

Closed Loop Control of Three-Level Diode Clamped Inverter Fed IPMSM with Different Modulation Techniques

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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.

Index terms— interior permanent magnet synchronous motor (iPMSM), three-level diode clamped inverter, sinusoidal pulse width modulation (SPWM), space vector pulse

1 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.

44 SMPM motors have the permanent magnets mounted on the outer surface of the rotor, and IPM motors have the
 45 permanent magnets buried in the rotor core. IPM motors are newly developed motors with high torque density,
 46 high efficiency characteristics and additionally provide field weakening operation, which is impossible with the
 47 SMPM motors [5]- [8]. To improve the efficiency and performance of the drive, IPM motors are preferred in
 48 the industrial applications because they have the advantage of providing position control loop with accuracy,
 49 without a shaft encoder as in case of induction motors. PMSM can be accurately controlled by using vector
 50 control in which field oriented theory is used to control current, voltage and space vectors of magnetic flux. Field
 51 oriented control is a basic method in which real-time control of torque variations, rotor mechanical speed and
 52 phase currents to avoid current spikes during transient phases is possible [7]- [10].

53 To optimize the drive performance extending the speed range flux weakening control using number of control
 54 schemes have been presented [1]- [10]. However, drive performance, particularly the torque speed characteristics,
 55 strongly correlates with the employed modulation strategies. The basic modulation technique is a pulse width
 56 modulation (PWM) which not only reduces harmonic distortion but also gives constant switching frequency
 57 operation of the inverters. After having a detailed survey on various PWM techniques [16] it is concluded that
 58 space vector pulse width modulation (SVPWM) technique gives good performance. Switching pulse generation
 59 in SVPWM technique is given in [17]. SVPWM gives good performance, but however the complexity involved
 60 is more in calculating angle and sector. To reduce the complexity involved in SVPWM, a novel modulation
 61 technique named Unified voltage modulation or carrier based space vector pulse width modulation (CBSVPWM)
 62 is described using the concept of effective time [16]- [20]. By using this method the inverter output voltage
 63 is directly synthesized by the effective times and the voltage modulation task can be greatly simplified. The
 64 actual gating signals for each inverter arm can be easily deduced as a simple form using the effective time
 65 relocation algorithm. To meet medium and high power applications, multilevel inverters are becoming popular
 66 [11]- [13]. The neutral-point-clamped three-level inverter obtains growing interest in high voltage and power
 67 applications. Compared with the conventional two-level inverter, the three-level inverter has demonstrated
 68 significant advantages [14] [15]. As the level increases, the complexity involved in the modulation techniques
 69 also increases. In this paper a three-level diode clamped inverter fed IPMSM drive has simulated using this new
 70 CBSVPWM technique. Closed loop torque and speed control is studied using FOC with PI controller. The
 71 voltage equation of a synchronous motor on the d-q axis component is represented as following.

$$(1)$$

73 Where, λ_a : Armature flux linkages due to permanent magnets along the d-axis i_d, i_q : Armature currents
 74 components of d&q-axis V_d, V_q : Armature voltage components of d & q-axis L_d, L_q : d and q axis inductances
 75 R : Armature winding resistance : Angular velocity $p = d/dt$ Transforming (1) into a fixed coordinate, An
 76 IPMSM is constructed with permanent magnets embedded in the rotor core. This makes the rotor a salient pole
 77 and both magnetic torque and reluctance torque can be utilized.

78 The output torque equation of IPMSM is given by: (4)

79 The output torque T depends on the interlinkage flux λ_a and the difference between the d -and q-axis inductance
 80 $L_d - L_q$ Where, $P_n = N_p$ of poles pairs $I_a =$ Armature current amplitude, $\delta =$ Armature current lead angle
 81 from the q-axis The first term in the torque equation (??) represents the magnetic torque generated from the
 82 XIII Issue IX Version I 2 () Year δ "??", ,
 83 , interlinkage flux of the permanent magnets, the second term represents the reluctance torque generated by
 84 the differences between d-axis and q-axis inductance.

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87 Where T_L and δ "??" δ "??" m are load torque and motor speed respectively.

2 III.

3 Control Methods

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

4 a) Field Oriented Control (FOC)

101 The goal of the Field Oriented Control is to control the direct-and quadrature-axis current i_d and i_q to achieve
 102 required torque. By controlling i_d and i_q independently we can achieve a Maximum Torque per Ampere ratio to
 103 minimize the current needed for a specific torque, which increases the motor efficiency.

104 For a non-salient machine, control technique can be easily implemented because $L_d=L_q$ and produces only
105 one torque i.e electromechanical torque, Whereas for salient machine $L_d>L_q$ therefore the control is a bit more
106 difficult to implement since the motor produces both electromechanical and reluctance torque.

107 For non-salient pole machine the torque equation is given by: (7) From the above equation the torque producing
108 current is along the quadrature -axis. To reach maximum efficiency, the torque per ampere relationship should
109 be maximum. This can be easily obtained by keeping the direct-axis current to zero at all times. The control
110 systems reference currents i_d^* and i_q^* is gives as:(8) (9)

111 For salient pole machine the direct-and quadrature axis inductances are unequal and for the steady state
112 operation the torque equation is given as: (10) From the above equation there are two terms affecting the torque
113 production, the electromechanical torque (11) And the reluctance torque is The motor drive system dynamics
114 is also represented by (6) Figure ?? : Based on the principle of vector synthesis, the following equations can be
115 written as $X+Y+Z=1$ $V_x * X +V_y * Y+ V_z * Z = V^*$ (14)

116 The modulation ratio of three-phase three-level inverter is represented as follows $m = 1V^*/(2/3V_d) = 31V^*/2V_d$
117 (15)

118 The boundaries of modulation ratio are Mark1, Mark2, and Mark3. error is given to the PI controller. The
119 output of the PI controller is taken as quadrature axis current i_q . The reference direct-axis current $i_d =0$
120 is considered. The reference direct-axis current is compared with transformed current and given to another PI
121 controller. The Output of PI controllers goes to current controller where the voltages V_d and V_q can be generated.
122 From these voltages, reference voltages can be generated using different modulation techniques. The Switch is
123 used to carry out three modulation techniques. The reference waves which are generated compared with the
124 triangular waves and the pulses are obtained which are given to the 12 IGBT's of the three level diode clamped
125 inverter. The output of the inverter is given to the IPMSM to control the speed and torque of the motor.

126 IV.

127 5 Modulation Techniques a) Pulse Width Modulation

128 The basic control method in power electronics is the Pulse-width modulation (PWM). Except some resonant
129 converters, majority of power electronic circuits are controlled by PWM signals of various forms. In this technique
130 the duty ratio of a pulsating wave-form is controlled by another input waveform. The ON and OFF times of the
131 switches can be obtained by the intersections between the reference voltage waveform and the carrier waveform.
132 By changing the duty ratio of the switches the speed of the motor can be changed. The longer the pulse is closed
133 higher the power supplied to the load. The change of state between closing (ON) and opening (OFF) is rapid,
134 so that the average power dissipation is very low compared to the power being delivered.

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

139 6 b) Space Vector Pulse Width Modulation

140 The SVPWM technique for three-level inverter consists of 27 switching states out of which there are 24 active
141 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 ,
142 then V^* can be synthesized by V_x , V_y , and V_z . Assuming the duration of vector V_x , V_y , and V_z are T_x , T_y ,
143 and T_z respectively and $T_x +T_y +T_z = T_s$, where T_s is switching period. Then X, Y and Z can be defined as
144 the

145 When the reference vector falls into the others major sectors, similar argument can be applied. Replacing by
146 60, 120, 180, -240, and -300 respectively, the calculation of the entire coordinate plane can be established.

147 7 c) Carrier Based Space Vector Pulse Width Modulation

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

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

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

158 When the actual gating signals for power devices are generated in the PWM algorithm, there is one degree of
159 freedom by which the effective time can be relocated anywhere within the sampling interval.

160 Therefore, a time-shifting operation will be applied to the imaginary switching times to generate the actual
161 gating times (T_{ga} , T_{gb} , T_{gc}) for each inverter arm, as shown in Fig. 6. This task is accomplished by adding the

162 same value to the imaginary times as follows: $T_{ga} = T_{as} + T_{offset}$ (25) $T_{gb} = T_{bs} + T_{offset}$ (26) $T_{gc} = T_{cs} + T_{offset}$
 163 (27)

164 Where T offset is the 'offset time'

165 This gating time determination task is only performed for the sampling interval in which all of the switching
 166 states of each arm go to 0 from 1. This interval is called the "OFF sequence". In the other sequence, it is called
 167 the "ON sequence."

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

$$170 T_{ga} = T_s - T_{ga} \quad (28)$$

$$171 T_{gb} = T_s - T_{gb} \quad (29)$$

$$172 T_{gc} = T_s - T_{gc} \quad (30)$$

173 V. Three Level Diode Clamped Inverter

174 Multilevel inverters are becoming increasingly popular for high power applications, because their switched
 175 output voltage harmonics can be considerably V^* is in sector D14. Vectors V2, V7, and V14 will be employed to
 176 generate the required voltage. X, Y, and Z can be expressed as follows: reduced by using several voltage levels
 177 while still switching at the same frequency. $6 < \dots < /3$, ? ? ? $G1 T \times S = T S V_{dc}$

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

181 8 Output

182 9 Simulation Results

183 The simulation of the IPMSM electrical drive threelevel diode clamped IGBT inverter system is investigated.

184 The control scheme applied for the electrical drive is the field oriented control (F.O.C).

185 Three modulation techniques have been applied to the three level voltage source inverter

186 10 Conclusion

187 In this paper, the simulation model of closed loop control of three-level diode clamped inverter fed IPMSM drive
 188 using three different modulation techniques has studied. The output voltage, current of the inverter and the
 189 speed, torque and the three-phase currents of the IPMSM for SPWM, SVPWM and CBSVPWM have plotted.

190 From the analysis we can conclude that the CBSVPWM is similar to SVPWM but much simple, easy and the
 191 fastest method without much mathematical calculations like angle and sector determination as in SVPWM. This
 192 method can be easily extended to n-level inverter. THD of voltage and current also reduces with CBSVPWM.

193 11 THD

194 1 2

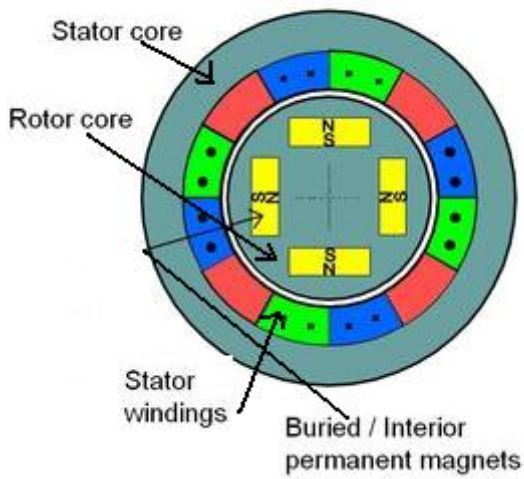
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1

Figure 1: Figure 1 :



2

Figure 2: Figure 2 :

$$\begin{bmatrix} \dot{P}_{st} \\ \dot{P}_{rg} \end{bmatrix} = \begin{bmatrix} R_s + \gamma L_{st} & \omega L_{st} \\ \omega L_{st} & R_s + \gamma L_{st} \end{bmatrix} \begin{bmatrix} i_{st} \\ i_{rg} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_{ac} \end{bmatrix}$$

Figure 3: F

$$\begin{bmatrix} \dot{P}_{sc} \\ \dot{P}_{sg} \end{bmatrix} = \begin{bmatrix} R_r + \gamma L_{rc} & \gamma L_{rc} \\ \gamma L_{rc} & R_r + \gamma L_{rg} \end{bmatrix} \begin{bmatrix} i_{sc} \\ i_{sg} \end{bmatrix} + \begin{bmatrix} \omega \psi_{sc} \\ \omega \psi_{sg} \end{bmatrix}$$

4

Figure 4: Figure 4 :

$$5 \quad v_{dc} = v_{\omega} + v_{\omega} \cos 2\theta$$

Figure 5: Figure 5 :

$$161 \quad v_{qs} = v_{\omega} + v_{\omega} \cos 2\theta$$

Figure 6: (16)Case 1 :

$$6 \quad v_{\omega} = (v_{ds} + v_{dq})/2$$

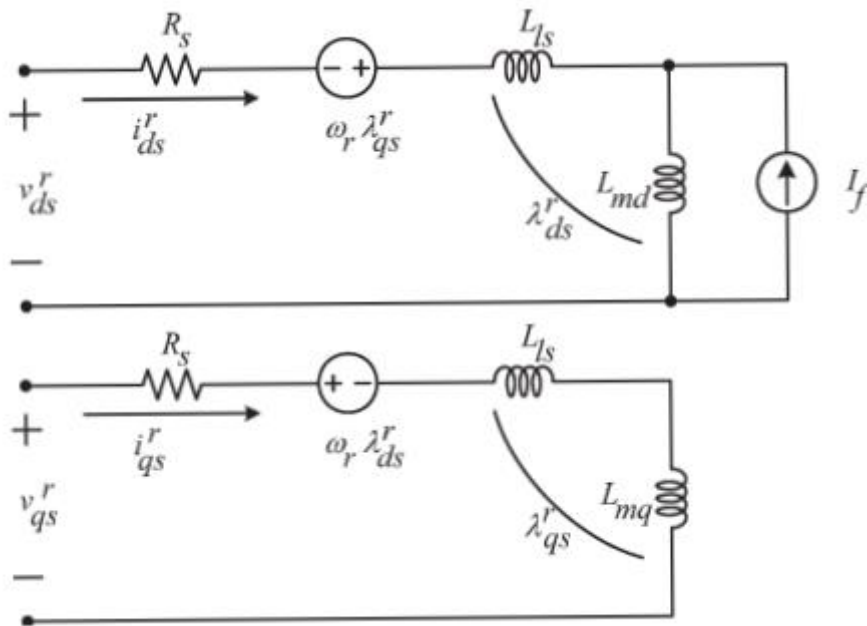
Figure 7: Figure 6 :F

$$1 \quad v_{\omega} = (v_{ds} - v_{dq})/2$$

Figure 8: X = 1

$$v_{\omega} = v_{\omega} \cos 2\theta$$

Figure 9: Closed



7

Figure 10: Figure 7 :

$$v = v_{dc} \{ \omega_r \lambda_{dq}^r + (L_{ds} - L_{dq}) i_{ds} i_{dq} \}$$

Figure 11:

$$711 \quad v_{ds} = v_{dc} \{ \omega_r \lambda_{dq}^r \cos 2\theta + 1/2 (L_{ds} - L_{dq}) i_{ds}^2 \sin 2\theta \}$$

Figure 12: Figure 7 Figure 11 :

$$1213141516 \quad v_{\omega} = \sqrt{v_{ds}^2 + v_{dq}^2}$$

Figure 13: Figure 12 :Figure 13 :Figure 14 :Figure 15 :Figure 16 :

1

Figure 14: Table 1 :

2

Figure 15: Table 2 :

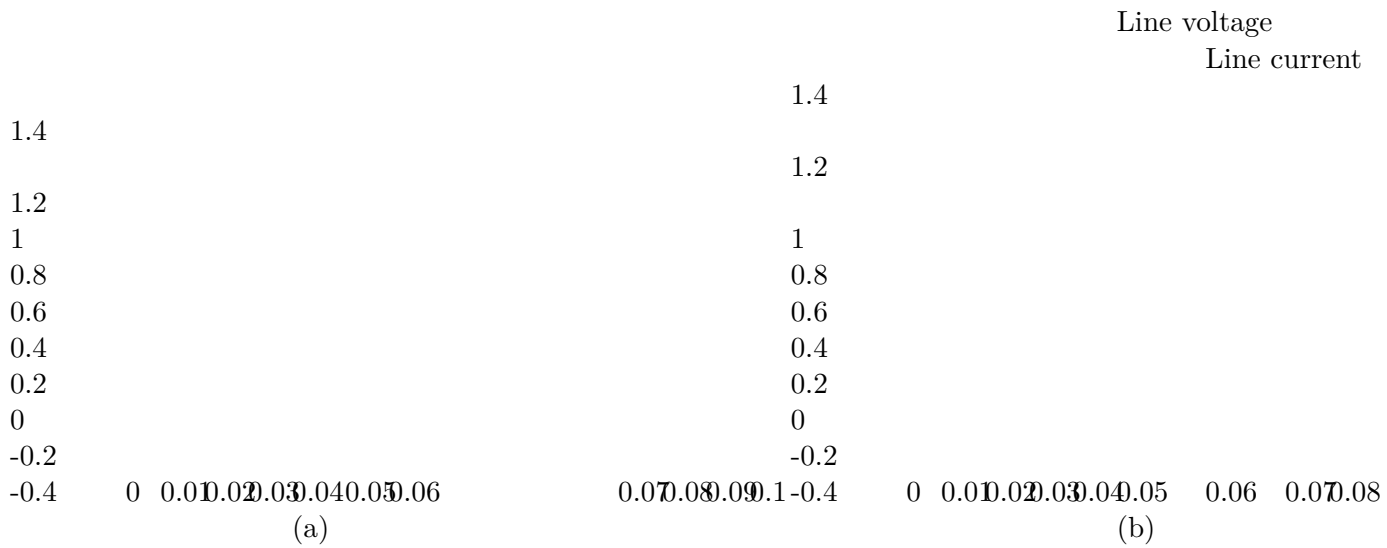


Figure 8 : Reference waveforms of SPWM(a),SVPWM(b), CBSVPWM(c)

Figure 16:

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