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Model Predictive Control of Three Phase Inverter Fed RL Load

Shaswat Chirantan
PhD. Scholar, Department of Electrical Engineering
Veer Surendra Sai University of Technology
Burla, Sambalpur, India
shaswat.chirantan443@gmail.com

Dr. Bibhuti Bhusan Pati
Professor, Department of Electrical Engineering
Veer Surendra Sai University of Technology
Burla, Sambalpur, India
bbpati_ee@vssut.ac.in

***Abstract*—The management strategy that uses a plant model for the prediction of future characteristics of a control variable is called as Model Predictive Control(MPC). This paper proposes a predictive model of a three phase inverter with passive RL load with load current as predicted variable & termed as Predictive Current Control(PCC). In the proposed PCC scheme Space Vector Modulation(SVM) technique is implemented for switching state selection of inverter for an assigned cost function in terms of reference & predicted current difference with most optimum value. Discretized forward Euler approximation is used to predict the load current. The MPC algorithm is implemented in a three phase inverter model using the MATLAB / SIMULINK environment.**

Keywords—cost function, discrete time model, inverter, MPC, PCC, SVM, switching states.

I. INTRODUCTION

MPC is becoming popular in many industrial applications and also in power systems because of its reliability, adaptability and fastness of control action. The general idea behind any predictive management is based on the system framework to forecasts the activities of control parameter and use the optimization criteria to select the correct key. In this work, the control action of PCC model is presented in a single controller by selecting the inverter switching states corresponding to the discrete model to foretell the future current, which minimizes the cost function. MPC based control technique has also attracted attention dealing with multivariable cases, nonlinearlities and constraints optimization. Its superior characteristics insist the power system with its ability to adapt for every control majors.

J Rodriguez and P Cortes [1] proposed the basic modeling of three phase inverter, cost function selection, discrete model of load current and switching states selection corresponding to voltage vectors. A control strategy for micro-grid based on MPC has been applied to BESS(Battery Energy Storage System in [2]. Charles, et al. [3] proposed a robust methodological analysis for two area load frequency control model where the performances of MPC is compared with various optimized controllers. Finite control set MPC applied to power converters was suggested by Kouro, et al. in [4]. Khan, et al. [5] suggested a controller for UPS system where the console uses a numerical hypothesis of the system to predict the voltage in response to each potential switch state for each sample period. A new MPC method relies on the slope method (Gradient Descent) was proposed by Yu Hyeung Jun, Thai-Than Ngin, and Hak-Man Kim in [6]. Vasquez Perez, Sergio et al. [7] describe the current trends and challenges of MPC that exist in the electronics applications. Rodriguez, Jos et al. [8] proposed a predictive control strategy applied to voltage source inverter for load current forecasting.Wang, et al. [9] demonstrated the design and implementation of a classic management strategy such as PID control, direct control and cascade control in a MATLAB / SIMULINK environment. Importance of model anticipation in the current scenario, since control of power electronics via MPC is the most efficient and reliable control scheme with reference to performance analysis ([10] & [11]). A fully field programmable real-time MPC (FPGA) gate array for direct matrix converter (DMC) by O Gulbudak and E Santi is available [12]. An adaptive model with fuzzy-logic controller with discrete-time model for induction motor speed control is described by Jabbour, and Christos Mademlis in [13]. In [14], a sliding model MPC scheme for three phase converter has been proposed by He, Tingting, et al. An economic MPC model for economic load despatch was suggested by Jia, Yubin, et al. in [15]. Application of model predictive control has been analyzed by many researchers which motivates the present problem.

II. THEORY

Discretization of general state space equations for kth sampling instant for proposed control scheme can be stated as :

$$x(k+1) = Ax(k) + Bu(k) \tag{1}$$

$$y(k) = Cx(k) + Du(k) \tag{2}$$

Where symbols carry usual meaning.

The cost function, which is the behavior required by the system, must be specified. This function takes into account future referrals, cases, and future processes:

$$J = f(x(k), u(k), ..., u(k+N)) \tag{3}$$

MPC is an optimization head that includes reducing the cost function J for a predetermined N time horizon when respecting the model and system constraints. The result is a series of tips for the best. The console will only execute the initial component of the series when the optimization problem is solved again within the sampling period using the newly measured data and each time a new order of the optimal key is obtained. The schematic of MPC control action is depicted in Fig.1.

$$u\,(k) = [10 \cdot 0]\ argminuJ \tag{4}$$

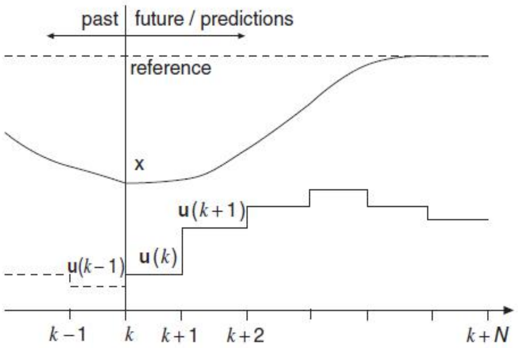


Fig. 1 Schematic of Model Predictive Control action

III. Contemplated Control Strategy

A. PCC

The projected current control scheme is based on the switching states generated by three phase inverter corresponding to the voltage vectors for which the cost function is minimum. The key features to be designed are a cost function, a predictive current control model which directly incorporate the inverter model based on switching states and a predictive model for load assigned. These modelings identify the upcoming characteristics of the control variables and generate an optimum control strategy.

B. Assignment of Cost Function

The cost function is defined as the difference between reference & measured currents and can be presented as:

$$g = \left| i^{*}{}_{\alpha}(k+1) - i^{p}{}_{\alpha}(k+1) \right| + \left| i^{*}{}_{\beta}(k+1) - i^{p}{}_{\beta}(k+1) \right| \tag{5}$$

Where subscripts α & β denote the real & imaginary components of current respectively, superscript * and *p* denote the reference & predicted elements respectively & *k* is the sampling instant.

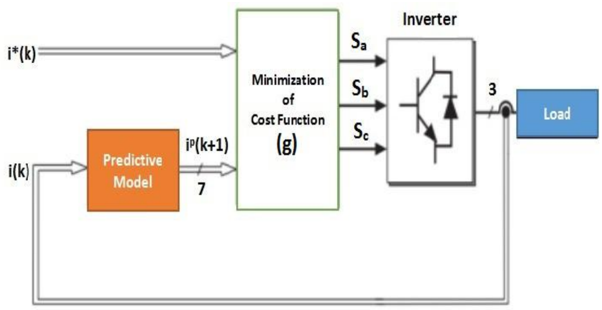


Fig.2 Predictive Current Control Scheme [1]

Fig.2 depicts the PCC scheme of three phase inverter. From the block diagram it can be visualized that the cost function is characterized by the reference & predicted current. Accordingly the optimum switching states(S_a,S_b,S_c) with reference to corresponding voltage vector of inverter has been fed to the load for optimal operation.

C. Test System

The voltage source inverter model considered for PCC is shown in Fig.3.

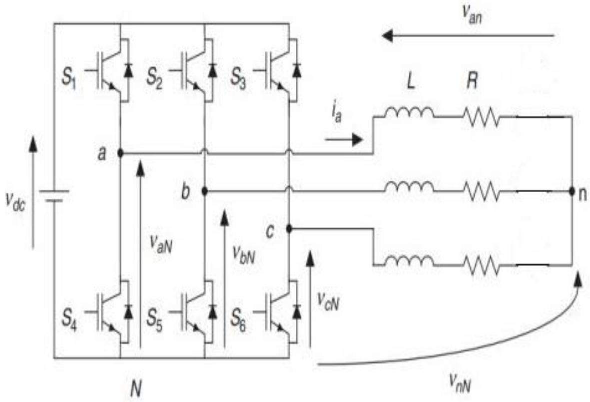


Fig.3 Three phase VSI Model

In the inverter model there are two switches in each leg and both are complement to each other in terms of operation. The switching signals for all six switches, voltage vectors, load current dynamics and discrete model of load current is summarized in [1].

TABLE.I: Switching Signals of Three Phase Inverter

Switch	States	S_a	S_b	S_c
S1	ON	1	-	-
	OFF	0	-	-
S2	ON	-	1	-
	OFF	-	0	-
S3	ON	-	-	1
	OFF	-	-	0
S4	ON	0	-	-
	OFF	1	-	-
S5	ON	-	0	-
	OFF	-	1	-
S6	ON	-	-	0
	OFF	-	-	1

The phase to neutral voltages of each phase generated by the inverter can be written as follows:

$$v_{aN} = S_a V_{dc}\,,\ v_{bN} = S_b V_{dc}\,,\ v_{cN} = S_c V_{dc} \tag{6}$$

Where V_{dc} is the DC source voltage of the inverter.

The output voltage(v) can be expressed in terms of phase to neutral voltages.

$$v = \frac{2}{3}\left(v_{aN} + a v_{bN} + a^2 v_{cN}\right) \tag{7}$$

Where $a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$, is the unitary vector represents the 120 degree phase difference between the phases.

TABLE.II: Voltage Vectors corresponding to Switching Signals

S_a	S_b	S_c	Voltage Vector(V)
0	0	0	$V_0 = 0$
1	0	0	$V_1 = \frac{2}{3}V_{dc}$
1	1	0	$V_2 = \frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	0	$V_3 = -\frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	1	$V_4 = -\frac{2}{3}V_{dc}$
0	0	1	$V_5 = -\frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
1	0	1	$V_6 = \frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
1	1	1	$V_7 = 0$

D. Equations for Load Current Dynamics

From Fig.3 the load current dynamics equations can be obtained as follows:

$$v_{aN} = L\frac{di_a}{dt} + Ri_a + v_{nN} \tag{8}$$

$$v_{bN} = L\frac{di_b}{dt} + Ri_b + v_{nN} \tag{9}$$

$$v_{cN} = L\frac{di_c}{dt} + Ri_c + v_{nN} \tag{10}$$

Putting equation (8), (9) & (10) in equation (7), the overall load dynamics can be as:

$$v = L\frac{d}{dt}\left(\frac{2}{3}\left(i_a + ai_b + a^2 i_c\right)\right) + R\left(\frac{2}{3}\left(i_a + ai_b + a^2 i_c\right)\right) + \frac{2}{3}(v_{nN} + av_{nN} + a^2 v_{nN}) \tag{11}$$

Equation (11) can be further expressed as:

$$v = L\frac{di}{dt} + Ri \tag{12}$$

Where ,
L = Load Inductance,
R = Load Resistance,
i = Load Current

Load current , $i = \frac{2}{3}(i_a + ai_b + a^2 i_c)$ (13)

In equation (11), the fourth term is neglected as:

$$\frac{2}{3}(v_{nN} + av_{nN} + a^2 v_{nN}) = v_{nN}\frac{2}{3}(1 + a + a^2) = 0 \tag{14}$$

E. Discrete Time Model for Predictive Load Current

The discretized forward Euler approximation for load current prediction is written as:

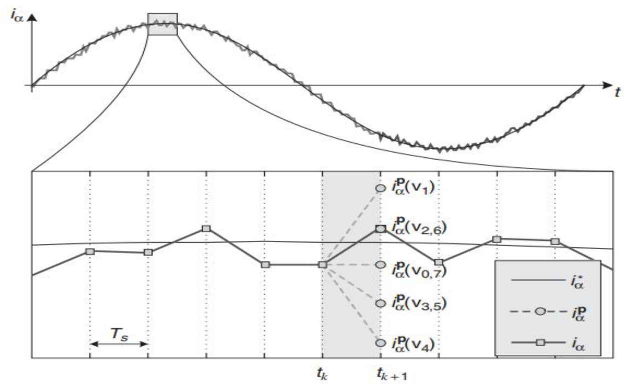
$$\frac{di}{dt} = \frac{i(k+1) - i(k)}{T_s} \tag{15}$$

The predicted load current at sampling instant k+1 can be expressed as below.

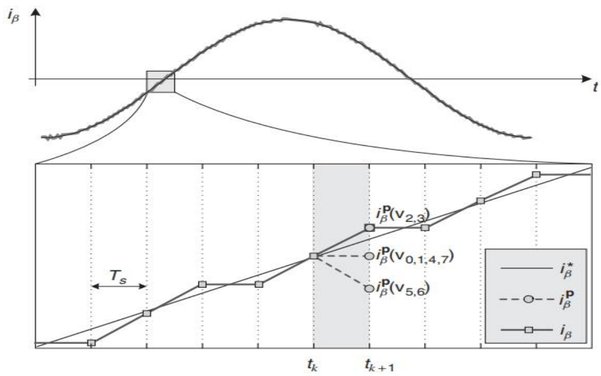
$$i^p(k+1) = \left(1 - \frac{RT_s}{L}\right)i(k) + \frac{T_s}{L}v(k) \tag{16}$$

Where
v(k)=voltage vector generated by inverter

F. Principle of Operation of Predictive Current Control



(a) i_α



(b) i_β

Fig.4

Real & Reactive components of load current corresponds to respective voltage vectors from V_0 or V_7 applied at sampling instant k are depicted in Fig. 4a & 4b respectively. Also we can see that voltage vectors V_2 and V_6 are the vectors those can minimize the error in the real part of load current(i_α) and similarly from Fig.4b, it can be seen that voltage vector V_2 and V_3 can minimize the error in the imaginary part of load current(i_β). Hence by analyzing both the error in real & imaginary part of load current we can predict that, voltage vector V_2 is the one that obtains least value of cost function. Consequently the switching signal corresponds to voltage vector V_2 is applied to the inverter for optimal operation.

G. *Proposed Methodology*

Based upon space vector modulation(SVM), switching states are generated w.r.t corresponding voltage vectors(TABLE.II) and accordingly cost functions [Eq.(5)] are computed for each voltage vectors & the states with least value of cost function is fed to the inverter. PCC scheme is implemented in MATLAB/SIMULINK environment.

IV. Predictive Control Simulation Results

A. *Parameters for the Predictive Control Simulation*

TABLE.III

Parameter	**Value**
Sampling Time(Ts)(in sec)	25e-6
Load Resistance(in ohm)	10
Load Inductance(L)(in Henry)	10e-3
Amplitude of Back-emf(in volt)	100
Back-emf frequency(f_e)(in rad/sec)	2*pi*50
DC Link Voltage(V_{dc})(in volt)	520
Amplitude of reference current(I_ref) (in Amps)	10
Reference frequency(f_ref)(in rad/sec)	2*pi*50

B. *Simulation Results*

The simulation has been carried out with reference to Fig.3 depicted earlier with a discrete update method. Sampling time can be selected according to the need of analysis. Here simulation is done for two cases:

(a) Ts = 25µs

(b) Ts = 100µs.

For each case simulink results are analyzed on the basis of load current and phase voltages of load. Two sampling times are taken for the analysis of ripple in voltage and current waveform.

i. *Current Characteristics*

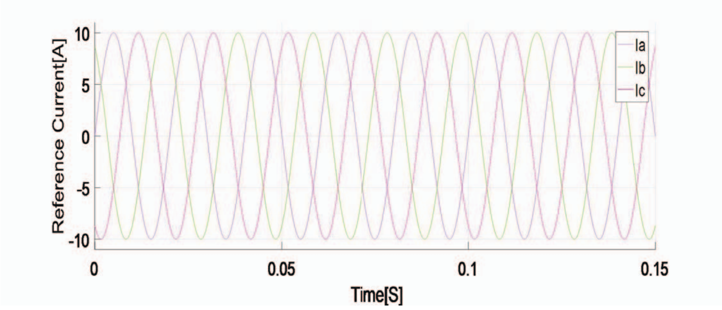


Fig.5 I_{abc} (Reference)

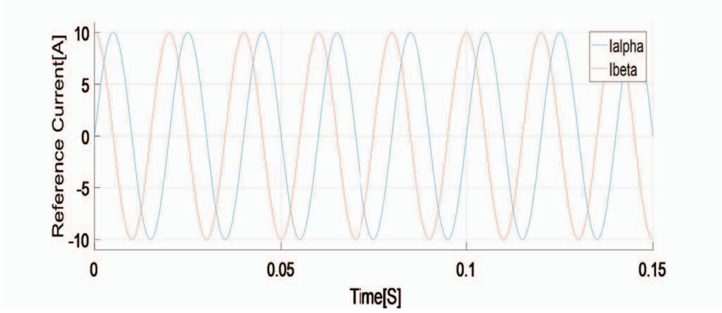


Fig.6 $I_{\alpha\beta}$ (Reference)

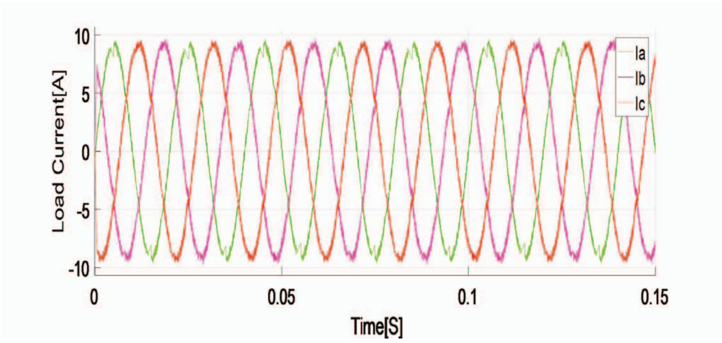


Fig.7 I_{abc} (Load) at T_s=25µs

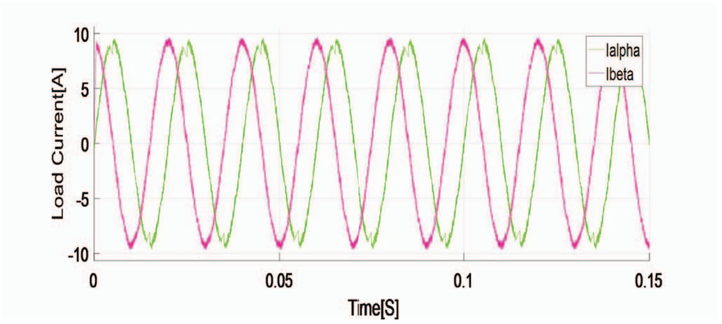


Fig.8 $I_{\alpha\beta}$ (Load) at T_s=25µs

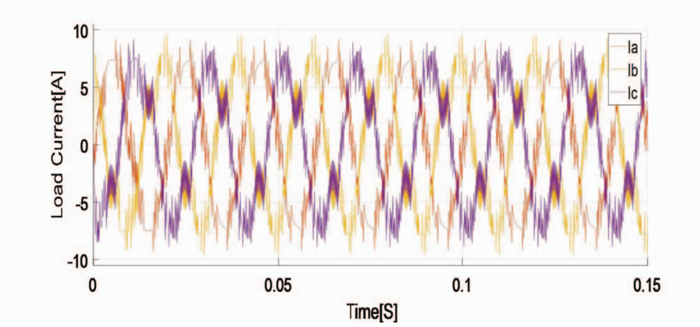


Fig.9 I_{abc} (Load) at T_s=100µs

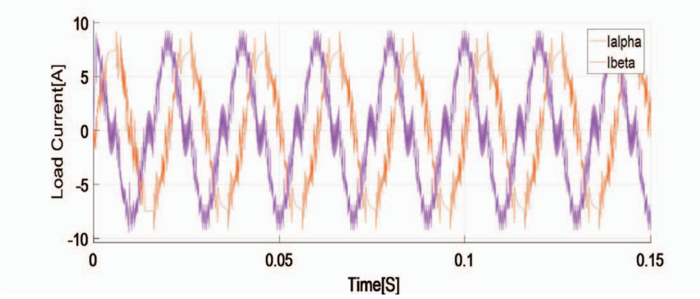


Fig.10 $I_{\alpha\beta}$ (Load) at T_s=100µs

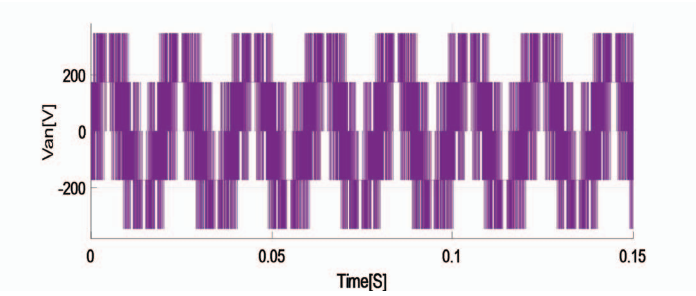
To reduce the number of projections, control can be performed as two-phase complex coordinates (αβ coordinates). Because the measurement of the reference and the load current is a three-phase variable, a coordinate transformation must be applied to each signal. The transformation from *abc* to *αβ* coordinates can be accomplished through the following conversion formula, which can be isolated into its real and imaginary components as follows.

$$i_\alpha = \frac{2}{3}\left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right) \tag{17}$$

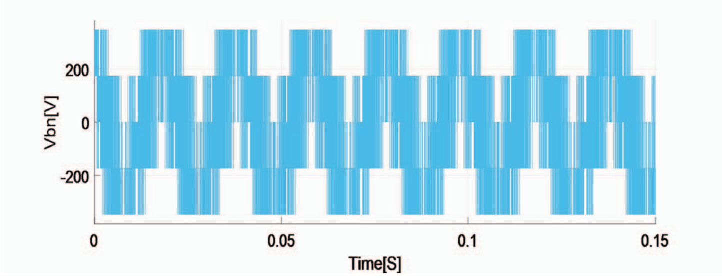
$$i_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c\right) \tag{18}$$

Where i_a, i_b, i_c represent the phase components of current in phase a, b & c respectively. Where, i_α = Real part of current component in αβ coordinates, i_β = Imaginary part of current component in αβ coordinates

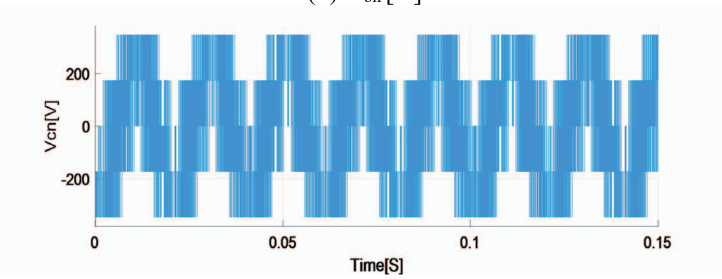
ii. Voltage Characteristics



(a) V_{an} [V]

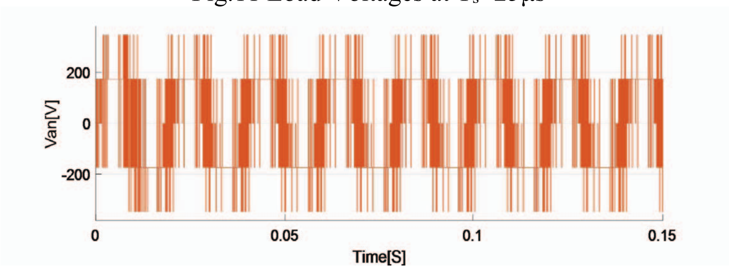


(b) V_{bn} [V]

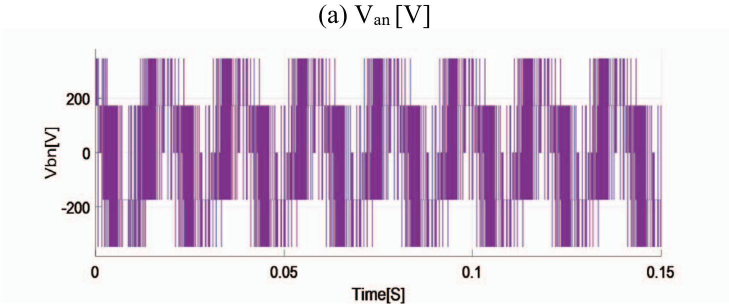


(c) V_{cn} [V]

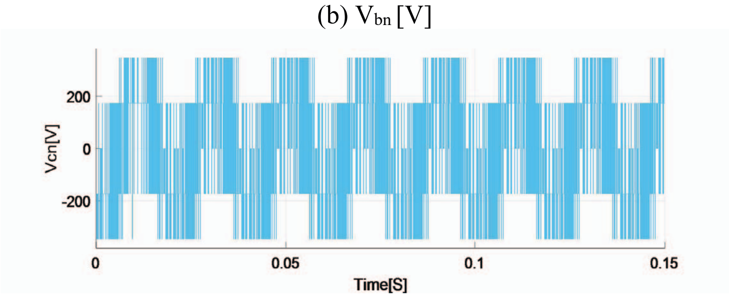
Fig.11 Load Voltages at T_s=25µs



(a) V_{an} [V]



(b) V_{bn} [V]



(c) V_{cn} [V]

Fig.12 Load Voltages at T_s=100µs

From the current & voltage characteristics depicted above the ripple phenomena can be analyzed at both the sampling time of 25µs and 100µs.

V. CONCLUSION

PCC scheme is designed based on discretization of load current, which makes the control system more flexible and optimized certain parameters like switching losses, reactive power control, motor torque control, whereas the linear control techniques(PI.PD,PID) are based on linear modeling. Predictive Current Control technique is superior to linear controller in the sense that, PCC doesn't need any parameter to adjust unlike K_p, K_d & K_i in linear controller. Only a cost function to be defined in PCC. MPC algorithm for three phase inverter for ideal case has been implemented and the optimized voltage vector has been fed to the load connected for optimum operation of the test system. Further study and research can be done on the basis of THD & performance of various optimization techniques along with MPC for system optimum operation.

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