Field Oriented Control of IPMSM using Diode-Clamped Multilevel Inverter

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***Abstract*— This paper presents a Field Oriented Control of Interior Permanent Magnet Synchronous Motor (IPMSM) using three-level and five-level diode-clamped inverter. Field Oriented Control is a basic method in which real-time control of torque variations, rotor mechanical speed and phase currents can be possible. It controls the direct and quadrature axis currents to achieve required torque. The inverter switching pulses are generated using effective space vector pulse width modulation technique known as Centre Spaced Space Vector Pulse Width Modulation (CSSVPWM). This modulation technique is a simple and easy method to generate pulses similar to Space Vector Pulse Width Modulation (SVPWM) using the concept of effective time which reduces the complexity involved in calculation of angle and sector. The inverter output voltage can be directly synthesized by the effective times and the voltage modulation task can be greatly simplified. Three-level and Five-level diode-clamped inverter fed IPMSM analysis is done in MATLAB/SIMULINK.**

Keywords—Field Oriented Control (FOC), Centre Spaced Space Vector Pulse Width Modulation (CSSVPWM), Space Vector Pulse Width Modulation (SVPWM), Interior Permanent Magnet Synchronous Motor (IPMSM).

I. INTRODUCTION

Electric Motor Drives have been there from past 100 years. Till last decade of 20th century, DC motor drives were prominent because of their flexible control. In 1960s K. Hasses, introduced the Field Oriented Control of AC motors which replaced the DC motor drives. AC motors have several advantages such as much cheaper, requires less maintenance, no mechanical commutator, and wide range of speed control. Among AC motors, Induction Motor is the most commonly used but however now-a-days Permanent Magnet Synchronous Motors are becoming prominent because of their several attractive features. They have low inertia, high efficiency, high power density and good reliability. They find their applications in robotics, ships, windmills, compressors, pumps, fans and in vehicle drives. Due to the development of rare-earth magnetic materials like Neodymium Iron Boron ($Nd_2Fe_{14}B$) and Samarium Cobalt ($SmCo_5$, Sm_2Co_{17}) which have high energy density and high resistance for demagnetization, PMSM with small size and robustness is possible [16]. PMSMs are classified into two types, Permanent Magnet AC (PMAC) and Brushless DC motors (BLDC). PMAC motors are further classified into Surface Mounted Permanent Magnet (SMPM) Synchronous Motors and Interior Permanent Magnet (IPM) Synchronous Motors depending upon their rotor structures. SMPM motors have the permanent magnets mounted on the outer surface of the rotor whereas the IPM synchronous motors have the permanent magnets buried in the rotor core. With respect to air-gap torque, IPM is better than SMPM but however with respect to speed range availability when the same voltage is considered, SMPM is better [27]-[30].

Permanent magnet synchronous motors can be controlled easily using vector control method known as field oriented control. FOC is the basic method in which the real time control of torque variations, rotor mechanical speed and phase current spikes during transient phases is possible[16]-[17]. The drive performance, particularly the torque-speed characteristics strongly correlates with the employed modulation techniques. Pulse width modulation (PWM) is the basic modulation technique which reduces the harmonic distortion with constant switching frequency. Space Vector Pulse Width modulation is the new modulation technique for multilevel inverters which gives good performance. The drawback of this technique is high complexity in calculating angle and sector identification. In order to reduce this complexity, another modulation technique is introduced known as Centre Spaced SVPWM which uses the concept of effective time. The inverter output voltage is directly synthesized by the effective times and the voltage modulation task can be simplified [8]-[10]. The gating signals can be easily generated using effective time relocation algorithm. To meet the applications of medium and high power, multilevel inverters are playing a great role. Multilevel inverters are the array of power semiconductor switches and capacitor voltages with reduced harmonics in the output voltages [1]-[5]. As the level increase the output voltages will be nearer to the sinusoidal waveform. In this paper, the simulation analysis of three-level diode-clamped and five-level diode-clamped inverter fed IPMSM is done. The inverters are built using IGBT switches. Field oriented controller is used to control the torque-speed characteristics of IPMSM and the modulation technique is centre spaced space vector pulse width modulation.

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II. IPMSM MODELLING

IPMSM are newly developed motors with high torque density, high efficiency characteristics and additionally provide field weakening operation which is impossible with the SMPM motors. IPM motors are preferred in the industrial applications because they have the advantage of providing position control loop with accuracy [20]-[25].

The voltage equations for the PMSM are given as

$$V_a = RI_a + \frac{d\lambda_a}{dt} = RI_a + L_s\frac{dI_a}{dt} + E_a \tag{1}$$

$$V_b = RI_b + \frac{d\lambda_b}{dt} = RI_b + L_s\frac{dI_b}{dt} + E_b \tag{2}$$

$$V_c = RI_c + \frac{d\lambda_c}{dt} = RI_c + L_s\frac{dI_c}{dt} + E_c \tag{3}$$

The flux linkage not only depends on the current in the each phase it also depends on the mutual flux created by the other phase currents and the rotor position. The complexity of the flux linkage calculations can be reduced with reference frame transformation.

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{4}$$

The motor voltage equations in d-q reference frame after transformation is given as

$$V_d = RI_d + \frac{d\lambda_d}{dt} - \omega\lambda_q \tag{5}$$

$$V_q = RI_q + \frac{d\lambda_q}{dt} + \omega\lambda_d \tag{6}$$

Where

$$\lambda_d = L_d I_d + \lambda_{PM} \tag{7}$$

$$\lambda_q = L_q I_q \tag{8}$$

The instantaneous power in a three phase motor is given as

$$P = V_a I_a + V_b I_b + V_c I_c \tag{9}$$

The instantaneous power using d-q components is given as

$$P = \frac{3}{2}(V_d I_d + V_q I_q) \tag{10}$$

The electrical torque produced by the motor is given as

$$T = \frac{3}{2}p(\lambda_d I_q - \lambda_q I_d) \tag{11}$$

$$T = \frac{3}{2}p\left((L_d - L_q)I_d I_q + \lambda_{PM} I_q\right) \tag{12}$$

For a synchronous machine the relationship between the mechanical angular velocity ω_m and the electrical angular velocity ω is given by

$$\omega = p\omega_m \tag{13}$$

Finally the torque equilibrium equation is given as

$$T = (J + J_L)\frac{d\omega_m}{dt} + B\omega_m + T_L \tag{14}$$

III. CENTRE SPACED SPACE VECTOR PULSE WIDTH MODULATION

Centre spaced space vector pulse width modulation is a 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 time. The average values of three-phase leg voltages over an interval ΔT/2, in terms of the midpoint of the DC link is given as

$$V_{as} = V_{dc}\left(\frac{T_{sv1}}{\Delta T/2} + \frac{T_{sv2}}{\Delta T/2}\right) \tag{15}$$

$$V_{bs} = V_{dc}\left(-\frac{T_{sv1}}{\Delta T/2} + \frac{T_{sv2}}{\Delta T/2}\right) \tag{16}$$

$$V_{cs} = V_{dc}\left(-\frac{T_{sv1}}{\Delta T/2} + \frac{T_{sv2}}{\Delta T/2}\right) \tag{17}$$

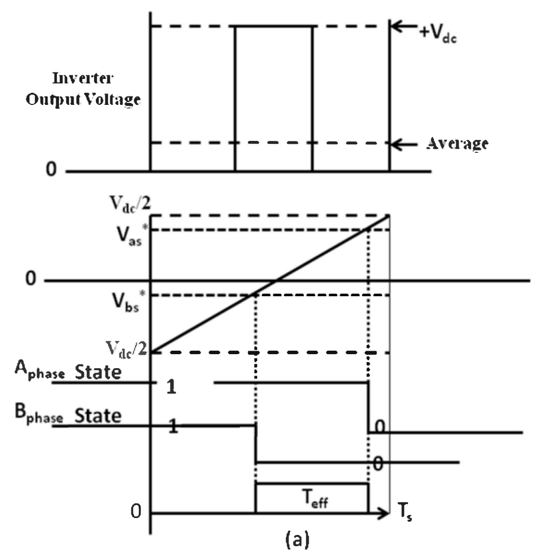

Fig.1 Relationship between the effective time and the output

By adding zero sequence signals to the three reference sinusoidal signals, an algorithm combining the space-vector PWM with the implementation of a triangular-comparison PWM can be obtained. 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[11]-[15]. The relationship between the effective time and the output voltage is shown in Fig.1.

The common offset voltage is given as

$$V_{off} = \frac{\max(V_{as}^*, V_{bs}^*, V_{cs}^*) + \min((V_{as}^*, V_{bs}^*, V_{cs}^*)}{2} \quad (18)$$

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

$$V_{off}^{'} = \frac{V_{dc}}{N-1} - \frac{\max(V_{as}^*, V_{bs}^*, V_{cs}^*) + \min((V_{as}^*, V_{bs}^*, V_{cs}^*)}{2} \quad (19)$$

To relocate the effective times at the centre of the sampling interval, a simple sorting algorithm is used to find out the minimum value and the maximum value among three imaginary switching times shown in Fig.2. So, the time shifting value of T_{offset} is

$$T_{offset} = \frac{1}{2} T_0 - T_{min} \quad (20)$$

$$T_{eff} = T_{max} - T_{min} \quad (21)$$

$$T_0 = T_s - T_{eff} \quad (22)$$

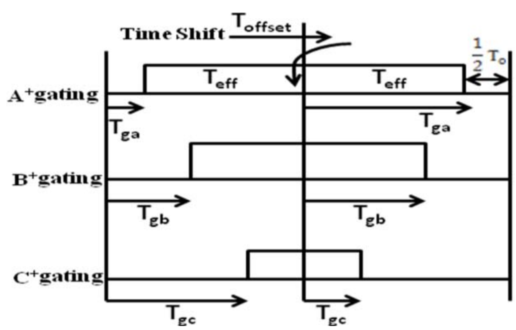

Fig.2 CSSVPWM gating generation

IV. DIODE CLAMPED MULTILEVEL INVERTER

The most prominent multilevel topology is the diode clamped inverter which employs clamping diodes to clamp the DC bus voltage and cascaded DC capacitors to achieve multiple steps in the output voltage.[6]-[7] Fig.3. shows the three-phase three-level diode-clamped inverter fed IPMSM. In three-level diode-clamped inverter, the DC-bus voltage is split into three levels by two series connected capacitors. The middle point N is called neutral point. The output voltage of V_{an} has three states $V_{dc/2}$, 0 and $-V_{dc/2}$. The switches S_{1ap} and S_{2ap} need to be turned on to get voltage level $V_{dc/2}$, switches S_{2ap} and S_{1an} need to turn on to get 0 level and the switches S_{1an} and S_{2an} need to turn on to get $-V_{dc/2}$. The switching sequence operation of a one-leg of a three-level inverter is shown in Table.1.

TABLE 1

Output Voltage	Switching Sequence			
	S_{1ap}	S_{2ap}	S_{1an}	S_{2an}
0	0	1	1	0
$V_{dc}/2$	1	1	0	0
$-V_{dc}/2$	0	0	1	1

* Switching Sequence operation of a three-level diode-clamped inverter

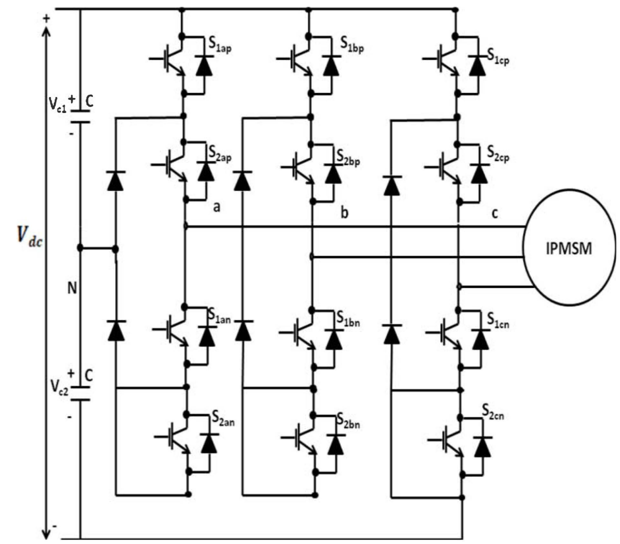

Fig.3. Three-level diode-clamped inverter fed IPMSM

In five-level diode-clamped inverter, the DC-bus voltage is split into five levels by four series connected capacitors. The output voltage V_{an} has five states such as $V_{dc/2}$, $V_{dc/4}$, 0, $-V_{dc/2}$ and $-V_{dc/4}$. Switches S_{1ap}, S_{2ap}, S_{3ap} and S_{4ap} need to be turned on to get voltage level $V_{dc/2}$, switches S_{2ap}, S_{3ap}, S_{4ap} and S_{1an} need to be turned on to get voltage level $V_{dc/4}$, switches S_{3ap}, S_{4ap}, S_{1an} and S_{2an} need to be turned on to get voltage level 0, switches S_{4ap}, S_{1an}, S_{2an} and S_{3an} need to be turned on to get voltage level $-V_{dc/4}$, switches S_{1an}, S_{2an}, S_{3an} and S_{4an} need to be turned on to get voltage level $-V_{dc/2}$. The switching sequence operation of one-leg of a five-level inverter is shown in Table.2.

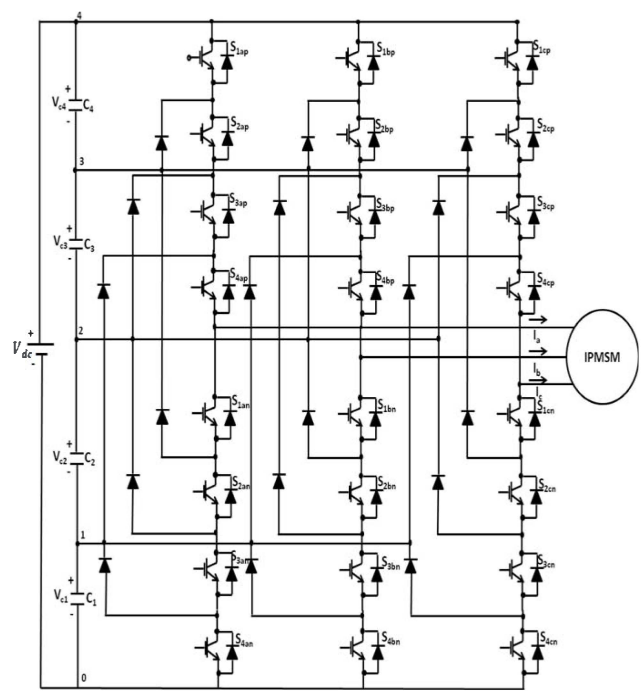

Fig.4. Five-level diode-clamped inverter fed IPMSM

TABLE 2

Output Voltage	Switching Sequence							
	S_{1ap}	S_{2ap}	S_{3ap}	S_{4ap}	S_{1an}'	S_{2an}'	S_{3an}'	S_{4an}'
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc}/4$	0	0	0	1	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

*Switching sequence operation of a five-level diode-clamped inverter

V. 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 which is electromechanical torque, whereas for salient machine $L_d \neq L_q$, therefore the control is difficult to implement since the motor produces both electromechanical and reluctance torque[18]-[19].

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

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} I_{sq}\right] \tag{23}$$

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 [26]. The control systems reference currents i_d^* and i_q^* is gives as:

$$i_q^* = \frac{T_e^*}{\frac{3}{2}\frac{P}{2}\lambda_{pm}} \tag{24}$$

$$i_d^* = 0 \tag{25}$$

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

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} I_{sq} - \left(L_q - L_d\right) I_{sd} I_{sq}\right] \tag{26}$$

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

$$\frac{3}{2}\frac{P}{2}\lambda_{pm} I_{sq} \tag{27}$$

And the reluctance torque:

$$\frac{3}{2}\frac{P}{2}\left(L_q - L_d\right) I_{sd} I_{sq} \tag{28}$$

The block diagram of closed loop field oriented control to investigate the speed and torque control with CSSVPWM for a voltage source three and five-level diode clamped inverter fed IPMSM is shown in Fig.5. Every time the currents and the voltages are measured and transformed into αβ reference frame. The currents are further converted into d-q frames using Park's transformation. The reference speed is compared with the motor speed and the error is given to the controller. The output of the PI controller is taken as quadrature axis current i_q. The reference direct-axis current i_d=0 is considered. The reference direct-axis current is compared with transformed current and given to another PI controller. The output of PI controllers goes to current controller where the voltages V_d and V_q can be generated. From these voltages, reference voltages can be generated using CSSVPWM technique. For generating the pulses for both three and five-level inverters, triangular waves are compared with the reference waves. For three-level inverter two triangular waves are required and for five-level inverter four triangular waves are required. Therefore for n-level inverter (n-1) triangular waves are required. The output of the inverter is given to IPMSM to control the speed and torque of the motor.

VI. SIMULATION RESULTS

The simulation results of the speed response of the field oriented control of three-level and five-level inverter fed IPMSM using CSSVPWM is shown in Fig.6. and Fig.7. The synchronous speed of IPMSM will be 1000RPM if the number of poles considered is p=6. Therefore the reference speed is given as 1000RPM. Synchronous motors runs at synchronous speed in its load range. To analyze the speed response of the motor 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 5 N-m is applied. Similarly at a time t=0.8 seconds, an additional load which demands a torque of 5 N-m is applied and the total torque demand is 10 N-m. At a time 1.4 seconds the load is again reduced to 5 N-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.8. and Fig.9. shows the output torque response of three and five-level inverter fed IPMSM. The torque pulsations in five-level inverter is less compared to three-level inverter. Fig.10. and Fig.11. shows the output line voltage response of a three and five-level inverter using CSSVPWM. Fig.12. and Fig.13. shows the output line current response of a three and five-level inverter using CSSVPWM. The current response of the

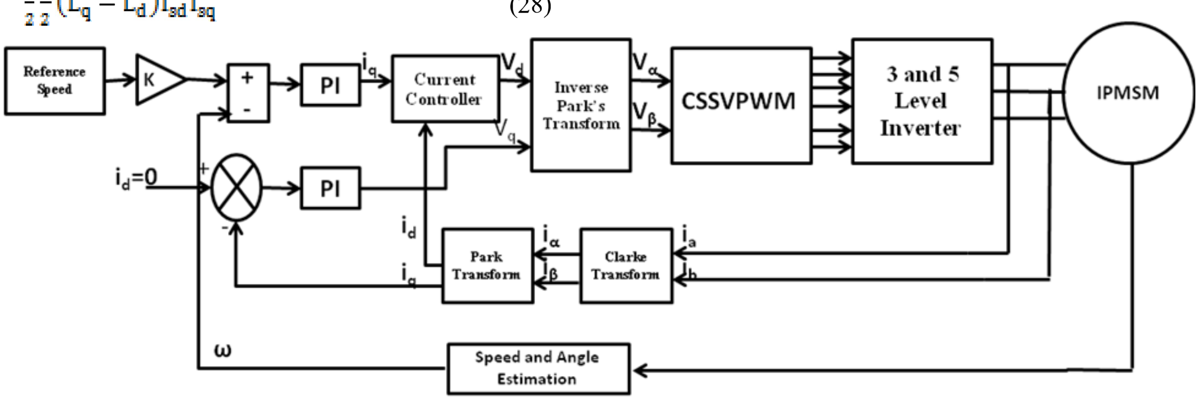

Fig.5. Block diagram of a field oriented control fed IPMSM

IPMSM motor changes with the load conditions. At no-load the current is zero, at 5 N-m the current magnitude is about 7A and at load 10 N-m the current magnitude is about 15A.

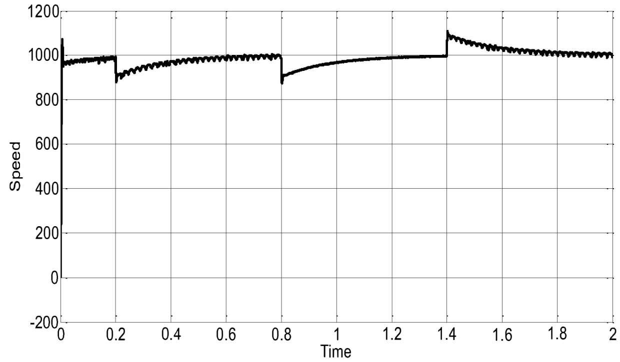

Fig.6. Speed response of three-level inverter fed IPMSM

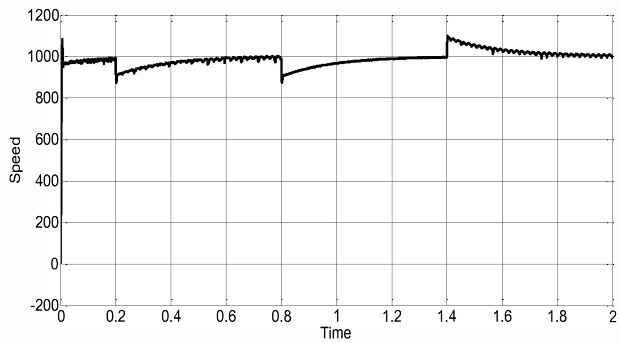

Fig.7. Speed response of five-level inverter fed IPMSM

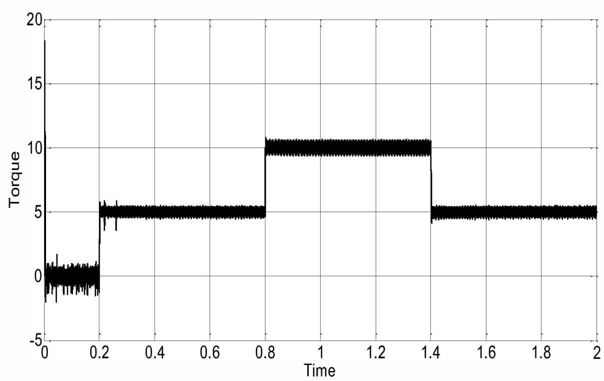

Fig.8. Torque response of three-level inverter fed IPMSM

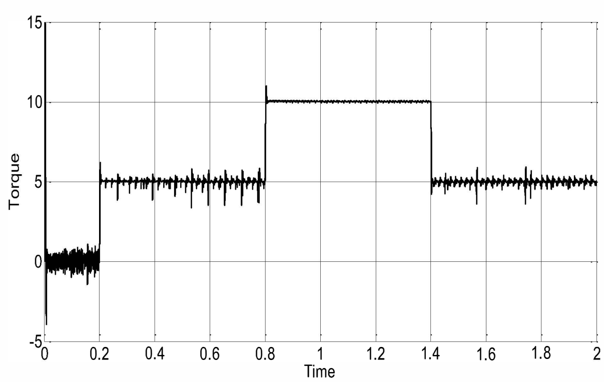

Fig.9. Torque response of five-level inverter fed IPMSM

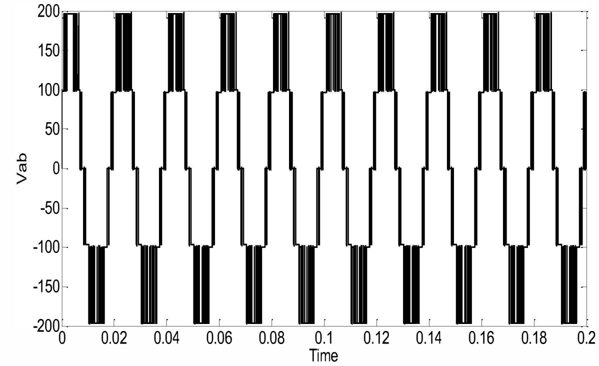

Fig.10. Output line voltage response of three-level inverter fed IPMSM

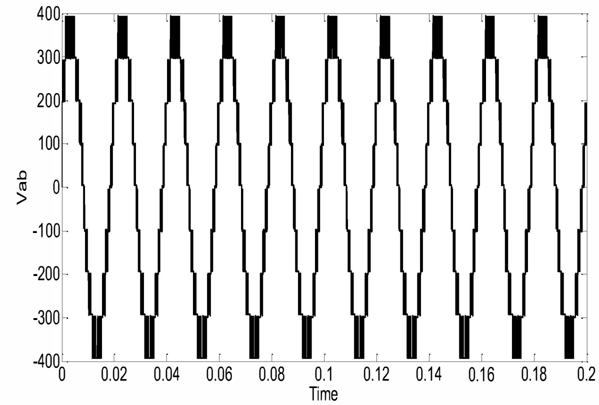

Fig.11. Output line voltage response of five-level inverter fed IPMSM

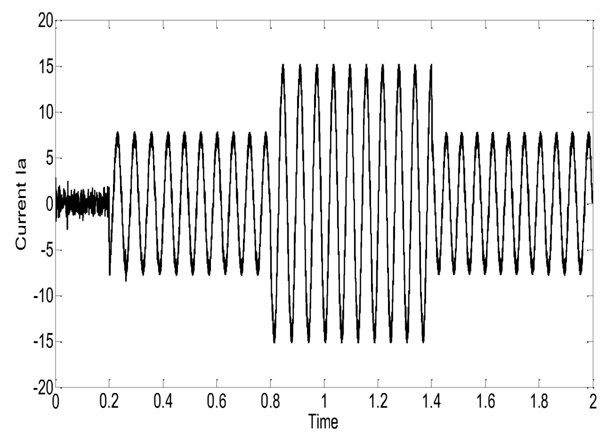

Fig.12. Output line current response of three-level inverter fed IPMSM

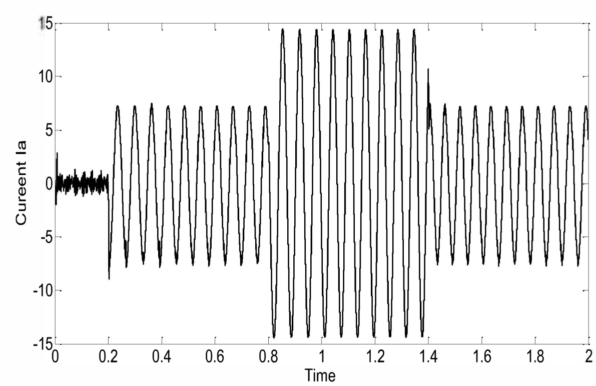

Fig.13. Output line current response of five-level inverter fed IPMSM

VII. CONCLUSION

In this paper the simulation analysis of three-level and five-level diode-clamped inverter fed interior permanent magnet synchronous motor using field oriented control is presented. The modulation technique used is centre spaced space vector pulse width modulation. The performance characteristics of three-level inverter fed IPMSM are compared with the five-level inverter. Five-level inverter gives better characteristics compared to three-level inverter. The response of the motor speed with different load conditions is also tested and absorbed that the speed of the motor remains almost constant for all the loaded conditions.

REFERENCES

[1] J.S. Lai and F. Z. Peng, "Multilevel Converters-A New Breed of Power Converters," IEEE Transactions on Industrial Application, Vol.32, PP:509-517, May/June 1996.

[2] M.D.Manjrekar, T.A. Lipo, "A Hybrid Multilevel Inverter Topology for Drive Applications," IEEE applied power electronics conference, 1998,PP:523-529.

[3] L.M.Tolbert, F.Z.Peng and T. Habetler, "Multilevel Converters for Large Electric drives," IEEE Transactions on Industrial application, Vol.35, PP:36-44, Jan/Feb 1999.

[4] 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.

[5] Leopoldo G.Franquelo, Jose Rodriguez, Jose I. Leon, Samir Kouro Ramon Portillo, and Maria A. M. Prats, "The Age of Multilevel Converters Arrives," IEEE Industrial electronics Magazine, Vol.2, No.2, PP:28-39,2008.

[6] Jose Rodriguez, Steffen Bernet, Peter K. Steimer, and Ignacio E.Lizama, "A Survey on Neutral-point-Clamped Inverters," IEEE Transactions on Industrial Electronics, Vol.57, No.7,PP:2219-2230,2010.

[7] Peter Barbosa, Peter Steimer, Jurgen Steinka, Luc Meysencl, Manfed Winkelnkemper and Nikola Celanovic, "Active Neutral-point-clamped Multilevel Converters," IEEE Conference Publication, 2005, PP:2296-2301.

[8] Dae-Woong Chung, Joohn-Sheok Kim and Seung-Ki Sul, "Unified Voltage Modulaiton Technique for real time three-phase power conversion," IEEE Transaction on Industrial Applications, Vol.34. No.2, PP:374-380, 1998.

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

[10] Jang-Hwan Kim, Seung-Ki Sul and Prasad N. Enjeti, "A Carrier-Based PWM Method with Optimal Switching Sequence for a Multi-level Four-leg VSI," IEEE Conference Publication, PP: 99-105, 2005.

[11] Z. Du, "Active Harmonic Elimination in Multilevel Converters," Ph.D. Dissertation, the University of Tennessee, 2005, Kholm, Sweden, 2005.

[12] B. P. Mc Grath, D. G. Holmes, and T. Lipo, "Optimized Space Vector Switching Sequences for Multilevel Inverters," IEEE Transactions on Power Electronics, Vol. 18, No. 6, Nov. 2003, PP:1293-1301.

[13] R.L. Kirlin, A.M. Trzynadlowski, "A unified approach to analysis and design of random pulse width modulation in voltage-source inverters," IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications, Vol. 44, Issue: 8, Aug. 1997, PP:763-766.

[14] V. Blasko, "Analysis of a hybrid PWM based on modified space-vector and triangle-comparison methods," IEEE Transactions on Industry Applications, Vol. 33, Issue: 3, May-June 1997, PP:756-764.

[15] D.G. Holmes, "The significance of zero space vector placements for carrier-based PWM schemes", IEEE Transactions on Industry Applications, Vol. 32, Issue: 5, Sept.-Oct. 1996, PP:1122-1129.

[16] Bimal K. Bose, " Power Electronics and Motor Drives Recent Progress and Perspective," IEEE Transactions On Industrial Electronics, Vol. 56, No. 2,PP:581-588,2009.

[17] Zhao Kaiqi, "The Study of Improved PI Method for PMSM Vector Control System Based On SVPWM," IEEE Conference Publication, PP: 1-4, 2011.

[18] J. Shi and Y. S. Lu, "Field-weakening operation of Cylindrical permanent magnet motors," Proceedings IEEE Int. Conf., PP: 864–869, Sept.1996.

[19] J.F Moynihan, "Indirect Phase Current Detection for Field Oriented Control of a Permanent Magnet Synchronous Motor Drive," International Conference of EPE'91, No.3, PP.611-616, 1991.

[20] Shanshan Wu, David Diaz Reigosa, Yuichi Shibukawa, Michael A. Leetmaa, Robert D. Lorenz, and Yongdong Li, "Interior Permanent-Magnet Synchronous Motor Design for Improving Self-Sensing Performance at Very Low Speed," IEEE Transactions on Industry Applications, Vol. 45, No. 6.PP:1939-1946,2009.

[21] Marian P. Kazmierkowski, Leopoldo G. Franquelo, Jose Rodriguez, Marcelo A. Perez, and Jose I. Leon, "High-Performance Motor Drives," IEEE Industrial Electronics Magazine,Vol.5,No.3,PP:6-26,2011.

[22] M. Nasir Uddin, Tawfik S. Radwan, G. H. George, and M. Azizur Rahman, "Performance of Current Controllers for VSI-Fed IPMSM Drive," IEEE Transaction on Industry Applications, Vol. 36, No. 6, PP: 1531-1538, 2000.

[23] C. Mademlis and N. Margaris, "Loss minimization in vector-controlled interior permanent-magnet synchronous motor drives," Industrial Electronics, IEEE Transactions on, Vol. 49, PP: 1344-1347, 2002.

[24] L. Parsa and H. Lei, "Interior Permanent Magnet Motors With Reduced Torque Pulsation," IEEE Transactions on Industrial Electronics, Vol. 55, PP: 602-609, 2008.

[25] Z. Yongchang, Z. Jianguo, Wei Xu and G. Youguang, "A simple method to reduce torque ripple in direct torque-controlled PMSM by using vectors with variable amplitude and angle," IEEE Transactions on Industrial Electronics, Vol. 58, Issue.7, 2011, PP: 2848-2859.

[26] J. Rodriquez, R. M. Kennel, J. R. Espinoza and M. Trincado, "High-Performance Control Strategies for Electrical Drives: An Experimental Assessment," IEEE Transactions on Industrial Electronics, Vol. 59, Issue.2, 2012, P.P. 812-820.

[27] Hai Zhu, Tsinghua and Yongdong Li, "Torque Ripple Reduction of the Torque Predictive Control System Permanent Magnet synchronous Motors," IEEE Transaction on Industrial Electronics, Vol.59, Issue.2, 2012, PP:871-877.

[28] C. Ui-Min, L. June-Seok and L. Kyo-Beum, "New Modulation Strategy to balance the neutral-point voltage for three-level neutral clamped inverter systems," IEEE Transaction on Energy Conversion, Vol. 29, Issue.1, 2014, PP:91-100.

[29] W. Huang, Y. Zhang, Z. Xingchun and G. Sun, "Assurate Torque Control of Interior Permanent Magnet Synchronous Machine," IEEE Transaction on Energy Conversion, Vol.21, Issue.1, 2014, PP:29-37.

[30] Anders Kronberg, "Design and Simulaiton of Field Oriented Control & DTC for PMSM with Positive Saliency," Uppsala University, 2012.