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Control of IPMSM with Two-level Diode Clamped Inverter for Electric Traction

G Sree Lakshmi, K Navya

Abstract— This paper presents the simulation and analysis of Field Oriented Control (FOC) of two-level diode-clamped inverter fed Interior Permanent Magnet Synchronous Motor (IPMSM) Drive for Electric Traction (ET) Application using various Modulation Techniques. The Electric Traction drives require high voltage operation which can be achieved by using Multilevel Inverters. By using series of power semiconductor switches with several low voltage DC sources one can achieve higher power output by synthesizing a staircase voltage waveform, which can be efficiently applied for Traction Drives. The output voltage is smoother and also eliminates the need of transformer in Electric Traction. The modulation techniques used are Sine Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) and Carrier Based Space Vector Pulse Width Modulation (CBSVPWM). An efficient and fast controller such as FOC is used to control torque of an IPMSM drive. The performance analysis of IPMSM drive for Electric Traction is analyzed with three different modulation techniques for different load variations.

Index Terms— Diode Clamped Inverter (DCI), Interior Permanent Magnet Synchronous Motor (IPMSM), Field Oriented Control (FOC), Electric Traction (ET), Sine Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), Carrier Based Space Vector Pulse Width Modulation (CBSVPWM).

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1 INTRODUCTION

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INDUSTRIAL application requires high power apparatus, for these reasons a series of power semiconductor switches with several lower voltage DC sources are used to produce higher power levels by synthesize a staircase voltage waveform. For multiple voltage sources capacitors, batteries and renewable energy voltage sources can be used. The concept of multilevel converters had come in to existence in the year 1975 [1],[2]. The multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Electric Traction Drives requires medium voltage and high power operation. In general, an electric traction transformer steps down the high catenary voltages 25 kV, 50Hz to low voltage 440 V, 50 Hz. Now, this can be obtained with the help of multilevel inverter, which eliminates the need of the transformer. As this bulky transformer reduces efficiency, increases weight, and cost. Multilevel inverters inturn reduces the Total Harmonic Distortion (THD) as the level of the inverter increase.

There are three types of multilevel inverters: Diode Clamped Multilevel Inverter (DCML) which came into existence in 1979 [3],[4],[5], Flying Capacitor Multilevel Inverter (FCML) came into existence in 1992 [6], and the third one Cascaded Multilevel Inverter (CML) came into existence in 1995 [7].

Each type of the inverter has its own advantages and disadvantages, depending upon the application one can use the required type. There are various modulation techniques available for the multilevel inverters [8]. Some of the important highs switching frequency modulation techniques are SPWM, SVPWM and CBSVPWM [9],[10].

Generally among AC machines, Induction Motors and Synchronous Machines are used for Electric Traction[11]. Permanent Magnet Synchronous Machines are most favorable due to its high efficiency, less weight and high power density when compared to induction machines. PMSM are designed to operate not only in the constant torque mode when their speeds are below the base speed but also in the constant power mode when the speeds are above the base speed. PMSM are classified into two types, Interior PMSM and Surface Mounted PMSM. IPMSM are newly developed motors with high torque density, high efficiency and additionally provide field weakening operation, which is impossible with the SPMSM. To improve the efficiency and performance of the drive, IPMSM are preferred in the Electric Traction applications because they have the advantage of providing position control loop with accuracy, without shaft encoder as in case of Induction Motors [12],[13],[14]. The most important and efficient method to control IPMSM is vector control method, which is divided into two types. Field Oriented Control (FOC) and Direct Torque Control (DTC). In FOC, the objective is to control the current vector and in DTC the objective is to control the torque producing flux vector. The constant torque operation can be obtained by conventional vector control. However, when the speed is above the base speed, the back EMF of PM motor is larger than the line voltage and then the motor suffers from the difficulty to continuously produce torque due to voltage and current constraints. This problem can be overcome with the help of flux-weakening technology, in which the operating speed range can

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be extended by applying negative magnetizing current component to weaken the air gap flux [15]. In this paper simulation analysis of field oriented control of two-level diode clamped inverter fed IPMSM drive using different modulation techniques for Electric Traction is done.

2 INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

The dynamic model of the permanent magnet synchronous machine (PMSM) is derived using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with only one set of two windings on the stator. The rotor has no windings, only magnets. The flux linkages of the stator q and d windings are derived from first principles. The physical modeling of the machine is developed from which the circuit model is derived.

The d- and q-axes stator voltages are derived as

$$V_{QS} = R_Q I_{QS} + P\lambda_{QS} \tag{1}$$

$$V_{DS} = R_D I_{DS} + P\lambda_{DS} \tag{2}$$

Where

P is the differential operator, d/dt

V_{QS} and V_{DS} are the voltages in the q- and d-axes windings

I_{QS} and I_{DS} are the q- and d-axes stator currents

R_Q and R_D are the stator q- and d-axes resistances

λ_{QS} and λ_{DS} are the stator q- and d-axes stator flux linkages

The dynamic equations of the PMSM can be written as

$$V = [R]I + [L]PL + [G]\omega_R I \tag{3}$$

The instantaneous input power is given by

$$P_I = I^T V = I^T[R]I + I^T[L]PI + I^T[G]\omega_R I \tag{4}$$

The air gap torque, T_e is derived from the terms involving the rotor speed, ω_m in mechanical rad/s, as

$$\omega_m T_e = P_a = I^T[G]I * \omega_R = I^T[G]I \frac{P}{2}\omega_m \tag{5}$$

Where P is the number of poles. Simplifying this we get the electromagnetic torque equation as

$$T_e = \frac{P}{2} I^T[G]I \tag{6}$$

Where the value of

$$I^T[G]I = \left[\lambda_{AF} + \left(L_D - L_Q\right)I_{DS}^R\right]I_{QS}^R \tag{7}$$

Therefore, the electromagnetic torque is obtained as

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{AF} + \left(L_D - L_Q\right)I_{DS}^R\right]I_{QS}^R(N - m) \tag{8}$$

$$P_I = \frac{3}{2}\left[V_{QS}^R I_{QS}^R + V_{DS}^R I_{DS}^R\right] \tag{9}$$

3 TWO LEVEL DIODE CLAMPED INVERTER

The main aim of the power electronic experts is to study about converters to increase power rating by increasing either voltage or current rating. Current source inverters play a main role in increasing the current magnitude. However, present research is going on to increase the voltage magnitude instead of current. To achieve these new converter topologies were developed.

In two-level inverter we get two different output voltage levels for the load $+V_{dc}/2$ or $-V_{dc}/2$ when the inverter is fed with V_{dc}. The three-phase two-level diode-clamped inverter fed IPMSM is shown in Fig. 1. The main difference between two-level and three-level diode clamped inverter exist with respect to the clamping diodes D_{1a} and D_{2a}. These two diodes clamp the switching voltage to half the level of the DC-bus voltage. The diode-clamped inverter produces (N-1)/2 levels above and below the zero level. If one has a chain of N-1 switches then there will be N-2 connections in between the switches. To these connection points the diode chains are being connected. Each diode chain has to bear the total capacitor voltage. There are six power switches in a two-level diode clamped inverter. When the pulses are given to the switches they conduct accordingly. When the positive switch is ON it gives $+V_{dc}/2$ voltage, during this period lower switch will be in OFF position and vice-versa. Therefore, by proper switching the power switches of three-phases we can get the output voltage. It is always ensured that the devices connected in series pairs S_1+S_4, S_3+S_6 and S_5+S_2, should never turn on at the same time. If they were turned on simultaneously, it would cause a hard short circuit of input levels, which would damage all the devices.

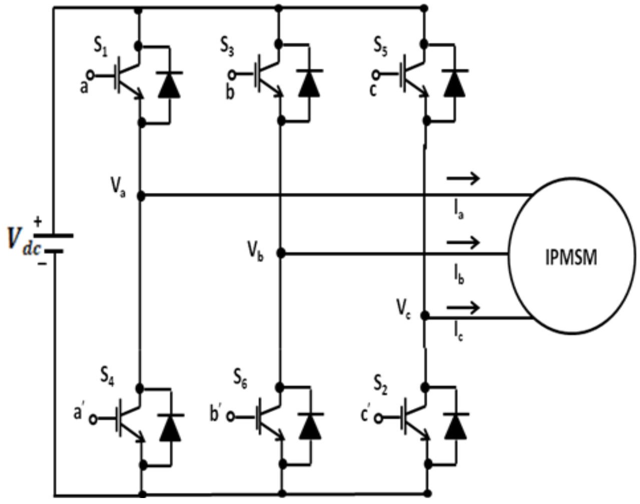

Fig.1. Two-level diode clamped inverter

4 MODULATION TECHNIQUES

4.1 Sine Pulse Width Modulation

Pulse width modulation technique was first proposed by Schonung and Stemmler in 1964. It is a simple method and used in many applications. Pulse width modulation is the process of modifying the width of the pulses by using a

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control signal; greater the control voltage, wider the width of the pulses generated. The sinusoidal of the desired frequency or at the fundamental frequency is used as the control voltage for a PWM circuit. The fundamental frequency of the output voltage waveform is the same as the frequency of the input control voltage.

By varying the duty ratio of the pulsating waveform, the switching operation of the switches is possible. The longer the pulse is closed compared to the opened periods, the higher the power supplied to the load is. The change of state between closing (ON) and opening (OFF) is rapid, so that the average power dissipation is very low compared to the power being delivered.

The advantages of PWM technique are:

- The output voltage control can be obtained without any additional components.
- Lower order harmonics can be eliminated.

The sinusoidal PWM implementation can be done using a triangular carrier signal with frequency f_c trying to modulate a reference signal with lower frequency f_s.

4.2 Space Vector Pulse Width Modulation

The best modulation technique for a multilevel inverter is SVPWM technique. The basic principle of SVPWM technique is, synthesizing the reference voltage vector by time averaging of the three nearest vector produced by the inverter. The reference voltage vector is the required command voltage which should be given to the application as required. SVPWM technique is based on the approximation of a rotating reference voltage space vector.

The advantages of SVPWM technique are:

- SVPWM technique produces lesser harmonics.
- The switching losses with SVPWM are reduced.
- The output crest voltage with SVPWM is increased by 1.115 times.
- This method gives higher torque and higher efficiency for the motors when the inverter is used for the drives.
- It gives 15% better utilization of the DC bus voltage. It also reduces the switching as well as the commutation losses.
- It gives the maximum output voltage at the rated frequency.
- On the whole it improves the inverter efficiency.

The maximum phase-to-center voltage by SPWM and SVPWM are respectively;

$$V_{max} = V_{dc}/2\text{: Sinusoidal PWM} \qquad (10)$$

$$V_{max} = V_{dc}/\surd 3\text{: Space Vector PWM} \qquad (11)$$

Where, V_{dc} is DC-Link voltage.

This means that Space Vector PWM can produce about 15 percent higher than Sinusoidal PWM in output voltage.

Algorithm for the SVPWM Technique

The different steps in the algorithm are:

- Transformation of 3-phase system to 2-phase system.
- Space vector voltage calculation.
- Finding the three nearest vectors.
- Dwelling times for the three nearest vectors.
- Switching instant times determination.
- Pulses to the inverter devices.

4.3 Carrier Based Space Vector Pulse Width Modulation

Carrier based space vector pulse width modulation is a novel voltage modulation technique called as 'unified voltage modulation' which is based on effective time concept. In this modulation the task is greatly simplified since the inverter output voltage is directly synthesized by the effective times. The effective voltage is applied to the load side, when the each phase switching states changes from 0 to 1 at different time during one sampling interval. Let T_s denotes the total sampling time and T_{eff} is the effective time which is the difference between two switching time T_{as}, T_{bs}. When T_{bs} is greater than T_{as}, then T_{eff} have negative value and a negative voltage is applied to load side. For one leg operation the relation between voltage and times is give as

$$V_{as}:V_{dc} = T_{as}:T_s \qquad (12)$$

From the above relation

$$T_{as} = \frac{T_s}{V_{dc}} * V_{as} \qquad (13)$$

Where, V_{as} is the equivalent phase-A voltage for the load side. This switching time can be negative as long as negative phase voltage is commanded. These times are known as imaginary switching times and the effective time can be obtained from the different values of each imaginary switching times.

$$T_{eff} = T_{as} - T_{bs} = \frac{T_S}{V_{dc}}\left(V_{as} - V_{bs}\right) \qquad (14)$$

The reference waveforms can be generated by adding a continuously varying offset voltage to the set of three phase voltage references which centers their envelope around zero at all times. The common offset voltage is given as

$$V_{off} = \frac{\max\left(V_{as}^* V_{bs}^* V_{cs}^*\right) + \min\left(V_{as}^* V_{bs}^* V_{cs}^*\right)}{2} \qquad (15)$$

An additional common mode voltage which correctly positions the first and last switching transitions in each switching period can be given as

$$V_{off} = \frac{V_{dc}}{N-1} - \frac{\max\left(V_{as}^*, V_{bs}^*, V_{cs}^*\right) + \min\left(V_{as}^*, V_{bs}^*, V_{cs}^*\right)}{2} \qquad (16)$$

Now, the effective time can be defined as the time duration between the minimum and the maximum value of three imaginary times, as given by

$$T_{eff} = T_{max} - T_{min} \qquad (17)$$

Where

$$T_{min} = \min\left(T_{as}, T_{bs}, T_{cs}\right) \qquad (18)$$

$$T_{max} = \max\left(T_{as}, T_{bs}, T_{cs}\right) \qquad (19)$$

When the actual gating signals for power devices are generated in the PWM algorithm, there is one degree of freedom by which the effective time can be relocated anywhere within the sampling interval. Therefore, a time-shifting operation will be applied to the imaginary switching times to generate the actual gating times (T_{ga},T_{gb},T_{gc}) for each inverter arm. This task is accomplished by adding the same value to the imaginary times as follows:

$$T_{ga} = T_{as} + T_{offset} \qquad (20)$$

$$T_{gb} = T_{bs} + T_{offset} \qquad (21)$$

$$T_{gc} = T_{cs} + T_{offset} \qquad (22)$$

Where, T_{offset} is the 'offset time'. This gating time determination task is only performed for the sampling interval in which all of the switching states of each arm go to 0 from 1. This interval is called the "OFF sequence". In the other sequence, it is called the "ON sequence".

In order to generate a symmetrical switching pulse pattern within two sampling intervals, the actual switching time will be replaced by the subtraction value, with sampling time as follows:

$T_{ga}=T_s-T_{ga}$ (23)

$T_{gb}=T_s-T_{gb}$ (24)

$T_{gc}=T_s-T_{gc}$ (25)

5 FIELD ORIENTED CONTROL

The objective of the Field Oriented Control is to control the direct and quadrature axis current i_d and i_q to achieve required torque. By controlling i_d and i_q independently we can achieve a Maximum Torque per Ampere ratio to minimize the current needed for a specific torque, which increases the motor efficiency. For a non-salient machine, control technique can be easily implemented because $L_d=L_q$ and produces only one torque called electromechanical torque.

For non-salient pole machine the torque equation is given by:

$$T_e = \frac{3}{2}\frac{p}{2}\left[\lambda_{pm} I_{sq}\right] \tag{26}$$

From the above equation the torque producing current is along the quadrature-axis. To reach maximum efficiency, the torque per ampere relationship should be maximum. This can be easily obtained by keeping the direct-axis current to zero at all times.

For salient pole machine the direct and quadrature axis inductances are unequal and for the steady state operation the torque equation is given as:

$$T_e = \frac{3}{2}\frac{p}{2}\left[\lambda_{pm} I_{sq} - \left(L_q - L_d\right) I_{sd} I_{sq}\right] \tag{27}$$

From the above equation there are two terms affecting the torque production, the electromechanical torque

$$T_{EM} = \frac{3}{2}\frac{p}{2}\left[\lambda_{pm} I_{sq}\right] \tag{28}$$

And the reluctance torque:

$$T_{RE} = \frac{3}{2}\frac{p}{2}\left[\left(L_q - L_d\right) I_{sd} I_{sq}\right] \tag{29}$$

6 ELECTRIC TRACTION REQUIREMENTS

Electric traction system should able to fulfill high dynamic requirements, assuring the functionality of the electric vehicle in the whole speed operating range and power demand under different environmental conditions. The torque-speed characteristics of an electric traction machine define its operating area. Fig.2. shows the different operating area for electric traction of PMSM. The first part corresponds to the "Constant Torque" zone, here the torque remains constant and the voltage increases with the speed. When the speed reaches the base speed, the machine operates in the second area called "Constant-Power" zone or field-weakening zone. In this area the stator voltage cannot longer be increase due to the voltage supply limitation, so remains constant to its maximum value. For electric traction application where voltage supplies is limited by the catenary, and the operation speed is large, this zone acquires an important relevance.

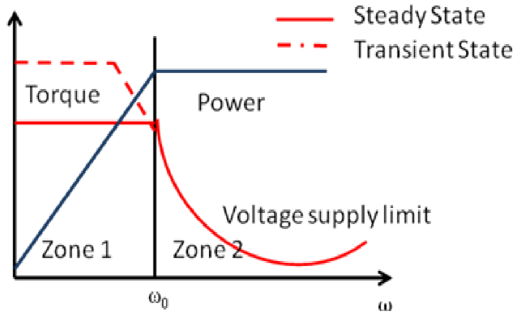

Fig. 2. Speed-Torque characteristics of a PMSM Machine

In field-weakening zone, the power is maintained constant by decreasing the I_q current which is nothing but torque. For IPMSM control, the control strategy has to take into account the requirements of the electric traction requirements and limits; mechanical, electrical, signaling or quality constraints. The control algorithm must be designed in order to provide the required high- dynamic response, minimizing the steady state errors by assuring the stability and robustness of the system against motor parameter variations optimizing the harmonic content of the generated signals by reducing the switching frequency in high power inverters.

7 SIMULATION RESULTS

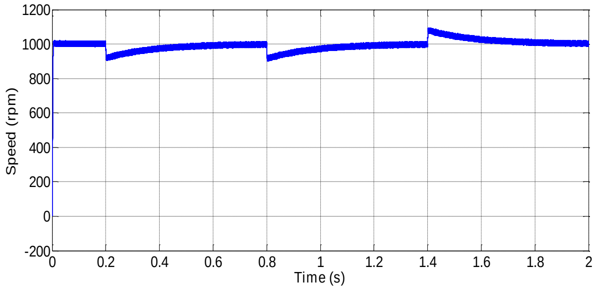

Fig. 3 (a). Speed response of a Two-level inverter fed IPMSM using SPWM

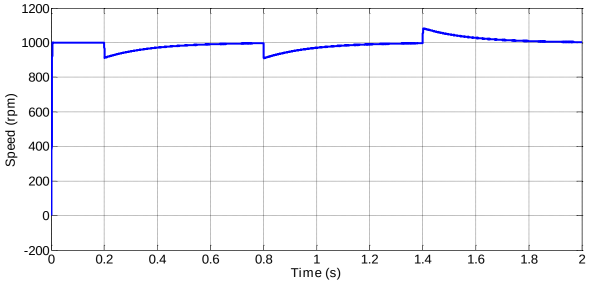

Fig. 3. (b) Speed response of a Two-level inverter fed IPMSM using SVPWM

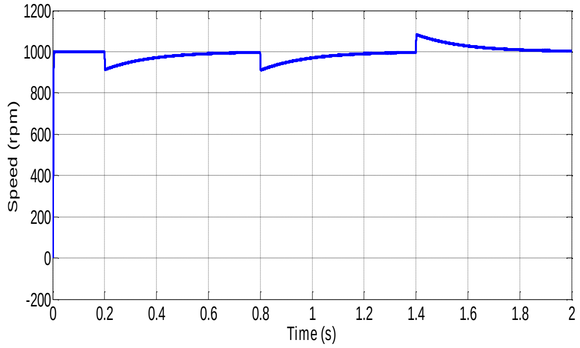

Fig. 3. (c) Speed response of a Two-level inverter fed IPMSM using CBSVPWM

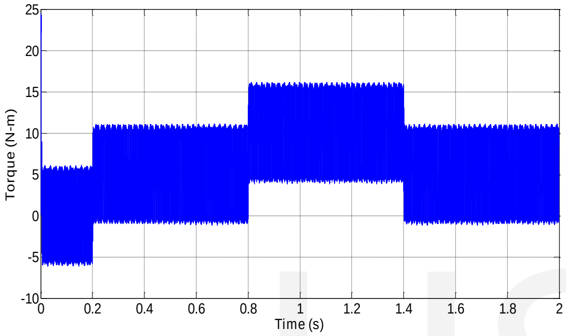

Fig. 4. (a) Torque response of a Two-level inverter fed IPMSM using SPWM

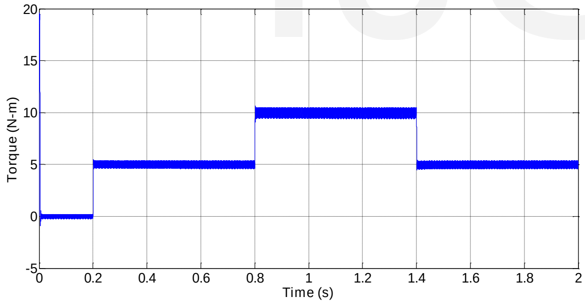

Fig. 4. (b) Torque response of a Two-level inverter fed IPMSM using SVPWM

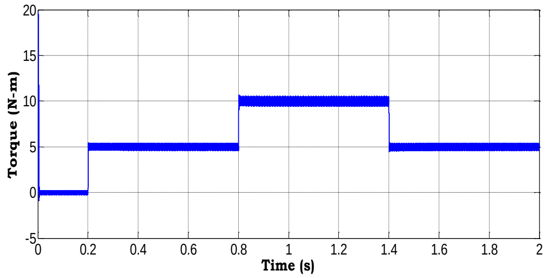

Fig. 4. (c) Torque response of a Two-level inverter fed IPMSM using CBSVPWM

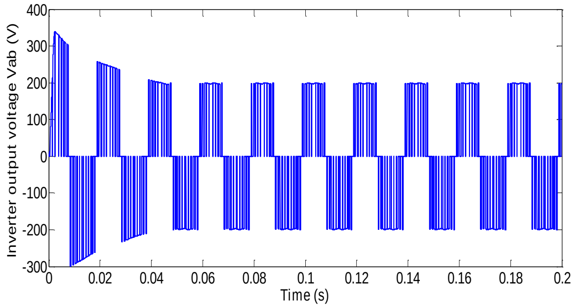

Fig. 5. (a) Output voltage response of a Two-level inverter using SPWM

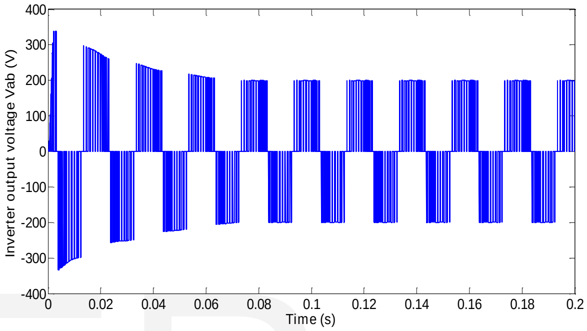

Fig. 5. (b) Output voltage response of a Two-level inverter using SVPWM

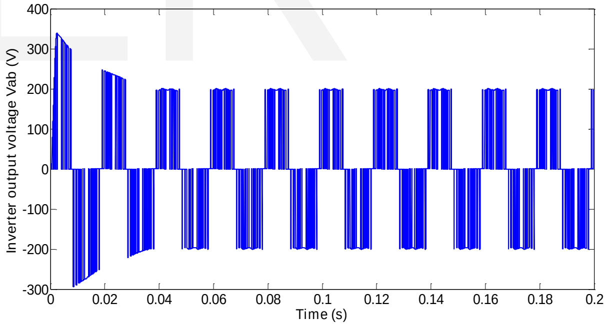

Fig. 5. (c) Output voltage response of a Two-level inverter using CBSPWM

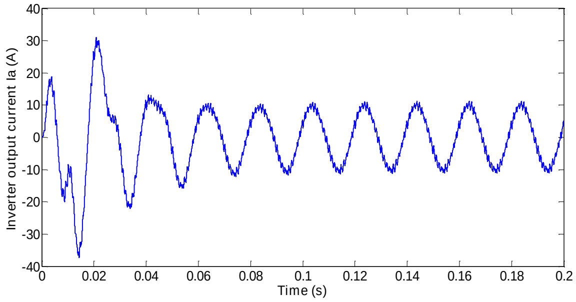

Fig. 6. (a) Output current response of a Two-level inverter using SPWM

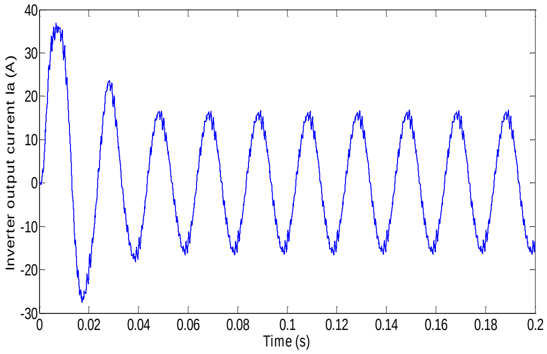

Fig. 6. (b) Output current response of a Two-level inverter using SVPWM

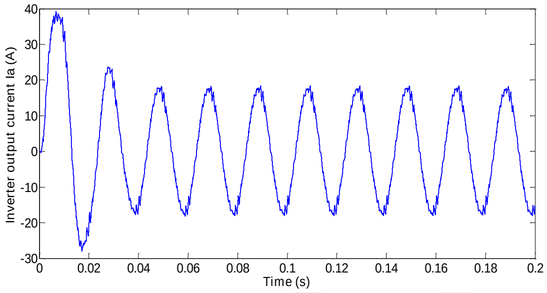

Fig. 6. (c) Output current response of a Two-level inverter using CBSVPWM

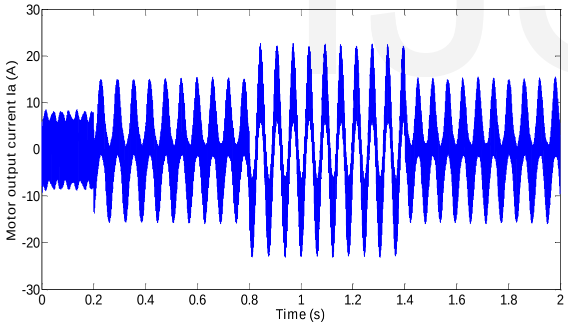

Fig. 7. (a) Motor output current response of a Two-level inverter fed IPMSM using SPWM

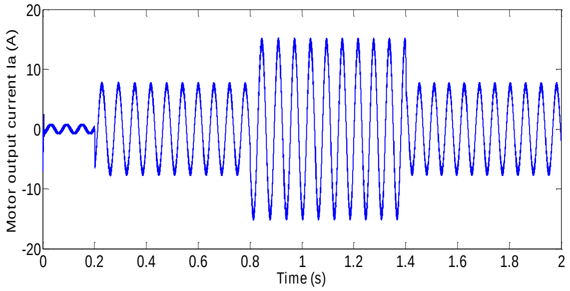

Fig. 7. (b) Motor output current response of a Two-level inverter fed IPMSM using SVPWM

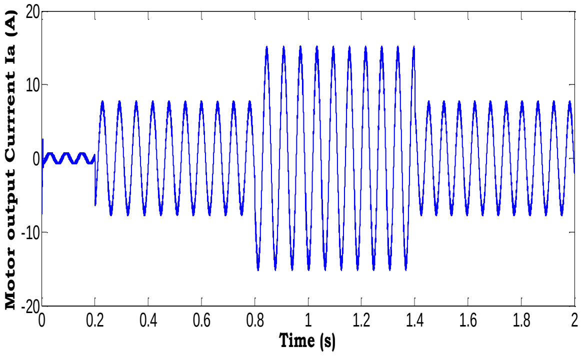

Fig. 7. (c) Motor output current response of a Two-level inverter fed IPMSM using CBSVPWM

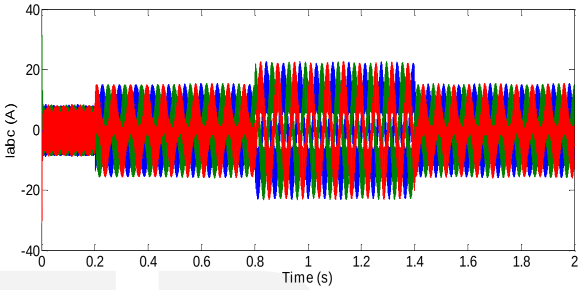

Fig. 8. (a) Three-phase currents of a Two-level inverter fed IPMSM using SPWM

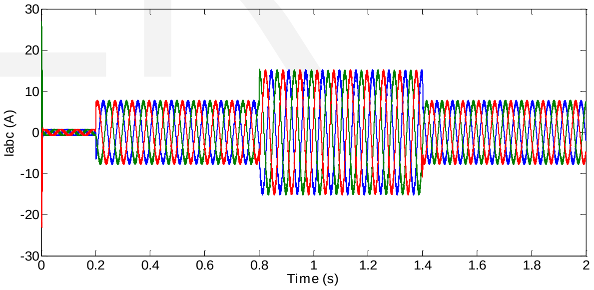

Fig. 8. (b) Three-phase currents of a Two-level inverter fed IPMSM using SVPWM

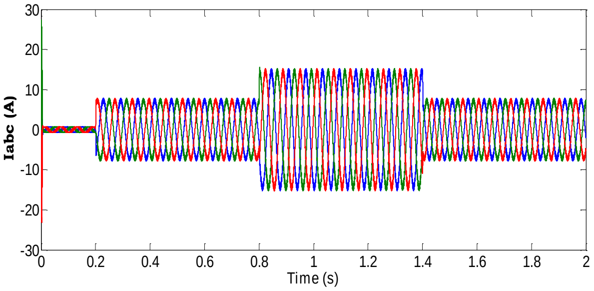

Fig. 8. (c) Three-phase currents of a Two-level inverter fed IPMSM using CBSVPWM

In the above results, Fig. 3(a), 3(b), 3(c) shows the speed response of the FOC of Two-level Inverter fed IPMSM using SPWM, SVPWM and CBSVPWM. The Synchronous speed of PMSM will be 1000RPM if the number of poles considered is p=6. Therefore the reference speed is given as 1000RPM. Synchronous motor runs at synchronous speed in its load range. To analyze the speed response of the IPMSM at different load conditions, three load changes were considered. Motor is started at ‘No load’ and at a particular time t=0.2 seconds, a load which demands a Torque of 5N-m is applied. Similarly at a time t=0.8 seconds, an additional load which demands a Torque of 5N-m is applied and the total torque demand is 10N-m. At a time 1.4 seconds the load is again reduced to 5N-m. There is a slight transient change in speed due to the change in load, but the speed of the motor reach synchronous speed within 0.25 seconds. Fig. 4(a), 4(b), 4(c) shows the torque response of IPMSM using SPWM, SVPWM and CBSVPWM. In the torque response of all the three modulation techniques, SPWM is more pulsating compared to SVPWM and CBSVPWM. The higher ripples of ±5N-m in case of SPWM technique is mainly due to the presence of harmonic voltages provided to the motor terminals. In SVPWM and CBSVPWM a torque ripples of ±2N-m was observed. Fig. 5(a), 5(b), 5(c) shows the output voltage response of the two-level inverter with SPWM, SVPWM and CBSVPWM. Fig. 6(a), 6(b), 6(c) shows the output line current response of the two-level inverter with SPWM, SVPWM and CBSVPWM. Fig. 7(a), 7(b), 7(c) shows the motor ouput current of the two-level inverter fed IPMSM with SPWM, SVPWM, and CBSVPWM. Fig. 8(a), 8(b), 8(c) shows the three-phase currents of the two-level inverter fed IPMSM with SPWM, SVPWM and CBSVPWM. From the speed and torque characteristics it is observed that, the speed of the motor is almost constant with different loaded conditions, therefore this property of IPMSM making us to use for Electric Traction application.

8 CONCLUSION

The simulation and analysis of a Two-level Diode-clamped inverter has been carried out and studied with different modulation techniques. FOC is applied for closed loop analysis. The output of the two-level inverter is fed to both IPMSM drive. The torque, speed and output current response characteristics of IPMSM were analyzed. The FFT analysis is carried out with three modulation techniques such as SPWM, SVPWM and CBSVPWM. Though two-level diode-clamped inverter is an effective topology, it creates harmonic distortions in the output voltage, EMI and high dv/dt which limits high power and high voltage applications. It also limits the operation at higher frequency due to switching losses and constraints of device ratings. However, implementation of the hardware is easy with two-level inverter compared to three-level inverter. This makes one to analyze the performance analysis using two-level inverter for IPMSM drive for Electric Traction Application. Also, it is observed that SPWM technique produces more harmonic content in output voltage and current of the inverter compared to SVPWM and CBSVPWM techniques. Therefore, CBSVPWM modulation technique gives smooth operation of IPMSM drive for Electric Traction Application.

REFERENCES

[1] R. H. Baker and L. H. Bannister, “Electric Power Converters,” U. S. Patent 3 867 643, Feb. 1975.

[2] Jose Rodriguez, Jih-Sheng Lai, and Fang Zheng Peng,“ Multilevel Inverters: A Survey of Topologies, Controls, and Applications,” IEEE Transactions on Industrial Electronics, Vol. 49, No. 4, PP:724-748,2002.

[3] Nabae, I. Takahashi and H. Akagi, “New Neutral-point Clamped PWM inverter,” IEEE Trans. Ind. Applicat., vol. IA-17, pp. 518-523, Sept./Oct. 1981.

[4] M. Carpita and S. Tenconi, “Novel Multilevel Structure for Voltage Source Inverter,” in Proc. EPE’91, 1991.

[5] N. S. Choi, *et al.*, “A general circuit Topology of Multilevel Inverter,” in Power Electronics Specialists Conference, 1991. PESC’91 Record, 22nd Annual IEEE, 1991, pp. 96-103.

[6] T. A. Meynard and H. Foch, “Multilevel conversion:high votlage choppers and voltage source inverters,” in Power Electronics Specialists Conference, 1992. PESC’92 Record, 23rd Annual IEEE, 1992, pp. 397-403, vol.1.

[7] P. W. Hammond, “A new approach to enhance power quality for medium voltage AC drives,” IEEE Tans. Ind. Applicat, vol.33, pp. 202-208, 1997.

[8] R. H. Baker, “Bridge Converter Circuit,” U.S. Patent 4 270 163, May 1981.

[9] Dae-Woong Chung, Joohn-Sheok Kim and Seung-Ki Sul, “Unified Voltage Modulation Technique for Real Time Three-phase Power Conversion,”IEEE Transaction, Vol.34, N0.2, PP:374-380,1996.

[10] Xiao-ling Wen and Xiang-gen Yin, “The Unified PWM Implementation Method for Three-Phase Inverters,” IEEE Conference Publication, PP:241-246,2007.

[11] Abhijit Choudhury, Pragasen Pillay and Sheldon S. Williamson, “DC-link voltage balancing for a three-level electric vehicle traction inverter using an innovative switching sequence control scheme,” IEEE Journal of Emerging And Selected Topics in Power Electronics, Vol.2, No.2, PP:296-307 June 2014.

[12] C. Calleja, A. Lopez-de-heredia, H. Gaztanaga, L. aldasoro and T. Nieva “Validation of a modified direct-self control strategy for PMSM in railway traction applications”, IEEE Transactions on Industrial Electronics, PP:1-12, 2016.

[13] Jorge Lara, Jianhong Xu and Ambrish Chandra, “ Effects of rotor position error in the performance of field oriented controlled PMSM drives for Electric Vehicle traction Applications,” IEEE Transactions on Industrial electronics, 2016.

[14] A. Choudhury, P. Pillay, and S. S. Williamson, “A hybrid based DC-link voltage balancing algorithm for a 3-level neutral-point-clamped (NPC) DC/AC traction inverter drive,” IEEE Journal of Emerging and selected Topics in Power Electronics, Vol.3, No.3, PP: 805-816, June 2015.

[15] T. M. Jahns and V. Blasko, “Recent Advance in Power Electronics Technology for Industrial and Traction Machine Drives,” Proc. IEEE, vol. 89, pp. 963-975, June 2001.