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Research Article

Indirect Field Oriented Control for Five Phase Three Level Neutral Point Clamped Inverter Fed PMSM Drive

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Abstract: This study deals with a five phase three level Neutral Point Clamped (NPC) inverter fed PMSM drive application. The motor performances depend upon mathematical model so the parameters vary are: noise, common mode voltage, flux variation and harmonic levels of the inverter or motor. Voltage saturation is one of the major problems of a motor which occurs due to speed oscillations, more current fluctuations. This problem can be solved by using PWM technique depends on the reference motor torque and flux. In this study Indirect Field Oriented Control (IFOC) NPC inverter is suggested to reduce the voltage saturation. The three level neutral point clamped inverter is widely used for medium and high level applications. Compared with standard two level inverter, this type of NPC inverters have more merits. It generates greater number of levels output waveform in lower harmonic content at the same switching frequency and less voltage stress across the semiconductor switches; finally motor performance and control schemes are verified by using MATLAB/SIMULINK.

Keywords: Five-phase inverter, indirect field oriented control, Neutral Point Clamped (NPC), PMSM drive, PWM, three levels

INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) drives can be used for high-performance and high-efficiency motor drives and electric vehicles applications. The main features and advantages are: high efficiency, good performance, low inertia ratio, high torque-to-volume ratio, good power factor, which is compared to induction and reluctance motors, PMSM with multi phase inverter arrangement has achieved high density and the simple arrangement is shown in Fig. 1 referred in Zhu and Howe (2007). A PMSM produces the air gap in magnetic field rather than using electromagnets. The multiphase Neutral Point Clamped (NPC) inverter based PMSM is proposed in this paper that has more advantages over traditional VSI fed drives, the multi phase PMSM is used to increases the frequency of pulsating torque, also decreased the torque pulsations, reduced the current harmonics, improved the phase voltage as well as torque/current relation for the same volume of the drive in Levi (2008).

A three-level Neutral-Point Clamped (NPC) inverter has been extensively used in medium to large-power industrial and drives applications in Gharakhani and Radan (2007) and Welchko *et al*. (2004). Since the three-level NPC inverter generates output waveform in lower harmonic content at the same switching frequency and less voltage stress across power electronic switches and more sinusoidal output voltage in Apsley *et al*. (2006) and Dujic *et al*. (2009). Which dominates the general voltage source inverter, the NPC inverter has recently been used in low-voltage drive applications, where a drive system specially required high power quality in Toliyat *et al*. (1991) and Lyra and Lipo (2002).

Although, the NPC inverter requires a control of the neutral point fluctuation and unbalance in Kouro *et al*. (2010). As compared to two level inverters, the proposed Neutral point clamped three level inverters have smaller steps of output voltage that justify motor issues due to long power cables between the inverter and the drives in Gonzàlez and Escalante (2010). These issues include voltage saturation and rate of common mode voltage rise at the motor terminals and motor shaft bearing currents increases. The NPC inverter topology has mitigates the rise of common mode voltage which is avoid bearing failure is dealt in Zhao *et al*. (2012). NPC inverter is constructed by using IGBT switches; which is used for high voltage inverting application with less switching losses. Varies control strategies are followed: PWM, SPWM, SVPWM etc., (Schweitzer *et al*., 2013; Apsley *et al*., 2006). For high performance applications required standard control techniques; compared with other control methods, IFOC algorithm is only suitable for handling the dynamic and variable load application. In IFOC control method has rotor flux vector is implemented by

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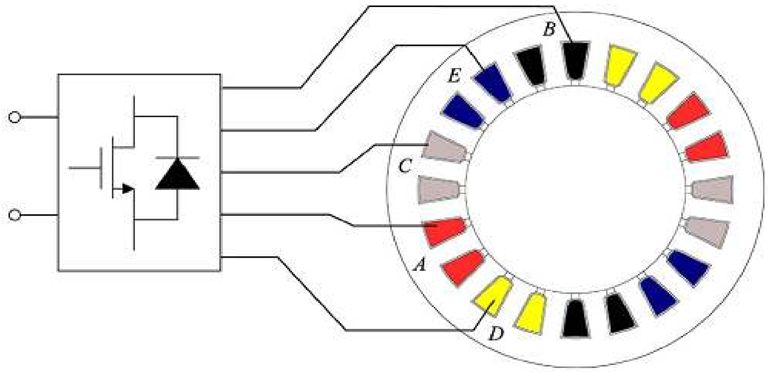


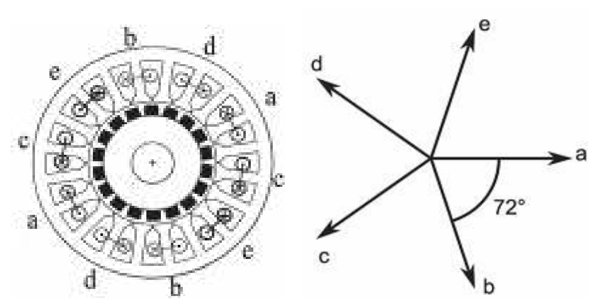
Fig. 1: Schematic diagram for five-phase motor drive

using the field oriented vector control equations, is required the rotor speed.

This study proposes the combination of IFOC strategy based on five phase three level NPC inverter fed PMSM drive for fast dynamics operation. The proposed five-phase arrangement increases the degree of freedom for different control schemes. NPC topology is accepted for industrial and high power applications because it requires optimum number of switches and produce better output voltage waveform additionally the NPC Scheme has eliminates the rise of common mode voltage. Since rise of common mode voltage is one of the main reasons for bearing failure. A practical control scheme of IFOC based three level neutral point clamped inverter is proposed for reduce the very common issue in PMSM operation; which has eliminates the torque ripples and voltage saturation under high speed operation and also provides higher reliability, better dynamic performance and higher efficiency.

MODELING OF FIVE-PHASE MOTOR PROTOTYPE

The PMSM model is described by using 20-slots 18-poles which is shown in Fig. 2. The proposed motor has been designed to obtain a high speed and transient torque and also maintain the fault-tolerance capability in Mecrow *et al*. (2004). In fact, the physical separation between the phases and mutual inductance values are very low. Therefore n number of phases is considered in PMSM; where 'n' is the number of phases that is derived from (360˚/n). It processes five phase stator windings are displaced with a phase difference of 72˚ degree for all individual phases in Ben Hamed and Sbita (2006). As increasing the number of phases in stator side, as machine has produced the lower space harmonic content with field. Hence the efficiency is also high; in multiphase inverter fed PMSM has equal stator windings and number of phase in Levi (2008) and Parsa and Toliyat (2005).



(a) (b)

Fig. 2: (a): Diagram for coil connection; (b): Diagram for five-phase star of slots

The model of five-phase PMSM in abcde transformation can be derived as follows directly in terms of circuit model.
Stator voltage is derived as Eq. (1):

$$V_s = R_s I_s + p\lambda_s \quad (1)$$

Air-gap flux linkages are presented by Eq. (1):

$$\lambda_s = \lambda_{ss} + \lambda_m \quad (2)$$

Substitute the flux linking stator winding currents in the stator windings in terms of the stator winding inductances:

$$\lambda_s = L_{ss} i_s + \lambda_m \quad (3)$$

L_{ss} is the stator inductance matrix which can contains the self and mutual inductances of the stator phases, from the above equation R_s, I_s, λ_s are the stator resistance, current, flux linkages matrices, respectively:

$$V_s = [V_a V_b V_c V_d V_e]^T \quad (4)$$

$$I_s = [I_a I_b I_c I_d I_e]^T \quad (5)$$

Matrix value of the stator inductances are given by ($\alpha = \frac{2\pi}{5}$):

$$L_{ss} = \begin{bmatrix} L_{aas} & L_{abs} & L_{acs} & L_{ads} & L_{aes} \\ L_{abs} & L_{bbs} & L_{bcs} & L_{bds} & L_{bes} \\ L_{acs} & L_{cbs} & L_{ccs} & L_{cds} & L_{ces} \\ L_{ads} & L_{dbs} & L_{dcs} & L_{dds} & L_{des} \\ L_{ads} & L_{ebs} & L_{ecs} & L_{eds} & L_{ees} \end{bmatrix} \quad (6)$$

Arbitrary transformation is introduced into the phase variable into rotating arbitrary angulary velocity. The transformed matrix is shown in the following Eq. (7):

$$\text{k} = \sqrt{\frac{z}{s}} \begin{bmatrix} \cos\theta\gamma & \cos\left(\theta\gamma - \frac{2\pi}{5}\right) & \cos\left(\theta\gamma - \frac{4\pi}{5}\right) & \cos\left(\theta\gamma + \frac{4\pi}{5}\right) & \cos\left(\theta\gamma + \frac{2\pi}{5}\right) \\ sin\theta\gamma & \sin\left(\theta\gamma - \frac{2\pi}{5}\right) & \sin\left(\theta\gamma - \frac{4\pi}{5}\right) & \sin\left(\theta\gamma + \frac{4\pi}{5}\right) & \sin\left(\vartheta\gamma + \frac{2\pi}{5}\right) \\ cos\theta\gamma & \cos\left(\theta\gamma - \frac{4\pi}{5}\right) & \cos\left(\theta\gamma - \frac{2\pi}{5}\right) & \cos\left(\theta\gamma + \frac{2\pi}{5}\right) & \cos\left(\theta\gamma - \frac{4\pi}{5}\right) \\ sin\theta\gamma & \sin\left(\theta\gamma + \frac{4\pi}{5}\right) & \sin\left(\theta\gamma - \frac{2\pi}{5}\right) & \sin\left(\theta\gamma + \frac{2\pi}{5}\right) & \sin\left(\theta\gamma - \frac{4\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (7)$$

From above used transformation matrix $\theta r = 0$.
$[K_s]^{-1}$ is derived from pseudo orthogonal property:

$$[K_s]^{-1} = \frac{5}{2}[K_s] \quad (8)$$

Voltage equation gets from transformation matrix which is multiplied with Eq. (1):

$$[K_s]V_s = [K_s]R_s i_s + [K_s]p\lambda_s \quad (9)$$

$$V_{qdxy0} = [K_s]R_s[K_s]^{-1}i_{qdxy0} + [K_s]p[K_s]^{-1}\lambda_{qdxy0} + \lambda_{qdxy0} \quad (10)$$

$$L_{qdxyo} = \begin{bmatrix} L_q & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & 0 & 0 \\ 0 & 0 & L_{ls} & 0 & 0 \\ 0 & 0 & 0 & L_{ls} & 0 \\ 0 & 0 & 0 & 0 & L_{ls} \end{bmatrix} \quad (11)$$

$$L_d = L_{ls} + L_m \quad (12)$$

$$L_q = L_{ls} + L_m \quad (13)$$

$$\lambda_m = \begin{bmatrix} \lambda_m \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (14)$$

$$V_q = R_s i_q + p\lambda_q + \omega\lambda_m + \omega L_d i_q \quad (15)$$

$$V_d = R_s i_d + p\lambda_{qd} - \omega L_q i_d \quad (16)$$

$$V_x = R_s i_x + pL_{ls} \quad (17)$$

$$V_y = R_s i_y + pL_{ls} \quad (18)$$

$$V_0 = R_s i_0 + pL_{ls} \quad (19)$$

Finally the electromagnetic torque equation is derived as:

$$T_e = \left(\frac{5}{2}\right)\left(\frac{p}{2}\right)\{\lambda_d i_q - \lambda_q i_d\} \quad (20)$$

Where λ is the inertia and p is the number of poles pairs.

THREE LEVEL NEUTRAL POINT CLAMPED (NPC) INVERTER

The five phase three level inverter topology is proposed for the high power drive application and the circuit configuration is shown in Fig. 3, which is constructed by using two series-connected dc link voltages. The midpoint of the two DC link voltages is denoted as ‘n’ which is called as neutral point. The Complementary switch pairs (S1, S1’) and (S2, S2’) and two clamping diodes (D1, D1’) are present in each leg which is connected in series. One half of the source voltage flows through the two level inverting arrangements.

The NPC inverter can produce three voltage levels on the output side: the DC bus positive voltage, zero voltage and DC bus negative voltage. The Two Level Inverter can only connect the output to either the positive bus or the negative bus. For a first phase operation, when IGBTs S1 and S2 are turned on, the output is connected to VP; when S2 and S1’ are on, the output is connected to V0; and when S1’ and S2’ are on, the output voltage is connected to negative side.

Table 1 produces the NPC circuit's switching states (phase A) and respective inverter phase voltage of five-phase three-level NPC inverter, where the switches that are turned on and conduction for a particular phase leg is always adjacent and in series (Holtz and Oikonomou, 2007).

NPC inverter has more advantages. All phases can share a common dc bus voltage, which is minimizes the capacitance requirements of the inverter. For this reason, a back-to-back inters connection or adjustable speed drives connection is possible for this topology. Efficiency is high in fundamental switching frequency.

IFOC control structure: Figure 4 illustrates the overall block diagram of IFOC scheme based three levels NPC fed five phases PMSM drive is considered

Table 1: Output voltage and switching states

Switching state	S1	S2	S1'	S2'	Vxo (x = a, b, c, d, e)
P	ON	ON	OFF	OFF	+Vdc/2
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	-Vdc/2

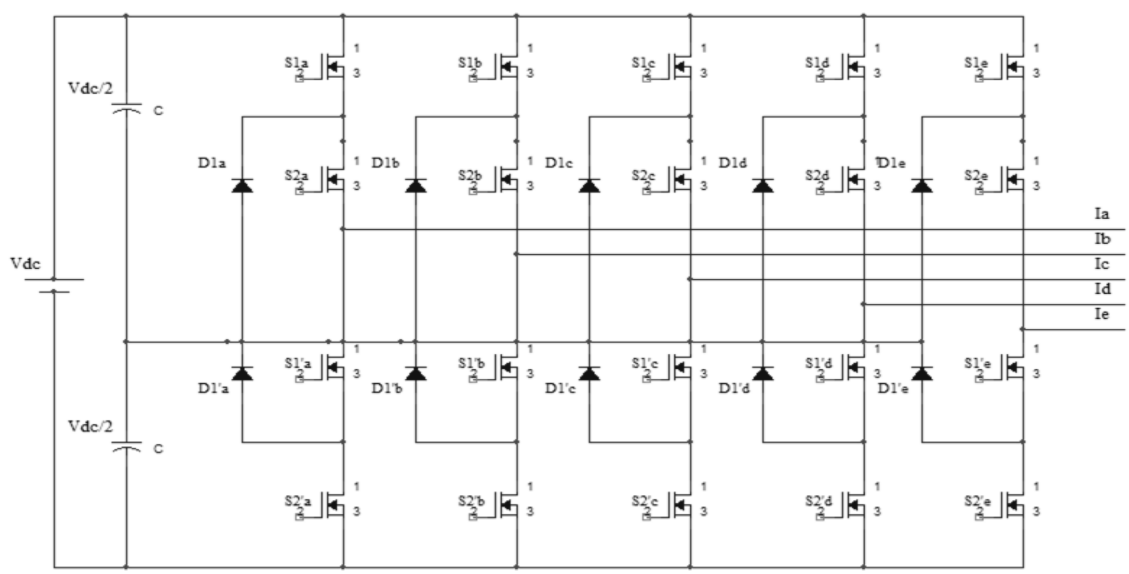


Fig. 3: Five phase three level NPC inverter

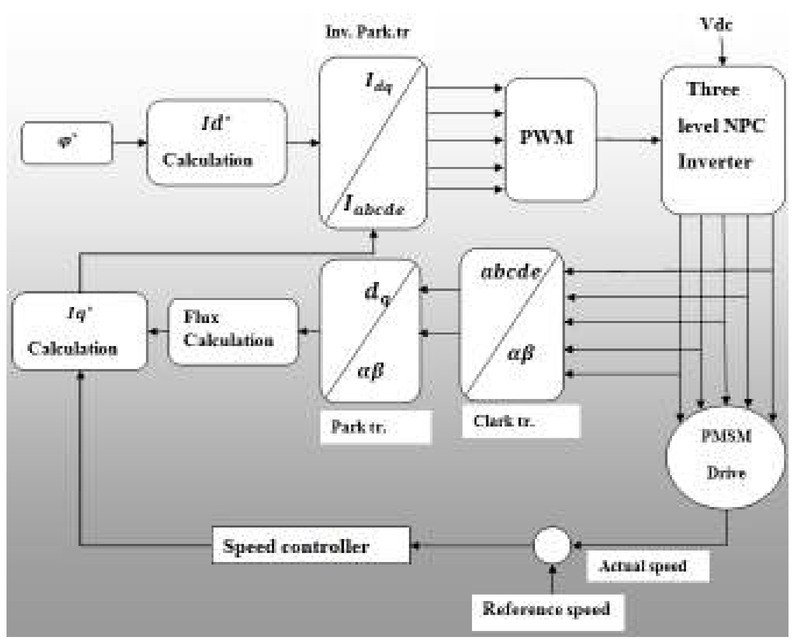


Fig. 4: Block diagram for IFOC topology

and investigated. The most common vector principle is independently control the torque and flux in PMSM. The actual rotor speed is compared with the reference speed with the help of speed controller and which is produce reference q-axis current I_q^*. The indirect field oriented control method, different type of co-ordinate transformation has produce stator voltage or stator current in rotating reference frame at the angular velocity, the d&q axis are responsible for stator current produced torque and flux. Those field and torque currents are orthogonal with two vector axis (d&q). D-axis reference current $i_d{}^*$ is may be computed by using the reference torque, finally the variable PWM pulses are generated for NPC inverter arrangement in Ben Hamed and Sbita (2006):

$$i_{qs}{}^* = \frac{2}{5}\frac{2}{p}\frac{L_r}{L_m}\frac{T_{ref}}{\Psi_r} \quad (21)$$

Where Ψ_r is rotor flux, which is derived in Eq. (22):

$$\Psi_r = \frac{L_m}{\tau_r s+1} i_{ds} \quad (22)$$

where,
L_m : Magnetization inductance
L_r : Rotor inductance
τ_r : Rotor time constant
D : Axis referred stator reference current $i_{ds}{}^*$:

$$i_{ds}{}^* = \frac{\Psi_{ref}}{L_m} \quad (23)$$

Table 2: Simulation model parameter for PMSM

Parameter	Value
Resistance	1.4 Ω
d-axis inductance	6.6 mH
q-axis inductance	5.8 mH
Stator inductance	6.6 mH
Inertia	0.00176 N.m.sec^2/rad
Friction factor	0.000388 N.m.sec/rad
Pole pairs	3
Rated flux	0.1546 Wb

By using the rotor speed ω_r and the slip frequency ω_{sl}, which is given in Eq. (24):

$$\omega_{sl} = \frac{1}{\tau_r}\frac{i_{ds}{}^*}{i_{qs}{}^*} \quad (24)$$

Angle of the rotor flux θ_e:

$$\theta_e = \int(\omega_{sl} + \omega_r)dt \quad (25)$$

SIMULATION RESULTS

The performance of the five phases PMSM has been verified under MATLAB/SIMULINK environmental. SimPower system is used for modelling work. Motor parameters are followed in Table 2. The vector control based IFOC algorithm is used to achieve constant speed at transient torque condition. The effective stator side current variation also obtained. The overall proposed circuit is shown in Fig. 5. Which is

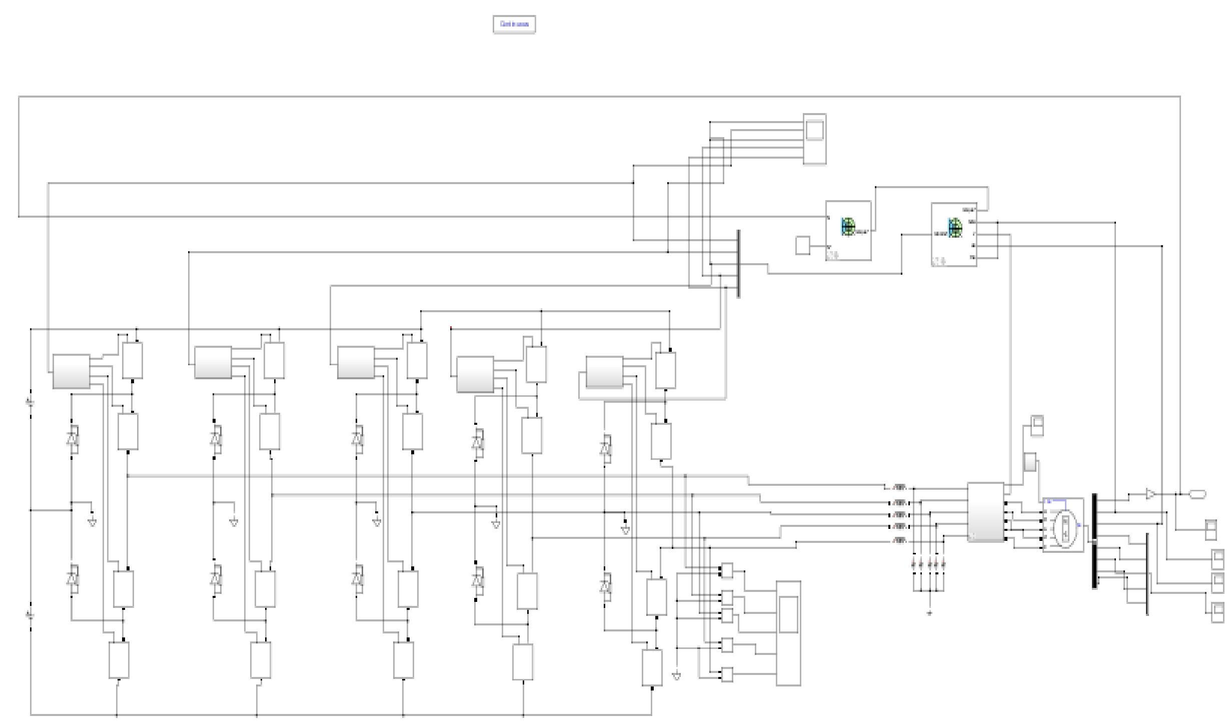


Fig. 5: Simulation circuit of the NPC with five level PMSM

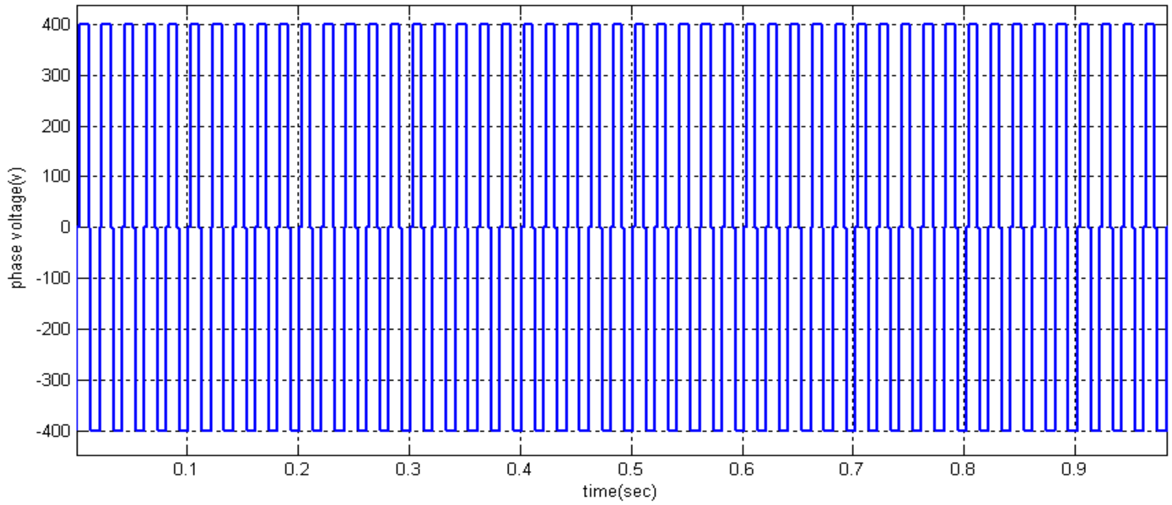


Fig. 6: Simulation result of NPC three level phase voltage

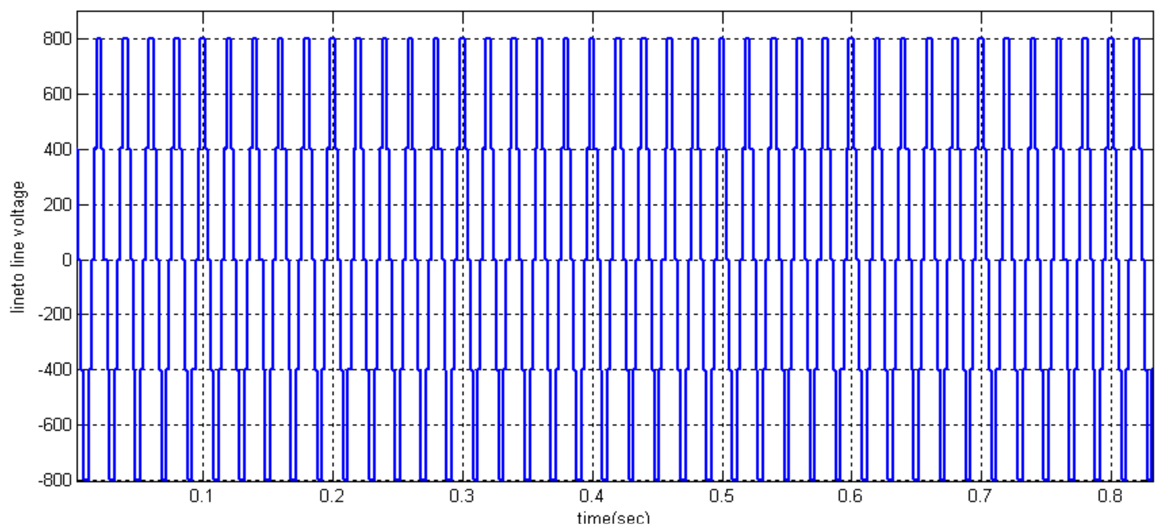


Fig. 7: Simulation result of NPC line to line voltage

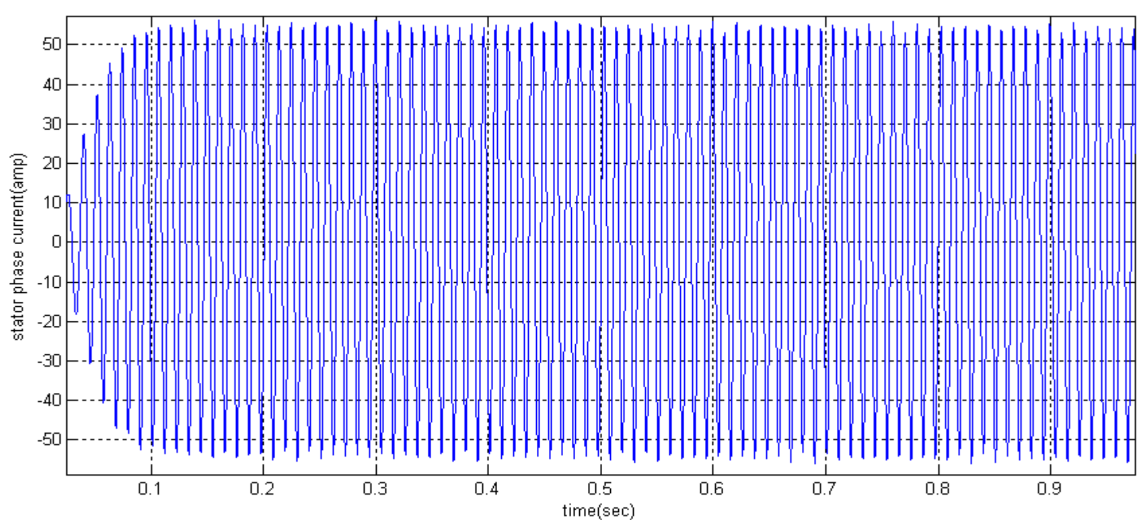


Fig. 8: Stator phase current waveform

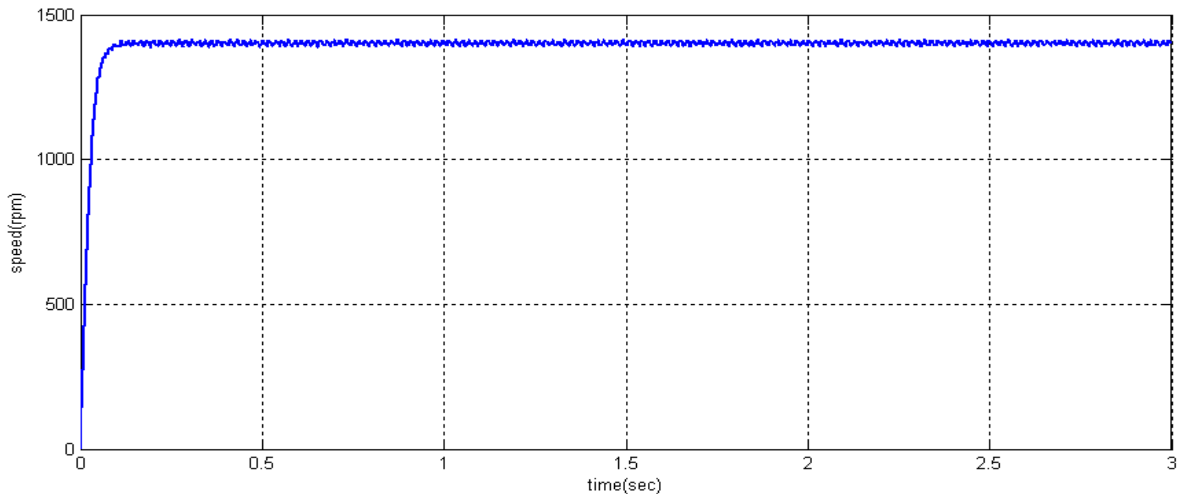


Fig. 9: Speed waveform

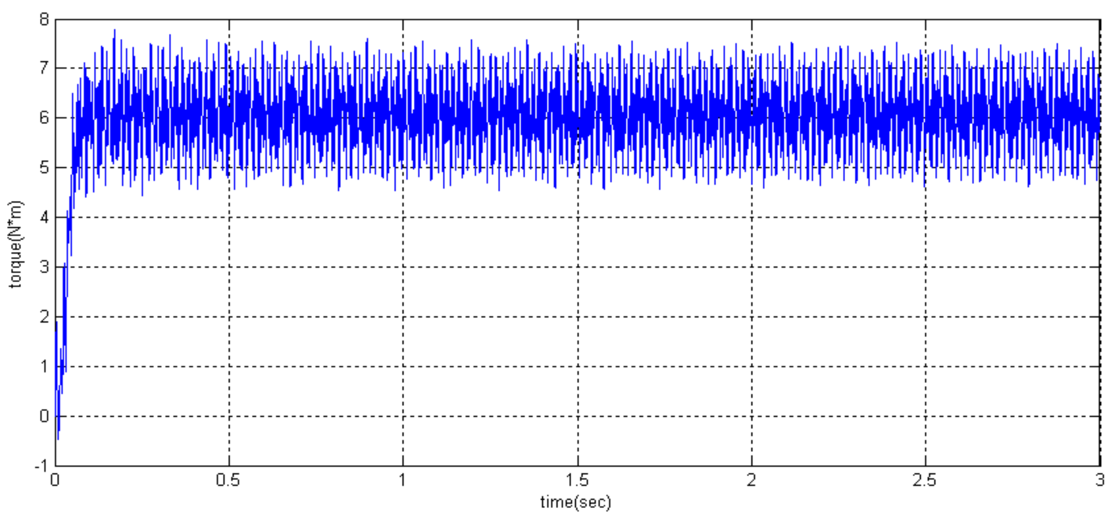


Fig. 10: Electromagnetic torque waveform

shows that the three level based NPC inverter is directly fed with five phase PMSM. The three level phase to ground voltage is shown in Fig. 6. Even though, the line to line voltage is shown in Fig. 7. Single phase stator current is shown in Fig. 8. After starting process with load condition, a transient load torque T = 7.6 N.m is achieved at 0.2 sec and at the same period constant speed has been obtained N = 1400 rpm (Fig. 9 and 10).

CONCLUSION

Voltage saturation is one of the major problems as a motor which occurs due to speed oscillations, more current fluctuations. In this study, the five-phase NPC inverter is proposed to eliminate the voltage saturation and torque ripples using PWM technique depends on the reference motor torque and flux. Indirect Field Oriented Control (IFOC) NPC inverter is suggested to reduce the voltage saturation. Since the three level neutral point clamped inverter is widely used for medium and high level applications. The simulation results have provided the excellent constant speed and transient torque response for the proposed system. This proposed controller IFOC-PWM has produced constant speed and torque response.

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