Diode Clamped Multilevel Inverter fed SPMSM

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Abstract: **This paper presents the control of SPMSM drive by using diode clamped three and five level inverters. The pulses are generated using Carrier Based Space Vector Pulse Width Modulation (CBSVPWM). Control technique like Field oriented control used for closed loop operation. Compared to conventional Space Vector Pulse Width Modulation (SVPWM), CBSVPWM is very fast and easy to implement digitally, which also reduces the complexity involved in calculation of angle and sector as in case of conventional SVPWM. It can also be extended to n-level.**

Index Terms: **Diode Clamped Multilevel Inverter (DCMI), Surface Mounted Permanent Magnet Synchronous Motor (SPMSM), Carrier Based SVPWM (CBSVPWM) and Filed Oriented Control (FOC).**

I. INTRODUCTION

Among AC motors the most prominent motor till date is the Induction Motor, however in current generation Permanent Magnet Synchronous Motors are gaining importance due to numerous advantages such as being light weight, gives high performance and have higher efficiency. The PMSM is an energy efficient motor operating at unity power factor. The advanced research in magnetic materials enables high flux densities to PMSM with good power density [1]-[3].

IPMSM and SPMSM are the two classifications of Sine PMSM. If the permanent magnets are buried inside the rotor core then they are treated as IPMSM and if they are buried on the rotor surface they are called as SPMSM. When air-gap torque is considered, IPMSM is better and when speed range is considered for the same voltage, then SPMSM is better. However, if the air gap power is considered, SPMSM is good compared to IPMSM [3]-[6].

The torque speed characteristics of any motor directly depend upon the type of modulation technique used. The modulation technique used in this paper for the analysis of SPMSM is CBSVPWM. This is based on the effective time calculation which is a simple and fast method to reduce the complexity involved in the calculation of angle and sector in case of SVPWM. The output voltage of the inverter is synthesized using effective time, and the gate signals are generated using effective time relocation theorem [7]-[9]. Multilevel inverters are used in wide range for high power and medium power applications. Among multilevel inverters, diode clamped inverters have their enormous advantages for high voltage and power applications [10]-[12]. With respect to the output voltage harmonics three level and five level inverters have significant advantages [13]. As the level increases the output voltage has less harmonics and gives the smooth operation for the SPMSM [14].

PMSM are generally used in application which requires high performance and high efficiency. The high performance of the motor can be obtained if the motor has smooth speed control for the entire range with full torque control even at zero speeds. In order to achieve such type of control, good control method should be used. The best method for PMSM control is the field oriented control. The principle of the FOC is to decompose the stator current into magnetic field component and torque generating component. These two components can be controlled separately like DC motor control. In this paper FOC for three-level and five-level diode clamped inverter is fed to SPMSM drive to analyze its performance using CBSVPWM [15]-[16]. Section II gives the mathematical modeling of SPMSM, Section III-Control methodology, Section IV gives the details of the modulation technique used and Section V gives the working of three and five-level diode clamped inverter.

II. MATHEMATICAL MODELLING OF SPMSM

The PMSM d-q axis voltage representation is shown below [1].

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R+PL_d & -\omega L_q \\ \omega L_d & R+PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\varphi_a \end{bmatrix} \tag{1}$$

Where,

φ_a : Armature flux linkages
i_d, i_q : d-axis & q-axis component currents
V_d, V_q : d-axis and q-axis component voltages
Ld, Lq : d-ais and q-axis component inductances
R: Resistance of the armature
p: angular velocity

Equation (1) into α – β fixed coordinate, equation (2) is derived

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R+PL_\alpha & PL_{\alpha\beta} \\ \omega L_{\alpha\beta} & R+PL_\beta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_{re} K_E \begin{bmatrix} -\sin\theta_{re} \\ \cos\theta_{re} \end{bmatrix} \tag{2}$$

Where, $L_\alpha = L_0 + L_1 \cos 2\theta$ (3)

$$L_\beta = L_0 - L_1 \cos 2\theta \tag{4}$$

$$L_{\alpha\beta} = L_1 \sin 2\theta \tag{5}$$

$$L_0 = \frac{L_d + L_q}{2} \tag{6}$$

$$L_1 = \frac{L_d - L_q}{2} \tag{7}$$

The output torque equation of IPMSM is given by:

$$T = P_n \{\phi_a i_q + (L_d - L_q) i_q i_d\} \tag{8}$$

$$T = P_n \left\{\phi_a i_a \cos\beta + \frac{1}{2}(L_d - L_q) i_q^2 \sin 2\beta\right\} \tag{9}$$

For a surface-mounted PMSM $L_d = L_q$ rotor magnetic linkages is a constant, so the above Eq. (9) becomes

$$T = K_t i_q \tag{10}$$

The motor drive system dynamics is also represented by

$$T_e = T_L + B\omega_m + Jp\omega_m \tag{11}$$

Where T_L and ω_m are load torque and motor speed respectively [1]-[4].

III. CONTROL METHODOLOGY

The main principle of the FOC is to control both the currents i_d and i_q independently to achieve the required torque. With this control maximum torque per ampere ratio for minimizing the current needed for the specific torque can be obtained by which the efficiency of the motor can be increased. FOC for SPMSM can be done equating $L_d = L_q$ which in turn gives Electromagnetic torque alone.
For SPMSM the torque equation is given as:

$$T_e = \frac{3}{2}\frac{p}{2}\left[\lambda_{pm} I_{sq}\right] \tag{12}$$

The maximum efficiency can be obtained by keeping d-axis current zero and the torque producing current is along q-axis.
The reference d and q axis currents for FOC are given as:

$$i_q^* = \frac{T^*}{\frac{3}{2}\frac{p}{2}\lambda_{pm}} \tag{13}$$

$$i_d^* = 0 \tag{14}$$

IV. MODULATION TECHNIQUE

CBSVPWM is a fast and efficient modulation techniques which limits the complexity involved in calculation of sector and the angle as in case of conventional SVPWM. In case of conventional SVPWM it is necessary to calculate the sector and the location of the voltage vector in the sector and also the angle of the space vector. These calculations make the system complicated as the level of the inverter goes on increasing. So, to simplify the analysis, a new technique is introduced called CBSVPWM. It is based on "effective time re-location algorithm" which is simple and easy and can be implemented for n-level inverters digitally. The switching states of the inverter are shown in the Fig. 1. The general formula for calculating the switching times is given as:

$$T_{xs} = \frac{T_s}{V_{dc}} V_{xs}^*, (x = a, b, c) \tag{15}$$

The difference between the maximum and minimum values of the times is called as effective time.

$$T_{eff} = T_{\max} - T_{\min} \tag{16}$$

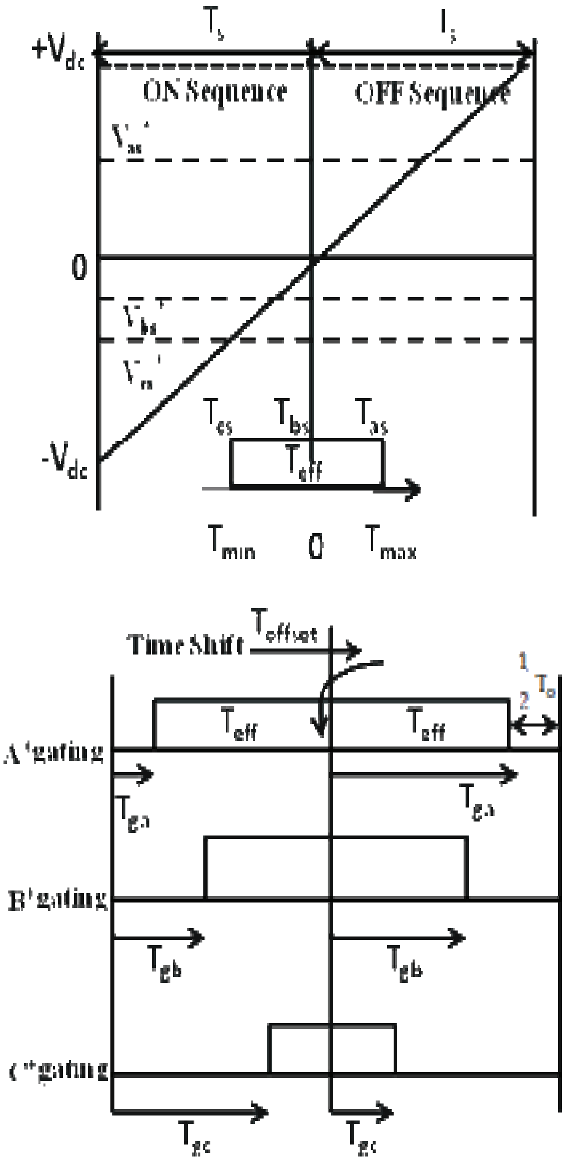

Fig. 1 Actual gating time generation for CBSVPWM

Where
T_{min} is the minimum value of T_{as}, T_{bs}, and T_{cs};
T_{max} is the max value of T_{as}, T_{bs} and T_{cs}.
The gating times can be calculated by adding the T_{offset}, the off-set time value to T_{as}, T_{bs}, and T_{cs}
The actual switching times for the two sampling patterns can be calculates by subtracting the gating times (T_{ga}, T_{gb}, T_{gc}) from the sampling times T_s,

V. THREE AND FIVE LEVEL DIODE CLAMPED INVERTERS

Multilevel inverters are popular for high power applications because as the level of the inverter increases the output voltage harmonics can be reduced to a greater extent, which gives the smooth operation for the motor connected to it. There are three topologies in multilevel inverters, among three diode clamped is the one which is widely used. In this topology for clamping DC bus voltage a diode is used and the output of the inverter is the stepped waveform. For a m-level inverter, the number of switching devices are 2(m-1) and (m-1)*(m-1) clamping diodes with (m-1) DC link capacitors.

The three-phase three-level diode clamped inverter fed to SPMSM is shown in the Fig. 2. It consists of two capacitors to synthesize the DC supply voltage. Every leg contains four switches with four anti-parallel diodes. For positive $V_{dc}/2$ the top two switches of the each leg should be triggered and for the negative $V_{dc}/2$ bottom two switches of the each leg should be triggered. For the zero voltage one switch from top and one switch from bottom should be triggered. The maximum output voltage obtained in this case is half the DC source.

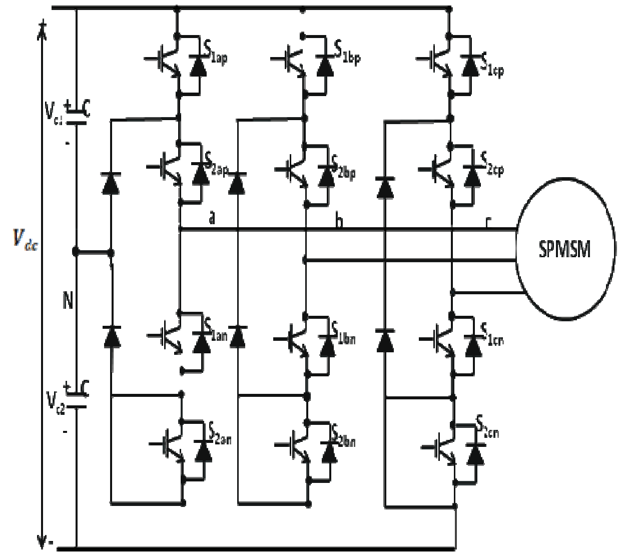

Fig. 2 Three-phae 3-level inverter fed SPMSM

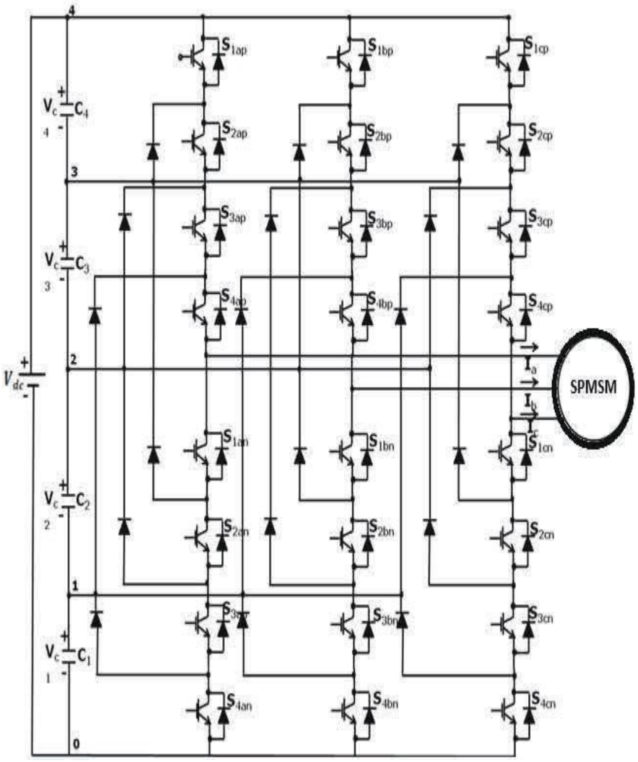

Fig. 3 Three-phase 5-level diode clamped inverter fed SPMSM

The five level diode clamped inverter fed SPMSM is shown in Fig. 3. In this case also one DC source is required and four capacitors are required to split the DC voltage. Each leg contains eight switches with eight ani-parallel diodes. The switching sequence of the five-level inverter can be explained as, to have an output voltage of $V_{dc}/2$ the top four switches from each leg should conduct. To have an output voltage of $V_{dc}/4$ the three switches from top and one switch from bottom should conduct. Also to have an output voltage of $-V_{dc}/2$, the bottom four switches should conduct at a time and to have an output voltage of $-V_{dc}/4$ one switch from top and three switches from bottom should conduct. To have a zero output voltage two switches from top and two switches from bottom should conduct. The anti-parallel diodes help us in clamping the DC voltages and to synthesize the output voltage into 5 levels. The output of the inverter with 5-level is given to the Surface Mounted SPMSM for the analysis. There are 27 switching states in 5-level inverter. The complexity increases if the SVPWM modulation is used. For this purpose CBSVPWM is used as the modulation techniques and the generated pulses are given to the switches. In this method there is no need to identify the sector and the angle of the voltage vector as in case of SVPWM. So, as the level of the inverter increase to get the smooth output waveform, the simple and easy modulation technique such as CBSVPWM is used. This modulation technique gives the same quality of the inverter output voltage as one get from the SVPWM technique.

VI. RESULTS OF DCML INVERTER FED SPMSM

The analysis of the SPMSM drive is done using MATLAB SIMULINK. The control diagram is as shown in the Fig. 4. The modulation technique used to generate the pulses for the inverter is the CBSVPWM and for closed loop control of the drive Field Oriented Control is used. The output speed, torque, line currents, three-phase currents, line voltages of the 3-level and 5-level inverter has plotted. Performance characteristics comparison is done between the 3-level and 5-level inverter fed to SPMSM drive. The drive is subjected to different loads and the change in the speed response is studied in both the cases. Fig. 5(a) & (b) shows the speed responses of the 3-level & 5-level inverter fed to SPMSM drive. Fig. 6. (a) & (b) shows the torque responses of the 3-level and 5-level inverter fed to SPMSM drive. Fig. 7(a) & (b) shows the SPMSM line current response when fed to 3-level & 5-level inverter. Fig 8 (a) & (b) shows the three-phase currents of the SPMSM drive when fed to 3-level and 5-level inverters. Fig. 9 (a) & (b) shows the 3-level and 5-level inverter output voltage waveforms. The parameters used in simulation while designing the SPMSM are

The d- axis Inductance is L_d=0.0058 Henry;
The q-axis Inductance is Lq=0.0058Henry;
The resistance value is 1.4 ohm and
The permanent magnet flux is 0.1546 webers.
The no. of poles is 6;
The value of F= 0.000038818.The value of J = 0.00176;

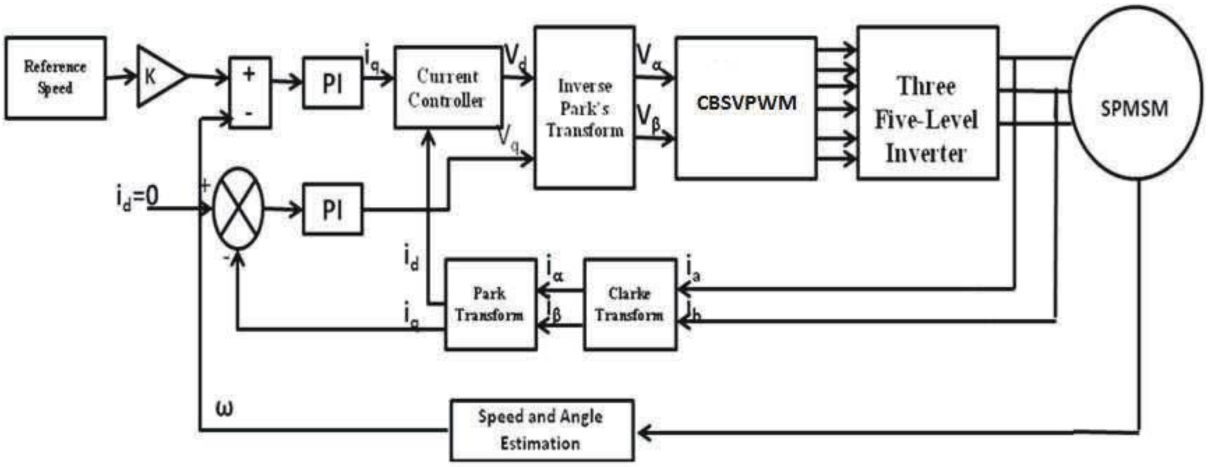

Fig.4. FOC of SPMSM using Diode Clamped Multilevel Inverter with CBSVPWM

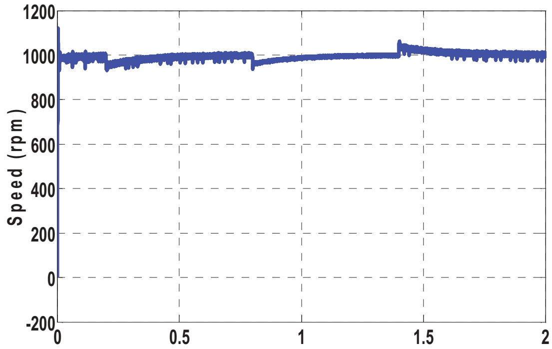

Fig.5.(a). Speed response of three-level DCI fed SPMSM drive

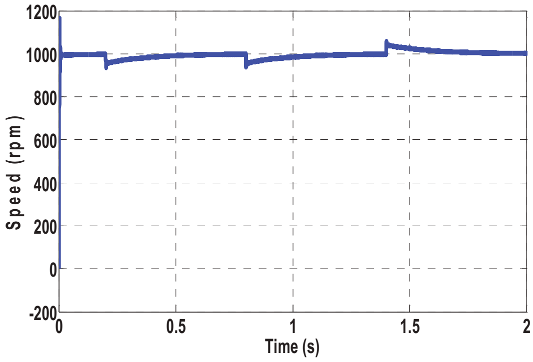

Fig.5.(b). Speed response of five-level DCI fed SPMSM drive

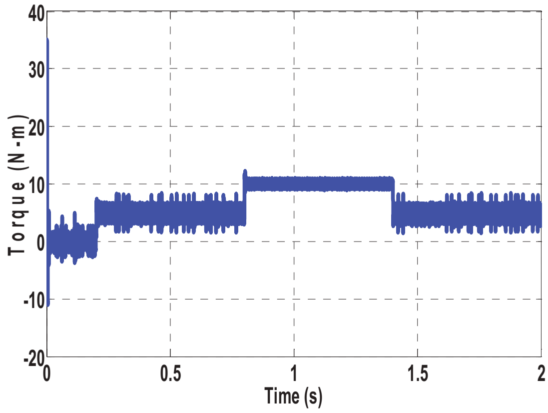

Fig.6.(a). Torque response of three-level DCI fed SPMSM drive

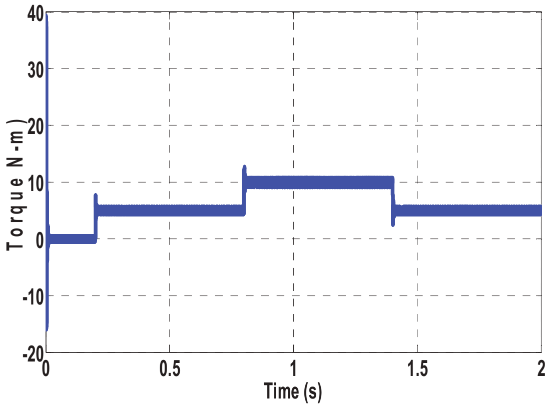

Fig.6.(b). Torque response of five-level DCI fed SPMSM drive

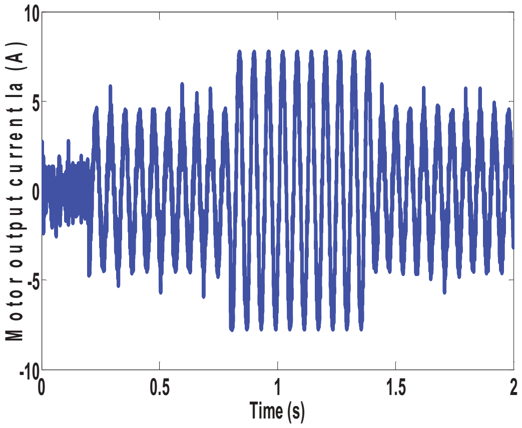

Fig.7. (a). Line current response of three-level DCI fed SPMSM

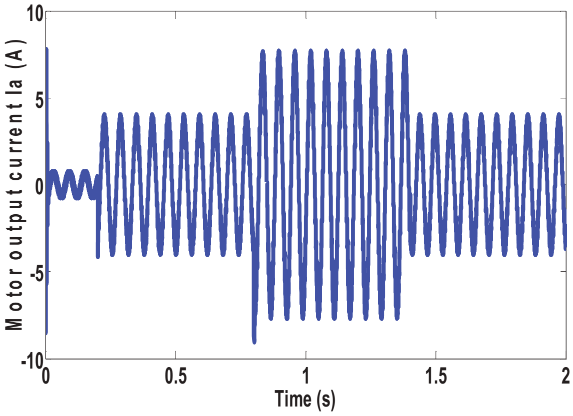

Fig.7. (b). Line Current response of five-level DCI fed SPMSM

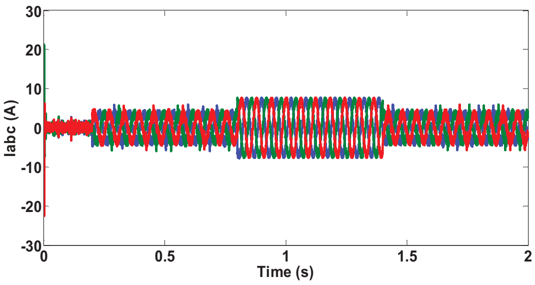

Fig.8. (a). 3-Φ current responses of three-level DCI fed SPMSM

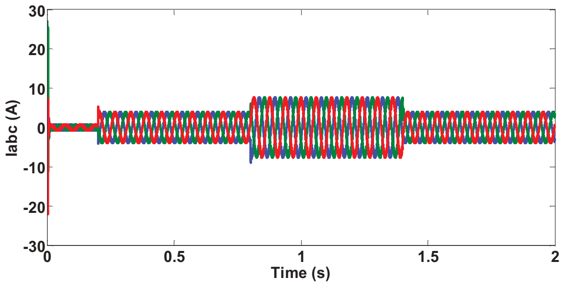

Fig.8. (b). 3-Φ current responses of five-level DCI fed SPMSM

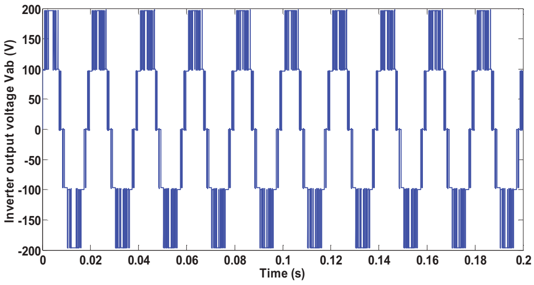

Fig.9.(a) Output voltage response of three level DCI fed SPMSM

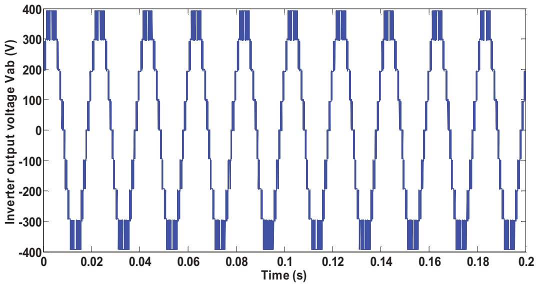

Fig.9.(b) Output voltage response of five-level DCI fed SPMSM

VII. CONCLUSIONS

In this paper, the analysis is done with 3-level and 5-level diode clamped inverter fed to SPMSM drive. The modulation technique use is CBSVPWM and the control technique is FOC. The inverter output is fed to the SPMSM drive and the speed-torque characteristics of the motor are studied at different load conditions. The load torque is changed to 5Nm, 10Nm & again 5Nm at 0.2, 0.8 and 1.2 secs. It has been observed that the change in speed at different loads is very less and remains almost constant and the response settles very fast in case of five-level inverter. The motor characteristics are very smooth and the speed changes with respect to the load changes are very fast as the level of the inverter increases. The modulation technique CBSVPWM is very fast and easy to implement digitally which can be extended to n-level.

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