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Predictive Control of Three-Phase Cascaded Multilevel Inverter

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Abstract

This paper investigates the performance of a Cascaded Multilevel inverter (MLI) controlled by Model Predictive Control (MPC). This inverter can be used for many applications such as for the induction motor drives or the grid connected systems. The cascaded MLI has 125 discrete space voltage vectors out of which many vectors are redundant. In order to reduce the complexity of calculations only 61 non-redundant vectors are used. The simulation is carried out in MATLAB/SIMULINK software and the results obtained are discussed. From the results, it can be verified that the MPC Controlled Cascaded MLI achieves a minimum current Total Harmonic Distortion (THD). Further, it also shows an excellent response when the load is dynamically changed.

Keywords: Cascaded MLI, Model Predictive Control, Current Control, Predictive Current Control, Switching States, Total Harmonic Distortion, Voltage Vectors

1. Introduction

Today, MLI is much relied upon as a very viable solution for medium voltage high voltage applications. This inverter synthesizes the ac voltage from many levels of DC voltage[1,13]. The various advantages of MLI are its capability of reducing voltage stress on power switches, dv/dt ratio and common node voltage, thus increasing the quality of the output. There are number of different topology of MLI such as cascaded MLI, diode clamped MLI and flying capacitor MLI. Out of which cascaded MLI has various advantages such as modularity, flexibility, extendibility and reliability.

There are various classical control techniques for cascaded MLI which are discussed in the literature such as hysteresis current control, linear control with Pulse Width Modulation (PWM) and Space Vector Modulation (SVPWM) and predictive current control[8,12]. Out of these predictive current control out performs other control with its ability such as high dynamic performance and improved current quality[7,9,11]. This controller is attracted the attentions of the researches because of the increase in computational capability of the current digital processers. There are various predictive control techniques available such as hysteresis current control. trajectory based predictive control and Model Predictive Control (MPC)[2–3].

The MPC control is used here since they required no modulator, involves low complexity, online computation is possible and constraints can be included[4–5]. This paper is structured as follows: the Section II includes the description of MPC, Section III includes the modelling and simulation, Section IV includes the results and discussion and Section V includes the conclusion

2. Model Predictive Control

The control objectives of this controller can varied considerably according to the type of applications where it is used. It can be electromagnetic torque for electric drives[14], active and reactive powers for rectifiers[11], and the currents for inverters systems[9]. Apart from different

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approach by considering power converter as a non linear actuator, several parameters like motor torque ripple minimization can be optimized. Moreover, it offers flexibility for fulfilling some objectives by taking functions from various blocks like PWM and cascaded multi loop PI control .The handing out time becomes more because of calculations[2].

The MPC algorithm works as explained below in the control algorithm:

1. The value of the reference is obtained from the outer control loop and the output is measured in the discrete domain.
2. Prediction of the load in the next sampling instant (k+1) for different voltage vectors using the model of the system.
3. Evaluation of the cost function g by the error generated between the reference and the predicted.
4. The value that minimises the g value is selected and the corresponding switching signals are given to the inverter.

Implementation of model predictive control to the 5-level cascaded multilevel inverter has been discussed below.

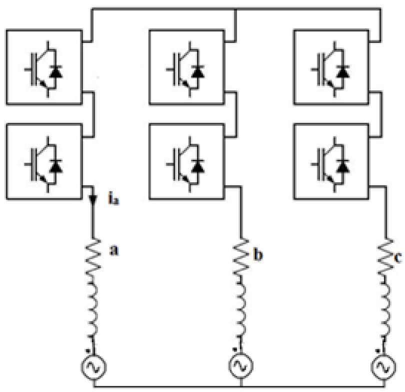

Figure 1. Cascaded H bridge three phase inverter.

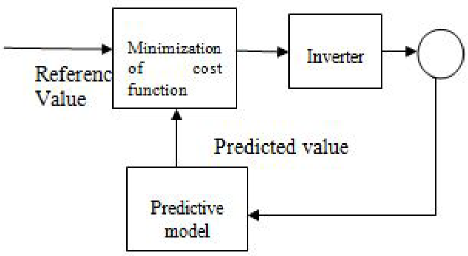

Figure 2. Block diagram of model predictive Control.

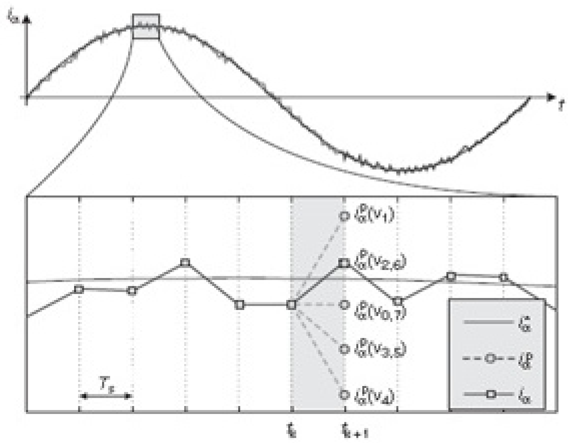

Figure 3. Implementation of the Predictive Control Strategy.

Considering the advantages of the MPC, this paper uses MPC for controlling MLI. First a model of the inverter is developed. Then the cost function is defined which takes into consideration the reference current and the predicted current. The actual current follows the prediction which has the minimum cost function.

2.1 System Modelling

The multilevel inverter of 5-level with Is of Cascaded H Bridge (CHB) connection contains 2 cells in each phase[3]. Each cell is fed from different voltage source and will generate a 5 level output voltage In a CHB inverter which contains N cells and L possible levels will have NL voltage vectors[4] so for a normal CHB 5-level inverter it contains 125 voltage vectors. Implementation of MPC to CHB requires the modelling of the inverter and also the current from the output of the inverter is sensed and the current will be converted to alpha beta dominie

Three phase to alpha –beta conversion

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} -2/3 & -1/3 & -1/3 \\ 0 & \sqrt{3}/3 & -\sqrt{3}/3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

The modelling of inverter and the load is as follows. The inverter modelling is based on the output levels

$$v_{an}(t) = v_{aN}(t) + v_{Nn}(t) \tag{1}$$

Where v_{aN} is the inverter output voltage of phase a, and v_{Nn} is the common-mode voltage, defined in

Terms of the inverter voltages as

$$v_{Nn}(t) = v_{aN}(t) + v_{bN}(t) + v_{cN}(t)/3 \tag{2}$$

the load model is as follows

$$v_{an} = Ldi_a/dt + Ri_a + e_a \quad (3)$$

$$v_{bn} = Ldi_b/dt + Ri_b + e_b \quad (4)$$

$$v_{cn} = Ldi_c/dt + Ri_c + e_c \quad (5)$$

By applying the Laplace transform to the above equations transfer functions from voltage to current at the *RL* load are obtained:

$$\frac{I_a}{V_{an} - E_a} = \frac{1}{LS + R} \quad (6)$$

$$\frac{I_a}{V_{bn} - E_b} = \frac{1}{LS + R} \quad (7)$$

$$\frac{I_a}{V_{cn} - E_c} = \frac{1}{LS + R} \quad (8)$$

For generating the voltage vectors we us the state space analysis in order to find the predictive value of the current

$$a = e^{j2\pi/3} = -1/2 + j\sqrt{3}/2 \quad (9)$$

$$v = 2/3(v_{aN} + a\,v_{bN} + a^2 v_{cN}) \quad (10)$$

Where

$$v_{aN} = s_a{}^{*}V_{dc}$$

$$v_{bN} = s_b{}^{*}V_{dc}$$

$$v_{cN} = s_c{}^{*}V_{dc}$$

Eg:- for switching state $(S_a, S_b, S_c) = (0, 0, 0)$ generates voltage vector V_0 defined as

$$v_0 = 2/3(0 + a0 + a^2 0) = 0$$

Calculation of all 125 vectors for each instant will be burden for the controller instead of calculating all the 125 vectors by removing the residues we will get 61 voltage vectors among (Residing horizon principle)[5]. Those 61 vectors are represented in the hexagon given below. Number of redundancy of the switching states is shown in Figure 4. Outer layer switching states contains the redundancy value of 0

The layer next to it contains redundancy of 1the switching states which is 2nd from the outer layer contains redundancy of 2 and the inner layer which containing 6 switching states have the redundancy value of 3. The inner most layer containing only one switching state has the redundancy value of 4. The voltage vectors with respect to the level is given in Table 1.

Cost function for the current control of the inverter is given by[6,12]:

$$g = |i^{*}\alpha(k+1) - i_p\alpha(k+1)| + |i^{*}\beta(k+1) - i_p\beta(k+1)| \quad (11)$$

Where $i_p\alpha(k+1)$, $i_p\beta(k+1)$are the real and imaginary parts of the predicted load current vector $i_p(k+1)$, $i^{*}\alpha(k+1)$, $i^{*}\beta(k+1)$ are the real and imaginary:

The current prediction can be done through the Euler equation

$$\frac{di}{dt} = \frac{i(k+1) - i(k)}{T_s} \quad (12)$$

so the predicted value of the current will be given as

$$i_p(k+1) = (1 - RT_s/L)i(k) + (T_s/L)(v(k) - \hat{e}(k)) \quad (13)$$

Where R is the load resistance

L is the inductance

T_S is the sampling time

e represents the back EMF

The switching states will be changed with respect to the time a for every T_S sec the controller will calculate the values of all the 61 vectors and such that the vector which is having min value and the switching state which is causing it will be given as the input switching states to the inverter for that sampling. The simulation results for

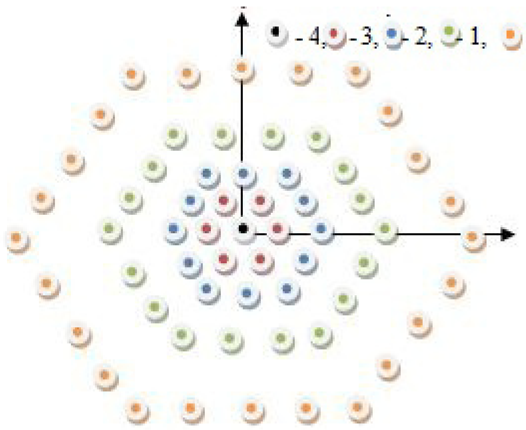

Figure 4. Switching states represented in hexagon

Table 1. Voltage vectors with respect to level

Level	Voltage vectors	Non redundant vectors
5	125	61
X	$(2x + 1)^3$	$12x^2 + 6x + 1$

sampling time of 40 us, inductance of 20 mh, resistance of 100 ohm and source voltage of 300 v are shown in Figure 5 and Figure 6.

3. Results and Discussion

MPC was implemented in mat lab/simulink software for the specifications given. The output current waveforms and the comparison with a actual waveform is presented in Figure 6. The waveform shown in Figure 5 is the three phase output currents.

The output is verified as the real time by applying a step. The response of MPC is very good for step change in reference current. As we can see in the figure below the MPC response for step change is less than 0.002msec. Blue-Output current; Green–reference current. From the Figure 7 it is clear that the output current piously tracks the reference current when there is dynamical change in load and sensed from the load are almost similar and in Figure 8 we can see the enlarged view of the response for the dynamic change.

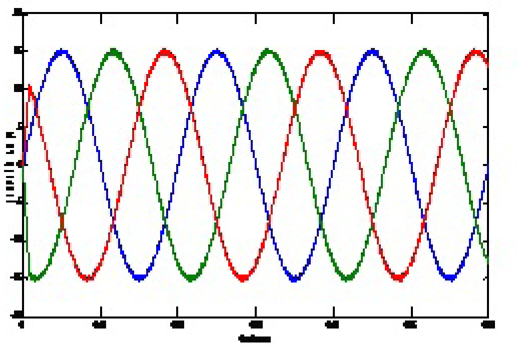

Figure 5. Output three-phase current plot.

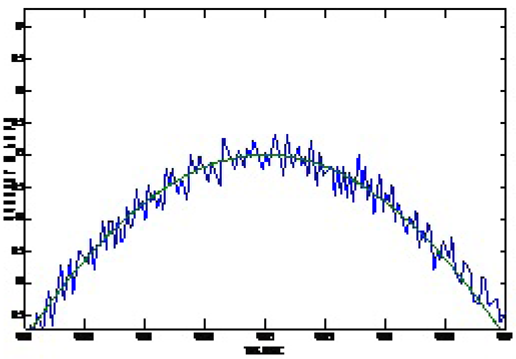

Figure 6. Comparison between reference and output current.

In Figure 9 shows the FFT analysis of the current using 125 voltage vectors

Results of the model predictive control using 61 vectors are as follows dynamic change in the reference is tracked by the output current as shown in Figure 10. The enlarged view of the current tracking is given in Figure 11. The FFT analysis of the 61 vector model is given in Figure 12. Even though the THD is bit high for 61 vector model but computation time is less such that the controller requires less number of calculations for every sampling time given

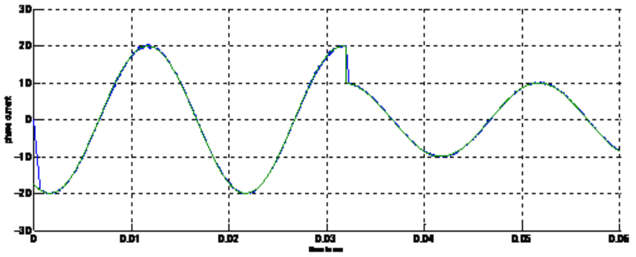

Figure 7. Response of MPC for sudden change in the reference for 125 vector model.

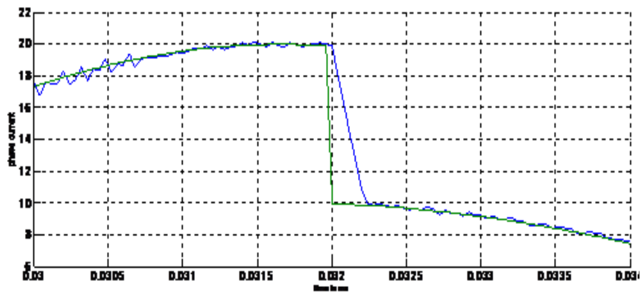

Figure 8. Enlarged view for sudden change in the reference.

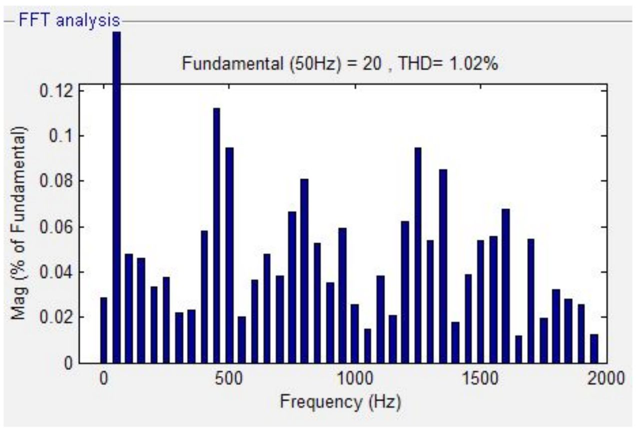

Figure 9. FFT analyses for 125 vector model.

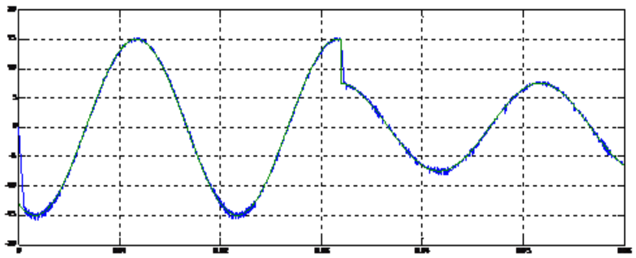

Figure 10. Response of MPC for sudden change in the reference for 61 vector model.

Figure 11. Enlarged view for the sudden change in 61 vector model.

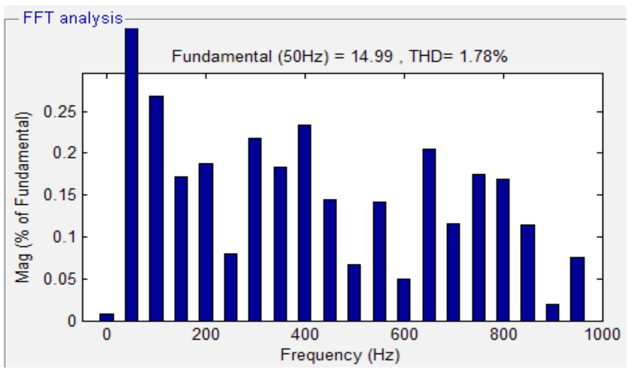

Figure 12. FFT analyses for 61 vector model.

4. Conclusion

A MPC approach for cascaded MLI is presented. The proposed approach considers a set of all possible switching states in order to reduce the number of calculations and make it applicable for execution in a standard control platform. The proposed control technique presents an accurate reference tracking with balanced inverter output voltages, reducing voltage stress on power switches, dv/dt ratio and common mode voltage, thus increasing the quality of the output. This predictive control method can also be applied to other MLI with more levels and switching states. Low harmonic content is reduced as a result of the large number of voltage vectors participating in control. The model predictive current controller was implemented in the Matlab/Simulink software, which was running in real time.

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