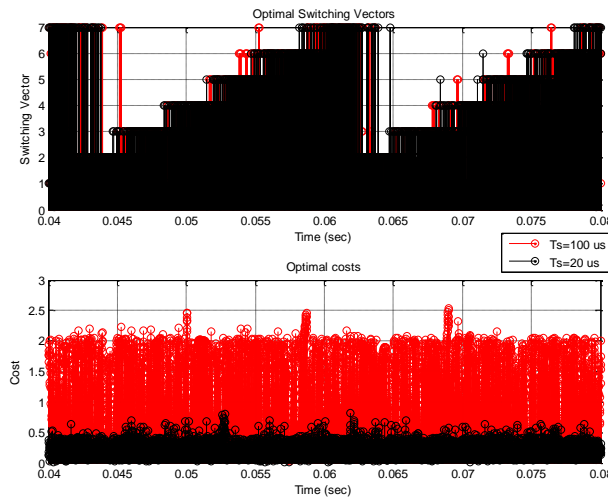


Figure 10. Optimal states and cost function for different values of sampling time

Figure 10, on the other hand shows the effect of the ratio  $L/T_s$  on the current waveforms. Only single phase current is showed to explain the effect. If the ratio is kept higher i.e.  $T_s$  smaller, current waveforms are less distorted. If we decrease the ratio by increasing  $T_s$ , the current THD increases and distortions occur. If this ratio becomes equal to  $R$ , current predictions are purely made on the basis of estimated back EMF and voltage vectors. For better results, this ratio should be kept around 100 to 200.

Finally Figure 11 gives the plots of the optimal costs and optimal states calculated by the MPC controller for a limited frame of time. There is no significant effect of sampling time on the optimal states

chosen for the inverter, however optimal costs are significantly reduced when smaller sampling times are used.

## 5. CONCLUSION

A modular way to interpret and implement model predictive control (MPC) for a three phase two level inverter is investigated. The basic stages involved in MPC implementation are broken down to simple modules based on SFGs and fundamental building block found in all digital control implementation and simulation software. The approach provides more intuition, flexibility and ease of code generation and modification of the MPC hardware implementation. This approach can be easily extended to incorporate higher prediction horizons and complex discretization methods for estimation. Future work may involve the extension of the approach to other applications such as drive control, increasing the prediction horizon by using vector representation and reduction of effective switching states through state transition diagrams.

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Muhammad Abbas Abbasi received his B.Sc. degree in Electronics Engineering from The Islamia University of Bahawalpur, Pakistan in 2004 and M.S. degree in Electrical Engineering from University of Engineering & Technology (UET), Taxila, Pakistan in 2012. Currently he is pursuing his PhD degree in Universiti Teknologi Malaysia (UTM). He is a full time faculty member at The Islamia University of Bahawalpur, Pakistan and has also worked in different control industries in Pakistan. He has taught courses in Control Engineering, Digital Signal Processing, FPGA based system Design and Electronics Systems. His research interests include Model Predictive Control of Power Converters and Drives, Predictive Direct Torque Control, FPGA based Control, and Signal Processing.



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