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CLOSED LOOP CONTROL OF THREE-LEVEL DIODE CLAMPED INVERTER FED IPMSM WITH DIFFERENT MODULATION TECHNIQUES

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G. Sree Lakshmi [α], S. Kamakshaiah [σ] & G. Tulasi Ram Das [ρ]

Abstract - In this paper a closed loop PI controller is designed to obtain the desired output torque, speed and stator phase current of interior permanent magnet synchronous motor (IPMSM) fed by a three-level diode clamped inverter which is built using twelve IGBTs (Insulated-gate Bipolar Transistor). Model of IPMSM is established using the equations describing dynamic behavior of interior permanent magnet synchronous motor in Matlab-Simulink respectively. Three modulation techniques has been studied, Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) and a novel Carrier Based Space Vector Pulse Width Modulation (CBSVPWM).The complex trigonometric calculations involved in conventional SVPWM techniques creates delay in computations and hence the drive response is weakened. Compared to the conventional SVPWM this method is simpler and avoids complex trigonometric calculations. Using MATLAB/ SIMULINK simulation and analysis of the novel scheme is carried out.

Keywords : *interior permanent magnet synchronous motor (iPMSM), three-level diode clamped inverter, sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVPWM), carrier-based space vector pulse width modulation (CBSVPWM), PI controller.*

I. Introduction

Electric motors have been developed over 100 years ago. Till last decades of 20th century DC motor drives dominated the field of variable speed drives because of their easier controllability. At the end of the 1960s K. Hasses, introduced the field oriented control of AC motor from then onwards DC drives declined because of several advantageous of AC motors such as much cheaper, less maintenance ,no mechanical commutator, and wider speed range [1]-[3]. Presently induction motor is the prominent motor used for all speed ranges. But however, synchronous motors are replacing them because of many attractive features compared to induction motors. The use of DC excited synchronous motor has been limited to generation and other high power applications. For medium power range drives due to higher price and more complex structure they cannot compete with induction motors [4]-[6]. If the DC excited rotor winding is replaced by permanent magnets, then the structure is greatly simplified, no excitation winding is required which ensures higher efficiency because there are no current circuits in the rotor due to which copper losses are reduced and also cooling is much easier compared to induction motor. The use of modern rare-earth magnetic materials enables high flux densities and facilitates the construction of motors with unsurpassed power density [5].

Permanent magnets can be manufactured in many shapes, depending on the design PM electric machines can be first classified into two groups, namely, PMDC and PMAC. PMDC machines are similar to the conventional DC commutator machines except the field is generated by permanent-magnets located in the rotor. The PMAC machines can be further classified into trapezoidal and sinusoidal types. The trapezoidal PMAC machines also called "brushless DC motors" (BLDCM) were developed because of the simple control of those machines. Sinusoidal PMAC machines are classified into two groups with respect to their rotor structures as; Surface Mount Permanent Magnet (SMPM) synchronous motors and Interior Permanent Magnet (IPM) synchronous motors. SMPM motors have the permanent magnets mounted on the outer surface of the rotor, and IPM motors have the permanent magnets buried in the rotor core. IPM motors are newly developed motors with high torque density, high efficiency characteristics and additionally provide field weakening operation, which is impossible with the SMPM motors [5]-[8]. To improve the efficiency and performance of the drive, IPM motors are preferred in the industrial applications because they have the advantage of providing position control loop with accuracy, without a shaft encoder as in case of induction motors. PMSM can be accurately controlled by using vector control in which field oriented theory is used to control current, voltage and space vectors of magnetic flux. Filed oriented control is a basic method in which real- time control of torque variations, rotor

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mechanical speed and phase currents to avoid current spikes during transient phases is possible [7]-[10].

To optimize the drive performance extending the speed range flux weakening control using number of control schemes have been presented[1]-[10]. However, drive performance, particularly the torque speed characteristics, strongly correlates with the employed modulation strategies. The basic modulation technique is a pulse width modulation (PWM) which not only reduces harmonic distortion but also gives constant switching frequency operation of the inverters. After having a detailed survey on various PWM techniques [16] it is concluded that space vector pulse width modulation (SVPWM) technique gives good performance. Switching pulse generation in SVPWM technique is given in [17]. SVPWM gives good performance, but however the complexity involved is more in calculating angle and sector. To reduce the complexity involved in SVPWM, a novel modulation technique named Unified voltage modulation or carrier based space vector pulse width modulation (CBSVPWM) is described using the concept of effective time[16]-[20]. By using this method the inverter output voltage is directly synthesized by the effective times and the voltage modulation task can be greatly simplified. The actual gating signals for each inverter arm can be easily deduced as a simple form using the effective time relocation algorithm. To meet medium and high power applications, multilevel inverters are becoming popular [11]-[13]. The neutral-point-clamped three-level inverter obtains growing interesting in high voltage and power applications. Compared with the conventional two-level inverter, the three-level inverter has demonstrated significant advantages [14][15]. As the level increases, the complexity involved in the modulation techniques also increases. In this paper a three-level diode clamped inverter fed IPMSM drive has simulated using this new CBSVPWM technique. Closed loop torque and speed control is studied using FOC with PI controller.

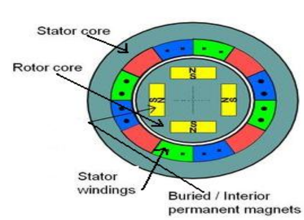

Figure 1 : Interior Permanent Magnet Motor

II. IPMSM

The voltage equation of a synchronous motor on the d-q axis component is represented as following.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R+pL_d & -\omega L_q \\ \omega L_d & R+pL_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\varphi_a \end{bmatrix} \qquad (1)$$

Where,

φa : Armature flux linkages due to permanent magnets along the d-axis

i_d, i_q : Armature currents components of d&q- axis

V_d, V_q: Armature voltage components of d & q- axis Ld, L_q: d and q axis inductances

R : Armature winding resistance

ω : Angular velocity

p : p=d/dt

Transforming (1) into $a-\beta$ fixed coordinate,

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} R+pL_\alpha & pL_{\alpha\beta} \\ pL_{\alpha\beta} & R+pL_\beta \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_{re}K_E\begin{bmatrix} -sin\theta_{re} \\ cos\theta_{re} \end{bmatrix} \qquad (2)$$

Where

$$\begin{aligned} &L_\alpha = L_0 + L_1 cos2\theta,\ \ L_\beta = L_0 - L_1 cos2\theta, \\ &L_0 = (L_d + L_q)/2,\quad L_1 = (L_d - L_q)/2 \\ &L_{\alpha\beta} = L_1 sin2\theta \end{aligned} \qquad (3)$$

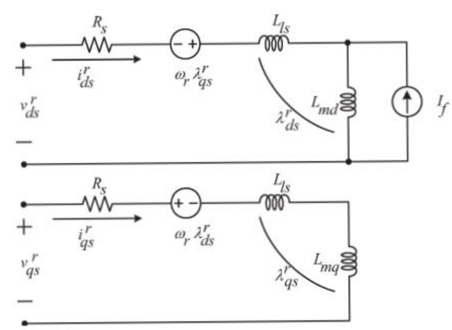

Figure 2 : Equivalent circuit of IPMSM in d and q axis

An IPMSM is constructed with permanent magnets embedded in the rotor core. This makes the rotor a salient pole and both magnetic torque and reluctance torque can be utilized.

The output torque equation of IPMSM is given by:

$$\begin{aligned} T &= P_n\{\varphi_a i_q + (L_d - L_q) i_d i_q\} \\ &= P_n\{\varphi_a i_a cos\beta + 1/2(L_d - L_q) i_a^2 sin2\beta\} \end{aligned} \qquad (4)$$

The output torque T depends on the interlinkage flux φa and the difference between the d- and q- axis inductance L_d- L_q

Where,

P_n= No. of poles pairs

I_a= Armature current amplitude,

$$I_a = \sqrt{i_q^2 + i_d^2} \qquad (5)$$

β=Armature current lead angle from the q-axis

The first term in the torque equation (4) represents the magnetic torque generated from the interlinkage flux of the permanent magnets, the second term represents the reluctance torque generated by the differences between d-axis and q-axis inductance.

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The motor drive system dynamics is also represented by

$$T_e = T_L + B\omega_m + Jp\omega_m \tag{6}$$

Where T_L and ω_m are load torque and motor speed respectively.

III. Control Methods

To run at different speeds, synchronous motors have to be driven by a Variable Frequency Drive (VFD). Electric motors control methods can be divide into two main categories depending of what quantities they control. Scalar Control controls only magnitudes, whereas the Vector Control controls both magnitude and angles. Scalar control is by V/f whereas vector control is possible by Field Oriented control (FOC). Scalar control is the simplest method to control a PMSM, in which frequency is kept constant depending on the speed required and there exist a relationship between voltage and current. No control over angles is utilized, hence the name scalar control. The method uses an open-loop control approach without any feedback of motor parameters or its position. This makes the method easy to implement and with low demands on computation power of the control hardware, but its simplicity also comes with some disadvantages. Vector control allows both magnitude and phase angle control by which higher dynamic performance of the drive system is possible.

a) Field Oriented Control (FOC)

The goal of the Field Oriented Control is to control the direct- and quadrature-axis current id and iq to achieve required torque. By controlling id and iq 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 Ld=Lq and produces only one torque i.e electromechanical torque, Whereas for salient machine Ld≠Lq therefore the control is a bit more difficult to implement since the motor produces both electromechanical and reluctance torque.

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

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} I_{sq}\right] \tag{7}$$

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. The control systems reference currents id* and iq* is gives as:

$$i_q^* = \frac{T_e^*}{\frac{3}{2}\frac{P}{2}\lambda_{pm}} \tag{8}$$

$$i_d^* = 0 \tag{9}$$

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

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} I_{sq} - \left(L_q - L_d\right) I_{sd} I_{sq}\right] \tag{10}$$

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

$$\frac{3}{2}\frac{P}{2}\lambda_{pm} I_{sq} \tag{11}$$

And the reluctance torque is

$$\frac{3}{2}\frac{P}{2}\left(L_q - L_d\right) I_{sd} I_{sq} \tag{12}$$

b) Closed loop PI control using FOC

The block diagram of closed loop PI control using FOC to investigate the speed and torque control with different modulation techniques such as SPWM, SVPWM and CBSVPWM for a voltage source three-level diode clamped inverter fed IPMSM is presented in fig. 3. Every time the currents and the voltages are measured and transformed into α-β reference frame. The currents are further converted into d-q frame using Park's Transformation. The reference speed is compared with the motor speed and the

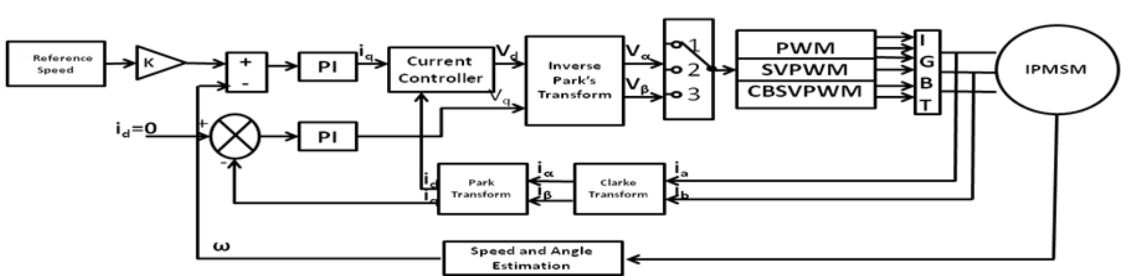

Figure 3 : Block diagram of closed loop control of three-level diode-clamped inverter using FOC with different modulation techniques

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error is given to the PI controller. The output of the PI controller is taken as quadrature axis current iq. The reference direct-axis current id =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 Vd and Vq can be generated. From these voltages, reference voltages can be generated using different modulation techniques. The Switch is used to carry out three modulation techniques. The reference waves which are generated compared with the triangular waves and the pulses are obtained which are given to the 12 IGBT's of the three level diode clamped inverter. The output of the inverter is given to the IPMSM to control the speed and torque of the motor.

IV. Modulation Techniques

a) Pulse Width Modulation

The basic control method in power electronics is the Pulse-width modulation (PWM). Except some resonant converters, majority of power electronic circuits are controlled by PWM signals of various forms. In this technique the duty ratio of a pulsating wave-form is controlled by another input waveform. The ON and OFF times of the switches can be obtained by the intersections between the reference voltage waveform and the carrier waveform. By changing the duty ratio of the switches the speed of the motor can be changed. The longer the pulse is closed higher the power supplied to the load. 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.

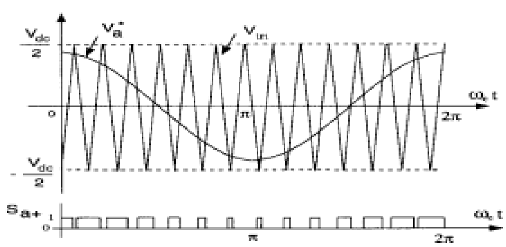

Figure 4 : Pulse width modulation

The theoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices The rapid rising and falling edges ensure that the semiconductor power devices are turned on or turned off as fast as practically possible to minimize the switching transition time and the associated switching losses.

b) Space Vector Pulse Width Modulation

The SVPWM technique for three-level inverter consists of 27 switching states out of which there are 24 active states and 3 zero states at the center of the hexagon. If the triangle sector is defined by vector V_x, V_y, V_z, then V* can be synthesized by V_x, V_y, and V_z. Assuming the duration of vector Vx, Vy, and Vz are Tx, Ty, and Tz respectively and $T_x+T_y+T_z$ = Ts, where Ts is switching period. Then X, Y and Z can be defined as the

$$X = T_x/Ts$$
$$Y = T_y/Ts \qquad (13)$$
$$Z = T_z/Ts$$

Based on the principle of vector synthesis, the following equations can be written as

$$X+Y+Z=1 \qquad (14)$$
$$V_x{}^*X + V_y{}^*Y + V_z{}^*Z = V^*$$

The modulation ratio of three-phase three-level inverter is represented as follows

$$m = |V^*|/(2/3Vd) = 3|V^*|/2Vd \qquad (15)$$

The boundaries of modulation ratio are Mark1, Mark2, and Mark3.

$$Mark_1 = (\sqrt{3}/2) / (\sqrt{3}\cos(\theta) + \sin(\theta))$$
$$Mark_2 = (\sqrt{3}/2)/(\sqrt{3}\cos(\theta) - \sin(\theta)); \quad \theta \le \pi$$
$$= (\sqrt{3}/4) / \sin(\theta) \quad \pi/6 < \theta \le \pi/3 \qquad (16)$$
$$Mark_3 = \sqrt{3} / (\sqrt{3}\cos(\theta) + \sin(\theta))$$

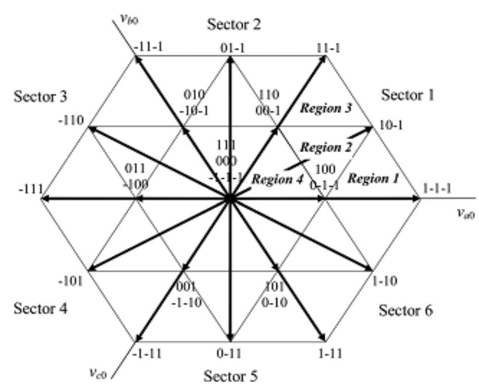

Figure 5 : Space vector hexagon for three-level inverter

Case 1 : When the modulation ratio m<Mark1, the rotating voltage vector V*is in sector D1, V* is synthesized by V0, V1, and V2

$$1/2X + 1/2[\cos(\pi/3)\, Y + j \sin(\pi/3)]\, Y = m\, [\cos(\theta) + j \sin(\theta)]$$

Using above equations, we can obtain X, Y, and Z as follows:

$$X = 2m\, [\cos(\theta) - \{\sin(\theta)/\sqrt{3}\}]$$
$$Y = m*4*\sin(\theta)/\sqrt{3} \qquad (17)$$
$$Z = 1-2*m\, [\cos(\theta) + (\sin(\theta))/\sqrt{3}]$$

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Case 2 : When (Mark1 < m < Mark2), V* is in sector D1, V* can be synthesized by V1, V2, and V7 and the corresponding X, Y, and Z are:

$$X = 1- m*4*\sin(\theta)/\sqrt{3}$$

$$Y = 1- 2*m. [\cos(\theta) - (\sin(\theta))/\sqrt{3}] \quad (18)$$

$$Z = -1 + 2*m [\cos(\theta) + (\sin(\theta))/\sqrt{3}]$$

Case 3 : When (Mark2<m<Mark3) and (0<θ<π/6), V* is in sector D13. V1, V13, and V7 are selected to synthesize V*.

$$X = -1 + 2*m [\cos(\theta) - (\sin(\theta))/\sqrt{3}]$$

$$Y = m*4*\sin(\theta)/\sqrt{3} \quad (19)$$

$$Z = 2-2*m [\cos(\theta) + (\sin(\theta))/\sqrt{3}]$$

Case 4 : When (Mark2 < m < Mark3) and (π/6<θ<π/3), V* is in sector D14. Vectors V2. V7, and V14 will be employed to generate the required voltage. X, Y, and Z can be expressed as follows:

$$X = 2*m [\cos(\theta) - (\sin(\theta))/\sqrt{3}]$$

$$Y = -1+ m*4\sin(\theta)/\sqrt{3} \quad (20)$$

$$Z = 2-2*m [\cos(\theta) + (\sin(\theta))/\sqrt{3}]$$

When the reference vector falls into the others major sectors, similar argument can be applied. Replacing θ by θ-60, θ-120, θ-180, θ-240, and θ-300 respectively, the calculation of the entire coordinate plane can be established.

c) Carrier Based Space Vector Pulse Width Modulation

Carrier based SVPWM allow fast and efficient implementation of SVPWM without sector determination. The technique is based on the duty ratio profiles that SVPWM exhibits. By comparing the duty ratio profile with a higher frequency triangular carrier the pulses can be generated, based on the same arguments as the sinusoidal pulse width modulation [8]. Figure 6 shows the switching states of sector 1 at different times during two sampling intervals. TS denote the sampling time and Teff denotes the time duration in which the different voltage is maintained. Teff is called the "effective time". For the purpose of explanation, an imaginary time value will be introduced as follows:

$$T_{xs} = \frac{T_S}{V_{dc}} \quad (21)$$

V_{as}^*, V_{bs}^* and V_{cs}^* are the A-phase, B -phase, and Cphase reference voltages, respectively. This switching time could be negative in the case where negative phase voltage is commanded.

Therefore, this time is called the "imaginary switching time".

$$T_{xs} = \frac{T_s}{V_{dc}}$$

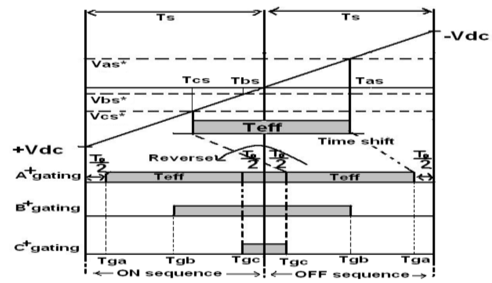

Figure 6 : Actual gating time generation for CBSVPWM

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

$$Teff = Tmax-Tmin \quad (22)$$

$$Tmin = \min(Tas,Tbs,Tcs) \quad (23)$$

$$Tmax = \max(Tas,Tbs,Tcs) \quad (24)$$

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, as shown in Fig. 6. This task is accomplished by adding the same value to the imaginary times as follows:

$$Tga=Tas+Toffset \quad (25)$$

$$Tgb=Tbs+Toffset \quad (26)$$

$$Tgc=Tcs+Toffset \quad (27)$$

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:

$$Tga=Ts-Tga \quad (28)$$

$$Tgb=Ts-Tgb \quad (29)$$

$$Tgc=Ts-Tgc \quad (30)$$

V. Three Level Diode Clamped Inverter

Multilevel inverters are becoming increasingly popular for high power applications, because their switched output voltage harmonics can be considerably

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reduced by using several voltage levels while still switching at the same frequency.

As well, higher input DC voltages can be used since semiconductors are connected in series for multilevel inverter structures, and this reduces the DC voltage each device must withstand. Among the multilevel topologies, the three-level diode clamped topology has been widely used.

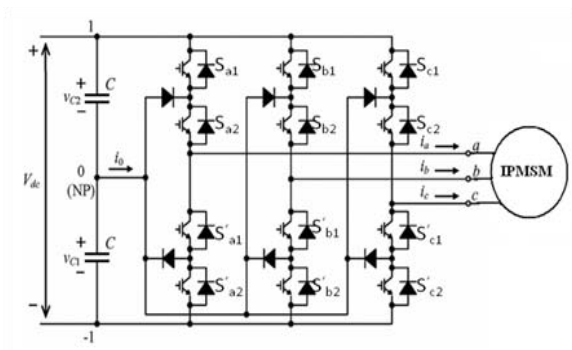


Figure 7 : Three-level diode clamped inverter fed IPMSM

Table 1 : Switching sequences for three level diode clamped inverter

Output Voltage	Switching Sequence			
	S_{a1}	S_{a2}	S_{a1}'	S_{a2}'
0	0	1	1	0
$V_{dc}/2$	1	1	0	0
$-V_{dc}/2$	0	0	1	1

Figure 7 shows the three-level diode clamped inverter fed to IPMSM drive, where only one DC source V_d is needed. Two capacitors are used to split the DC voltage and provide a neutral point Z.

The inverter leg A is composed of four active switches S_{a1}, S_{a2}, S_{a1} and S_{a2} ' with four antiparallel diodes D_1 to D_4. The switches are employed with IGBTs.

VI. Simulation Results

The simulation of the IPMSM electrical drive threelevel diode clamped IGBT inverter system is investigated. The control scheme applied for the electrical drive is the field oriented control (F.O.C).

Three modulation techniques have been applied to the three level voltage source inverter. The system used was investigated for steady and transient state. The output waveforms of SPWM, SVPWM and CBSVPWM are shown below. The parameters used in this simulation are shown in below:

L_d =0.0066; L_q=0.0058; R=1.4; PM_flux=0.1546;

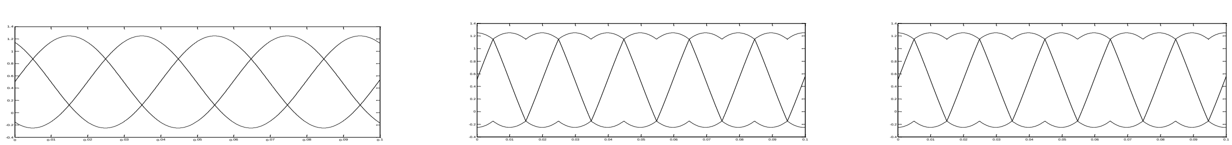
P=6; F=0.000038818; J=0.00176

VII. Conclusion

In this paper, the simulation model of closed loop control of three-level diode clamped inverter fed IPMSM drive using three different modulation techniques has studied. The output voltage, current of the inverter and the speed, torque and the three-phase currents of the IPMSM for SPWM, SVPWM and CBSVPWM have plotted. From the analysis we can conclude that the CBSVPWM is similar to SVPWM but much simple, easy and the fastest method without much mathematical calculations like angle and sector determination as in SVPWM. This method can be easily extended to n-level inverter. THD of voltage and current also reduces with CBSVPWM.

Table 2 : Comparison of THD for voltages and currents using SPWM, SVPWM, CBSVPWM

THD	SPWM	SVPWM	CBSVPWM
Line voltage	41.09	39.65	26.27
Line current	7.07	4.99	3.11



(a) (b) (c)

Figure 8 : Reference waveforms of SPWM(a),SVPWM(b), CBSVPWM(c)

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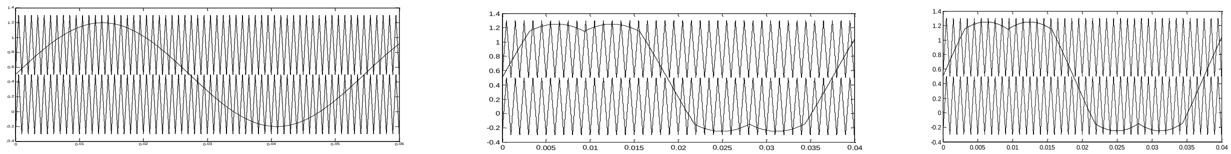
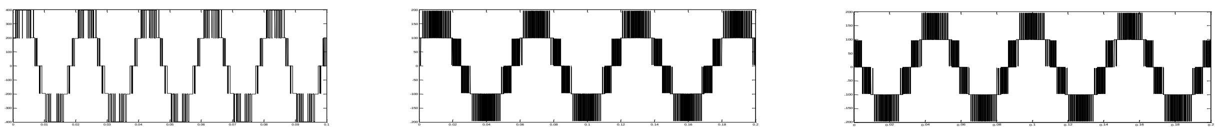


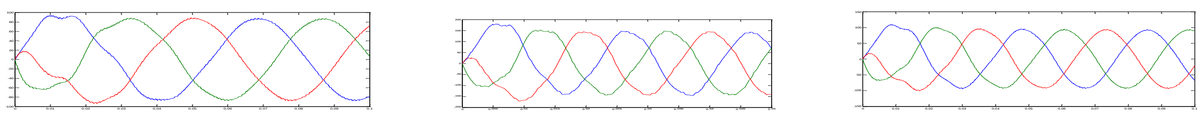
(a) (b) (c)

Figure 9 : Ref _carrier waveform of SPWM(a),SVPWM(b) and CBSVPWM(c)



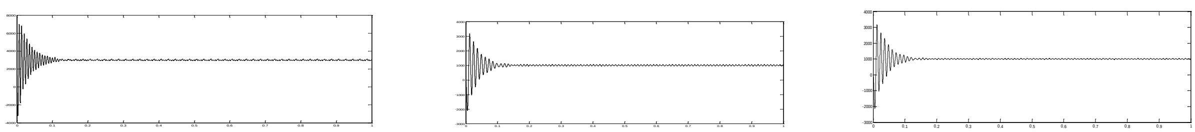
(a) (b) (c)

Figure 10 : Output voltage waveform of Three-level diode clamped inverter using SPWM(a), SVPWM(b) & CBSVPWM(c)



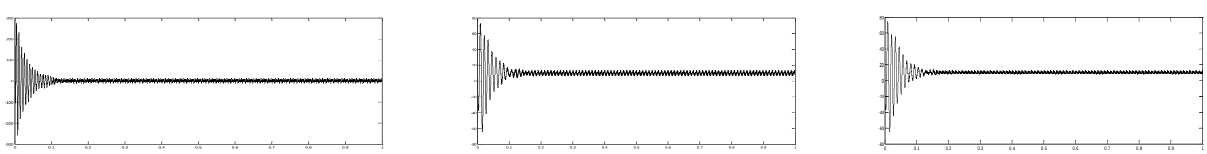
(a) (b) (c)

Figure 11 : Output three phase current waveform of Three-level diode clamped inverter using SPWM(a), SVPWM (b) and CBSVPWM(c)



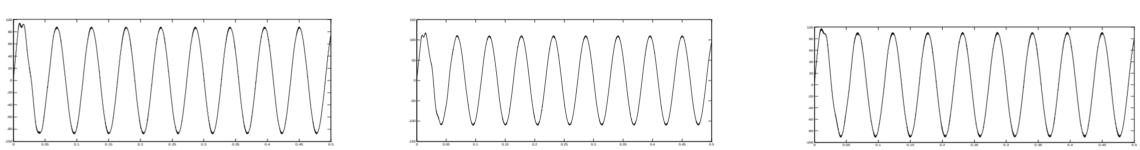
(a) (b) (c)

Figure 12 : Output speed response of Three-level diode clamped inverter fed IPMSM using SPWM(a), SVPWM (b) and CBSVPWM(c)



(a) (b) (c)

Figure 13 : Output torque response of Three-level diode clamped inverter fed IPMSM using SPWM(a), SVPWM (b) and CBSVPWM(c)



(a) (b) (c)

Figure 14 : Output phase current waveform of Three-level diode clamped inverter fed IPMSM using SPWM (a), SVPWM (b) and CBSVPWM(c)

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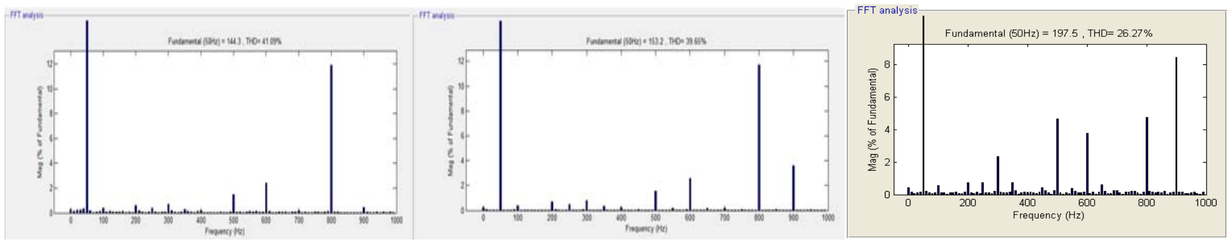
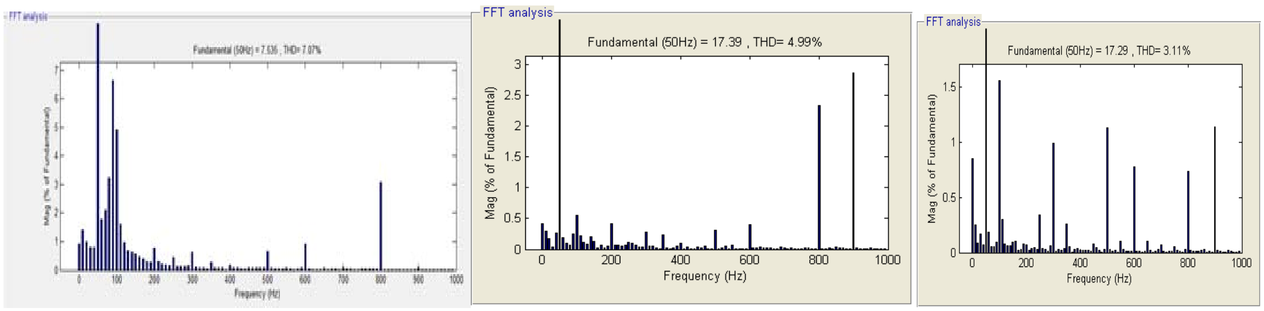


(a) (b) (c)

Figure 15 : THD of output line voltage of three-level diode clamped inverter fed IPMSM using SPWM(a), SVPWM (b) and CBSVPWM(c)



(a) (b) (c)

Figure 16 : THD of output phase current of Three-level diode clamped inverter fed IPMSM using SPWM(a), SVPWM(b) and CBSVPWM(c)

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