Minimization of Torque Ripples for PMBLDC Motor Drive Using Simplified IFOC Based H-Bridge Multi Level Inverter

M.Simon Darsingh1, V. Krishna Murthi2
1Research Scholar, 2Professor,
1Department of Electrical and Electronics Engineering,
2Department of Electronics and Communication Engineering,
1,2North East Frontier Technical University, Arunachal Pradesh, India
1simonphd123@gmail.com; 2krishnamurthieee16@gmail.com

Abstract— The minimization of torque ripples is requirement in high performance variable speed drive applications which need the smooth operation with minimum torque pulsations. In this paper presents the design and Simulink modeling of novel multi level five phase inverter topology for PMBLDC motor application. Moreover, the multiphase adjustable speed drives are nowadays considered as serious competitors for various applications, due to the certain advantages that have when compared to three phase motor drives. Generally the motor performances can be affected by more current harmonics, torque ripples, and voltage saturation due to wrong selection of rotor for drive. The H-bridge multiphase inverter arrangement is proposed for solving the issues also multiphase motor establishes by indirect field oriented control (IFOC) technique. Since these combinations should have more power handling capacity and produce high torque at same ampere volume of machine. In this paper an H-bridge four switches fed multiphase inverter produces the pure sinusoidal output voltage, low total harmonic distortion (THD) for PMSM. In order to analyzed and verified the proposed topology compared with conventional method of simulation results are carried out by using MATLAB/Simulink software tool.

Keywords— Multi Phase, Multi level inverter, torque ripple, voltage saturation, PMSM, IFOC, POD, vector control.

I. INTRODUCTION

In Permanent magnet synchronous motor (PMSM) drives used in all kinds more attractive in motion control applications such as High Speed Trains and electric vehicles. Due to simple structure, high power density, large torque-to-current ratio, good reliability, controllability, low inertia ratio, and good power factor, compared with induction and reluctance motors, a PMSM is to produce the air gap magnetic field rather than using electromagnets [1-2]. In PMSM drive operation, copper losses on stator and current harmonics and vibration can be occurred due to wrong selection of rotor shape, the vibration and current harmonics in permanent magnet motor is generated by more torque ripples, and voltage saturation [3]. Hence, the torque ripple minimization is highly interested by researchers in recent years. Multiphase machines have an increasing interest due to the attractive features compared with the traditional three-phase drives. Increasing the number of phases enables the reduced torque ripples in multiphase machines, thus the interest of multiphase machine has grown in the applications requiring lower vibration and acoustics [4]. Multiphase motors are able to continue the operating under the loss of one or more phases which mean higher fault tolerance thus multiphase motors are suitable candidate in applications which require higher reliability. PMSM are suitable to work in the most difficult industrial applications and to have low maintenance cost [5-6]. The five-phase PMSM has becomes the subject of many studies in the literature [7-8]. Because of those machines present a good compromise between the increasing of complexity of power electronics and the reduction of power per phase due to the greater number of phases. There are many strategies to control the multiphase PMSM [9]. One of the most popular ones is the field oriented control. This technique has been widely studied and developed since the advances in power semi-conductors technology. Indeed, it requires the calculation of Park transformation, the evolution of trigonometric functions and the regulation. This technique control offers good performances in both steady and transient state. In multi phase inverter fed motor operation, the motor requires a pure sinusoidal voltage and lower total harmonic distortion (THD). The traditionally, two-level PWM inverter requires high switching frequency or big inductance in output filter to satisfy the required THD [10-11]. A multi-level inverters (MLIs) are introduced to solve the problem. Therefore several MLI topologies have been suggested. Those are mainly classified into Neutral point clamped (NPC), flying capacitor (FC), and cascaded type [12-13]. The five phases PMSM model is derived from three phase PMSM. The proposed five-phase PMSM is the smallest commonly used phase variable based multiphase motor. Therefore n number of phases is considered in PMSM [14-15]. Where ‘n’ is the no 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. By increasing the number of phases in stator side, the machine has produced the lower space harmonic content in field. Hence the efficiency is also high; in multiphase inverter fed PMSM has equal stator windings and number of phase [15-16].
The proposed PMSM model is described by using 20-slots 18-poles which is shown in (fig. 1). The proposed motor has been designed to obtain a high speed and transient torque and also maintain the fault-tolerance capability [17]. In this paper, a circuit based on an H-bridge topology with four switches connected to the dc-link is proposed as a MLI topology. Also it is simple and the proposed PWM method uses one carrier signal for generating PWM signals. In addition of the switching sequence consider for the voltage balance of dc-link was proposed. H- Bridge Multiphase inverter required standard control techniques; compared with other control methods, IFOC algorithm is suitable for handling the dynamic and variable load application. In IFOC control method has rotor flux vector, which is implemented by using the field oriented vector control equations, is required the rotor speed. This paper proposes a detailed modeling, design and result evaluation of IFOC strategy based multiphase PMSM drive for fast dynamics operation of torque ripple minimization.

II. MODEL OF A FIVE PHASE PMSM

The poly phase induction machine performances are evaluated in (IEEE STD 112-2004), the major concentration of the test technique is to maintain standard current with improvements in instrumentation. As followed as, the multi phase synchronous motor has been developed.

![Fig.1 Coil connection and FE model of the five-phase motor](image1)

(Fig. 2) shows the phasor diagram of the phase to neutral voltage, $V_{AN}$ is taken as reference and the phase sequences which is considered at 72˚.

![Fig. 2 Relationship phasor diagram for voltage and current](image2)

The steady-state voltage equations of a five-phase PMSM in the rotor reference frame and abcde transformation can be written as follows;

Stator voltage is derived as in equation 1,

$$V_s = R_s I_s + \rho \lambda_s$$  \hspace{1cm} (1)

Air-gap flux linkages are presented by equation 2,

$$\lambda_s = \lambda_{ss} + \lambda_m$$  \hspace{1cm} (2)

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

$$\lambda_s = L_{ss} I_s + \lambda_m$$  \hspace{1cm} (3)

$L_{ss}$ is the stator inductance matrix which can contains the self and mutual inductances of the stator phases, from the above equation3, $R_s$, $I_s$, $\lambda_s$, are the stator resistance, current, flux linkages matrices respectively.
\[ V_s = [V_a V_b V_c V_d V_e]^T \]
\[ I_s = [I_a I_b I_c I_d I_e]^T \]

From equation 6, the matrix value of the stator inductances are given by \( \alpha = \frac{2\pi}{5} \)

\[ L_{ss} = \begin{bmatrix}
L_{aas} & L_{acs} & L_{ads} & L_{acs} \\
L_{bas} & L_{bcs} & L_{bds} & L_{bcx} \\
L_{cas} & L_{cxs} & L_{cds} & L_{cex} \\
L_{das} & L_{dcs} & L_{dds} & L_{dcs}
\end{bmatrix} \]

Arbitrary transformation is introduced into the phase variable into rotating arbitrary angular velocity. The transformed matrix is following;

\[ i_s = \begin{bmatrix}
\cos \theta_y & \cos \frac{2\pi}{5} & \cos \frac{4\pi}{5} & \cos \frac{6\pi}{5} & \cos \frac{8\pi}{5} \\
\sin \theta_y & \sin \frac{2\pi}{5} & \sin \frac{4\pi}{5} & \sin \frac{6\pi}{5} & \sin \frac{8\pi}{5} \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \]

From equation 7, transformation matrix \( \theta_y = 0 \), \( [K_S]^{-1} \) is derived from pseudo orthogonal property, is given in equation 8,

\[ [K_S]^{-1} = \frac{5}{2} [K_s] \]

Voltage equation is derives from transformation matrix which is multiplied with equation (1),

Where \( \lambda \) is the inertia and \( \rho \) is the number of poles pairs.

\[ [K_s] \vec{Y}_s = [K_s] R_s \vec{I}_s + [K_s] \rho \vec{\lambda}_s \]

\[ L_{qdxyo} = \begin{bmatrix}
L_q & 0 & 0 & 0 & 0 \\
0 & L_d & 0 & 0 & 0 \\
0 & 0 & L_x & 0 & 0 \\
0 & 0 & 0 & L_y & 0 \\
0 & 0 & 0 & 0 & L_0
\end{bmatrix} \]

\[ L_d = L_{ls} + L_m \]

\[ L_q = L_{ls} + L_m \]

\[ \lambda_m = \begin{bmatrix}
\lambda m \\
0 \\
0 \\
0
\end{bmatrix} \]

\[ V_q = R_s I_q + \rho \lambda_q + \omega \lambda_m + \omega L_d I_q \]

\[ V_d = R_s I_d + \rho \lambda_d q - \omega L_d I_q \]

\[ V_x = R_s I_x + \rho L_{ls} \]

\[ V_y = R_s I_y + \rho L_{ls} \]

\[ V_0 = R_s I_0 + \rho L_{ls} \]
III. TORQUE CHARACTERISTIC AND RIPPLE MINIMIZATION

Due to PWM pulse generation the high frequency pulsating torque has induced in components, inertia filers of the motors are reduced the pulsating effects. There are three essential causes are derived for torque pulsation. High frequency components, round effect with a period $2\pi/3$ angle, every commutation transient angle $\pi/3$ (B.K. Bose 2002). In synchronous motor pulsating torque highly generated in starting time (IEEE standard 1255-2000). At first, surface of the PMSM permanent magnet is enclosed with the smooth surface of the rotor inductance value of the d&q-axis are same. However the relative permeability of a permanent magnet is nearly equal to the air gap of the magnetic path. From the (fig. 3) the d-axis differs from q-axis inductance. Magnetic flux occurs in d-axis so q-axis inductance is greater than d-axis. The reluctance torque is generated by magnetic saliency from the several of inductance.

Accordingly, the generated torque of the PMSM consists of the magnetic torque and the reluctance torque as followed in equation,

$$T_e = \frac{5}{2} \left( \frac{p}{2} \right) \lambda_d iq - \lambda_q id$$

Therefore many pairs of d&q axis current can be generated in same rated torque condition.

IV. H-BRIDGE FOUR SWITCH AND FIVE-LEG INVERTER

The five phase multi level inverter arrangement has four switches and dc source connected simple structure. Because the proposed PWM method uses single carrier signal for generating PWM signals. Thus the ML arrangement has the following advantages over the conventional H-bridge inverters. Number of switching requirement is lesser than conventional multi-level inverter. Therefore, the proposed system is more reliable and cost competitive than the conventional two-level and multi-level inverters. The proposed H-bridge uses only four switches for regulating and switching losses are almost negligible. Four switches and five leg inverter have been established by comprising a dc link capacitor and active switches ($Q_p^+, Q_r^+, Q_n^-, Q_n$) located between dc-link and H-bridge. Voltage across the each switches has depends on the rated frequency and output voltage is derived from fundamental component. Thus the voltage across the dc link is $V_{dc}/2$. So, the dc -link switches ($Q_p^+, Q_r^+, Q_n^-, Q_n$) and the H-bridge switches are strategically connected to selected inverter side. Which has reduces system cost and enhanced the efficiency. The multilevel inverter has reduces current harmonics and generate a pure form or sinusoidal output voltage. The multiphase inverter is constructed by five legs and each leg has two switches; generally the multiphase (more than three phases) motors considered for high speed applications due to their inherent advantages compared with three phase drives. The multiphase inverter electric drive is limited to the controlling of the supply system. In fact it can be able to develop any static transformation system to change the phase number from three to n-phases. Five-phase VSIs covers single and three phase power applications. The main advantage of these five phase scheme is to provide always controllable and rated phase amplitude, and frequency. PMSM drive system requires sinusoidal voltage waveform. Therefore the five-phase VSI topology is operated as per the switching table: 1. However the proposed multi level inverter is operated depends on the switch angle based PWM pulse generation. Angle difference of the each leg is derived at 72°. Whereas, the (N-1) considered triangular carrier signals with the same frequency and amplitude are used so that they fully occupy continuous bands over the range +ve dc link voltage to −ve dc link voltage. Thus the proposed for five levels Inverter ($V_{DC}$, $V_{dc}/2$, $-V_{dc}/2$, $-V_{DC}$) according to the switching states. The operating modes are depends upon reference voltage $V_{ref}$. Here, the only one isolated dc source is required for the proposed 5 level inverter. The generation of the PWM signal for dc-link switches ($Q_p^+, Q_r^+, Q_n^-, Q_n$) can be explained as follows.
TABLE 1: SWITCHING FORMAT

<table>
<thead>
<tr>
<th>ANGLE /DEGREE</th>
<th>LEG1</th>
<th>LEG2</th>
<th>LEG3</th>
<th>LEG4</th>
<th>LEG5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>S1</td>
<td>S8</td>
<td>S10</td>
<td>S7</td>
<td>S9</td>
</tr>
<tr>
<td>36°</td>
<td>S1</td>
<td>S8</td>
<td>S10</td>
<td>S2</td>
<td>S9</td>
</tr>
<tr>
<td>72°</td>
<td>S1</td>
<td>S3</td>
<td>S10</td>
<td>S2</td>
<td>S9</td>
</tr>
<tr>
<td>108°</td>
<td>S1</td>
<td>S3</td>
<td>S10</td>
<td>S2</td>
<td>S4</td>
</tr>
<tr>
<td>144°</td>
<td>S1</td>
<td>S3</td>
<td>S5</td>
<td>S2</td>
<td>S4</td>
</tr>
<tr>
<td>180°</td>
<td>S1</td>
<td>S3</td>
<td>S5</td>
<td>S2</td>
<td>S4</td>
</tr>
<tr>
<td>216°</td>
<td>S6</td>
<td>S3</td>
<td>S5</td>
<td>S2</td>
<td>S4</td>
</tr>
<tr>
<td>252°</td>
<td>S6</td>
<td>S8</td>
<td>S5</td>
<td>S7</td>
<td>S4</td>
</tr>
<tr>
<td>288°</td>
<td>S6</td>
<td>S8</td>
<td>S5</td>
<td>S7</td>
<td>S9</td>
</tr>
<tr>
<td>324°</td>
<td>S6</td>
<td>S8</td>
<td>S10</td>
<td>S7</td>
<td>S9</td>
</tr>
<tr>
<td>360°</td>
<td>S6</td>
<td>S8</td>
<td>S10</td>
<td>S7</td>
<td>S9</td>
</tr>
</tbody>
</table>

**Mode 1:** A signal subtracted from the reference signal by $V_{c}$, which has compared with the carrier signal. If $v_{\text{ref}} - V_{c} > v_{\text{carrier}}$, then the switches $Q_{P}$ and $Q_{N}$ are turned ON. Five phase inverter allows the power flow. (Fig.3) shows the switch operating states at five phase angles ($72^{°}$, $144^{°}$, $216^{°}$, $288^{°}$, $360^{°}$). At mode:1 Conduction starts from phase A, the switches Q1, Q3, Q9, and, Q10, Q2 are commutated.
Mode 2: The reference and carrier signals are directly compared. If $v_{\text{ref}} > v_{\text{carrier}}$, then the top switch $Q^+$ or $Q^-$ is turned on alternately. $Q_1, Q_3, Q_5,$ and, $Q_2, Q_4$ are commutated.

Mode 3: The signal of $-v_{\text{ref}}$ is directly compared with a carrier signal. If $-v_{\text{ref}} > v_{\text{carrier}}$, then the switch $Q^+$ or $Q^-$ is turned on alternately. Five phase inverter operated at 216° angle and Q6, Q3, Q5, Q2, Q4 are commutated. Initially the Q3, Q5 switches are allows +ve current flow and Q6, Q2,Q4 are –ve conduction. Impressing excitation for phases A, B,C , D and E, while there is still current flowing on the machine coils due to the last driving stage as indicated by the free-wheeling path. Such an approach is applied subsequently to all the remaining phases. Retrieving the currents derived from all those difference states. Where the current harmonic in rotor is the other important issues were found for accurate machine mathematical modeling. Here, the mutual inductance between phases and the armature reaction because of the distortion that occurs in existing brushless dc-machines. Additionally the conventional topology should require one phase with null current every time. But recent trend requires fourth order system, while a fifth phase is not kept off condition. However, each phase is permitting the dynamic operation and each stage has its own current, equivalent back emf. The induced voltage due to the changing emf delivers mechanical energy. Thus, the ripple less pure form of torque should be induced in five-phase BPM machine has to account for the air-gap flux distortion by the armature reaction.

### TABLE 2: PARAMETER SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H-Bridge topology</strong></td>
<td></td>
</tr>
<tr>
<td>DC link voltage</td>
<td>100V</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>2200μF</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>230μH</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>100μF</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td><strong>Five Phase PMSM</strong></td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td>1.4 Ω</td>
</tr>
<tr>
<td>d-axis inductance</td>
<td>6.6 mH</td>
</tr>
<tr>
<td>q-axis inductance</td>
<td>5.8 mH</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>6.6 mH</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.00176N.m.S²/rad</td>
</tr>
<tr>
<td>Friction Factor</td>
<td>0.000388 N.m.s/rad</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>3</td>
</tr>
<tr>
<td>Rated flux</td>
<td>0.1546 Wb</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

The proposed estimation demonstrated using MATLAB software. The overall performance of the proposed PMBLDC drive system operation is shown in Fig (4 & 5). Its explained overall simulation circuit and respective IFOC controller part. The simulation parameters are given in table 2. the indirect field oriented current and speed control included in the drive system is fed with dc link connected four switch based multilevel inverter.
The simulation results were considered for 11kW PMBLDC system. Switching frequency and sampling period Ts are 10 kHz and 100μs respectively. The good performance of estimation can be confirmed for both 1000rpm and 1500rpm. Also, the fast response to step change of speed can be seen through the estimated value. Therefore the following figures should represents varies steady state operations.
In (Fig. 6 & 7) shows the results of parameter estimation with overall performance of the proposed system. Also, the simulation was performed in two different systems (proposed and conventional) speed at 1500 rpm. Also, these results are categorized as performance during transient and steady state conditions. (Fig 8 & 9) shows the conventional system performance. The five level voltages for each phase are shown in (fig. 10). Maximum torque state can be achieved at 1500 rpm speed condition. Moreover, the actual torque ripple range should be greater than the reference torque (7-12 N*m). Ripple minimization of torque waveform is shown in (Fig. 11).
VI. CONCLUSION

This paper describes the design, and simulink modeling of novel multi level five phase inverter topology PMBLDC motor to minimize torque ripple. The multiphase motor establishes by indirect field oriented control strategy and POD PWM mode, which avoided large current and torque ripple. H-bridge four switches fed multiphase inverter produces the pure sinusoidal output voltage, low total harmonic distortion (THD) for PMSM. Finally, simulation results were presented and compared with conventional method. It can provide feasible and effective reduction of torque ripple and voltage saturation of the proposed strategy.
REFERENCE


