CHAPTER-III

MODELING AND IMPLEMENTATION OF PMBLDC MOTOR DRIVE

3.1 GENERAL

The PMBLDC motors used in low power applications (up to 5kW) are fed from a single-phase AC source through a diode bridge rectifier (DBR) followed by a smoothing DC capacitor. The commutation of the PMBLDC motor is accomplished electronically by a three-phase voltage source inverter (VSI) based on rotor position signals acquired using Hall effect sensors as shown in Fig. 3.1. However the Hall effect sensors reduce the reliable operation of these motors at high temperature and in harsh environment, besides increasing the motor volume and cost. Therefore, a need arises for removal of position sensors and operate the PMBLDC motors in position sensorless mode. Further, the power quality issues of complete position sensorless drive, also, need to be resolved. Accordingly, conventional the PMBLDC motor drive is modeled and simulated to analyze its behaviour with Hall sensors, so that the position sensorless operation can be planned and designed.

This chapter deals with the operating modes of the PMBLDC motor drive, modeling, simulation and hardware implementation of a PMBLDC motor drive operated under speed control with varying DC link voltage.

Fig. 3.1 PMBLDC motor drive operated in sensored mode
The simulated performance of the PMBLDC motor drive in sensored mode is analyzed for various power quality indices under dynamic and steady state conditions. The obtained results are validated on a prototype developed in the lab with the help of a digital signal processor (DSP) DSP 2812 (TMS320F2812, 2001).

3.2 CONFIGURATION AND OPERATING PRINCIPLE OF PMBLDC MOTOR DRIVE

The control of a PMBLDC Motor requires the information of commutation points only and Hall sensors are mostly used to get the PM rotor position information. The voltage source inverter performs the duty of commutator in electronic form. The inverter can be operated in two modes, namely 120° conduction mode and PWM control mode.

3.2.1 120° Conduction Mode

- The inverter switches (say S1-S6) are switched on so that the input DC current \( I_{dc} \) is symmetrically located at the center of each phase back-EMF wave Fig. 3.2.
- At any instant in time, one switch from the upper group (S1,S3,S5) and one switch from the lower group (S2,S4,S6) are on together, but both switches from same leg should not turn on simultaneously.

Three Hall sensors are used to ensure the correct timing of the switching/commutation of the devices. The related waveforms are shown in Fig. 3.2.

3.2.2 PWM Current Control Mode

- In this mode, the inverter controls the current and voltage supplied to PMBLDC motor by using PWM switching, in addition to commutation control. Varying the duty cycle of PWM results in variable average output current/voltage of the inverter.
- Two chopping modes can be used: feedback mode and freewheeling mode.

In feedback mode, two switches are switched on and off together (e.g. S1 and S6).
whereas in freewheeling mode, the chopping is performed only on one switch at a time.

Fig. 3.2 Back-EMF and current waveforms of a PMBLDC motor in 120° conduction mode

- During on time of the switches (considering S1 and S6 pair), the currents of phases a and c shall increase. However, during the off time of these switches, the currents will decrease through feedback diodes of respective switches.

- The average terminal voltage $V_{av}$ will be determined by the duty cycle of the PWM pulses applied on the VSI switches.

In the freewheeling mode of operation, when $S_6$ is turned on $V_{dc}$ is applied across phases ‘a’ and ‘c’, and the current increases. When $S_6$ is turned off, freewheeling current flows through $S_1$ and feedback diode of $S_5$ (effectively short-circuiting the motor terminals) and the current decreases (due to the back-EMF). The back-EMF and current waveforms for PWM control mode are shown in Fig. 3.3.
3.3 MODELING OF PMBLDC MOTOR DRIVE

The PMBLDC motor drive mainly consists of a three phase VSI, an electronic commutator and a PMBLDC motor.

3.3.1 Voltage Source Inverter (VSI)

The three phase voltage source inverter (VSI) has six switches in bridge configurations for feeding PMBLDC Motor. It uses insulated gate bipolar transistors (IGBTs) to reduce the switching loss and stress, because of its operation at lower frequency compared to PFC converter. Fig. 3.4 given below shows the PMBLDC motor drive fed by a VSI, in which only two switches are on at any time, one from upper group (i.e. S1, S3, S5) and one from lower group (i.e. S2, S4, S6). From this logic, voltage across ‘a’ phase for the star connected windings of the PMBLDCM can be calculated as

\[ V_{ao} = \frac{V_{dc}}{2} \text{ when } S5=\text{On and S6=Off} \]  

(3.1)
\[ V_{ao} = -V_a/2 \text{ when } S5 = \text{Off and } S6 = \text{On} \]  

(3.2)

\[ V_{ao} = 0 \text{ when } S5 \& S6 \text{ both Off} \]  

(3.3)

\[ V_{an} = V_{ao} - V_{no} \]  

(3.4)

In the equivalent circuit of PMBLDC motor drive \( V_{ao} \), \( V_{bo} \), \( V_{co} \), and \( V_{no} \) are voltages of 3-phases and neutral point (n) with respect to virtual mid-point of the DC link voltage shown as ‘o’ in Fig. 3.4. The voltages \( V_{an} \), \( V_{bn} \), \( V_{cn} \) are voltages of 3-phases with respect to neutral point (n). The voltages (\( V_{bo} \), \( V_{co} \), \( V_{bn} \), \( V_{cn} \)) for other two phases of the VSI feeding PMBLDCM are generated using similar logic.

![Equivalent circuit of PMBLDC motor drive](image)

Fig. 3.4 Equivalent circuit of a VSI fed PMBLDC motor drive

### 3.3.2 Electronic Commutator

To provide the rotation, three Hall signals (\( H_a \), \( H_b \) and \( H_c \)) are fed to an electronic commutator to generate the switching signals for VSI as shown in Table 3.1.

Table 3.1 Switching signals for VSI, based on Hall signals

<table>
<thead>
<tr>
<th>Hall Signals</th>
<th>Switching signals for VSI switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_a )</td>
<td>( H_b )</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
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<tr>
<td>1</td>
<td>0</td>
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<td>1</td>
<td>0</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.3.3 PMBLDC Motor

The modeling equation for a PMBLDC motor includes

\[ V_{an} = R_i a + L(di_a/dt) + M(di_b/dt) + M(di_c/dt) + e_a \]  

(3.5)

\[ V_{bn} = R_i b + L(di_b/dt) + M(di_c/dt) + M(di_c/dt) + e_b \]  

(3.6)
\[ V_{cn} = R_i + L(d_i/dt) + M(d_i/dt) + e_c \quad (3.7) \]

where \( V_{an}, V_{bn} \) and \( V_{cn} \) are phase to neutral voltages, \( i_a, i_b, i_c \) are phase currents, \( L \) is self inductance per phase of the three phase windings and \( M \) is the mutual inductance between two phases. Back-EMF in the three star connected windings are \( e_a, e_b \) and \( e_c \) respectively (Singh et al., 2010).

In the matrix form the above equation can be written as

\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
L & M & M \\
M & L & M \\
M & M & L
\end{bmatrix}
p
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} \quad (3.8)
\]

where \( p = \) derivative operator. As the motor windings are star connected so

\[ i_a + i_b + i_c = 0 \]

\[ i_b + i_c = -i_a \quad (3.9) \]

so \( V_{an} = Ri_a + L(d_i/dt) + M(d(i_b+i_c)/dt) + e_a \)

or \( V_{an} = Ri_a + L(d_i/dt) - M(d(i_a)/dt) + e_a \)

or \( V_{an} = Ri_a + (L - M) (d_i/dt) + e_a \)

or \( V_{an} = Ri_a + L_a (d_i/dt) + e_a \quad (3.10) \)

where \( L_a \) is total inductance per phase due to self inductance and mutual inductance felt by other two phase windings. Similarly for other two phases

\[ V_{bn} = Ri_b + L_a(d_i/dt) + e_b \quad (3.12) \]

\[ V_{cn} = Ri_c + L_a(d_i/dt) + e_c \quad (3.13) \]

Back-EMF is given by the relation

\[ e_x = K_b f_x(\theta) \omega, \text{ x= a, b and c phase} \quad (3.14) \]

where \( x \) can be phase a, b or c and accordingly \( f_x(\theta) \) represents function of rotor position with a maximum value of \( \pm 1 \), identical to trapezoidal induced emf given as,

\[ f_a(\theta) = 1 \quad \text{for } 0 < \theta < 2\pi/3 \quad (3.15) \]

\[ f_a(\theta) = \{(6/\pi)(\pi-\theta)\}-1 \quad \text{for } 2\pi/3 < \theta < \pi \quad (3.16) \]
The functions $f_a(\theta)$ and $f_c(\theta)$ are similar to $f_a(\theta)$ with a phase difference of 120° and 240° respectively.

Therefore, the electromagnetic torque can be expressed as,

$$T_e = K_b\{f_a(\theta) i_a + f_b(\theta) i_b + f_c(\theta) i_c\}$$

The speed derivative is given as,

$$p\omega_r = (P/2) \left( T_e - T_l - B\omega_r \right)/(J)$$

The derivative of rotor position is given as,

$$p\theta = \omega_r$$

where $P$ is number of poles, $T_l$ is load torque, $J$ is moment of inertia (kg-m$^2$) and $B$ is friction coefficient (Nms/Rad). These equations (3.19-3.21) represent the dynamic model of the PMBLDC motor.

### 3.4 MATLAB SIMULATION MODEL OF PMBLDC MOTOR DRIVE

Based on the above modelling and design equations, a model of the PMBLDC motor drive is developed in the Matlab-Simulink environment as depicted in the Fig. 3.5 to evaluate the performance of the drive under different operating conditions.
3.5 HARDWARE IMPLEMENTATION OF PMBLDC MOTOR DRIVE

The hardware implementation of the PMBLDC motor drive requires signal conditioning circuit for current sensor and voltage sensor circuits which are discussed in detail below.

3.5.1 Development of Signal Conditioning Circuit For Current Sensors

The current sensors used for sensing various currents of the PMBLDCM drive are decided on the basis of maximum current to be sensed and the maximum voltage limit of ADC channels of the processor used for execution of control algorithm. The schematic diagrams of a signal conditioning circuit of the current sensor are shown in the Fig. 3.6 (ABB, 2004)

Current sensors are electronic transformers using closed loop Hall effect technology. These are used for the measurement of alternating, direct, and impulse currents, with galvanic insolation between the primary and secondary circuits. The primary current $I_p$ flowing through the sensor creates a primary magnetic flux. The magnetic circuit channels this magnetic flux. The Hall probe placed inside the air gap of the magnetic circuit develops a voltage proportional to this flux. The electronic circuit is used to amplify this voltage and converts it into a secondary current $I_s$. The output
provided by current sensor is always instantaneous value of current. The secondary
output current \( I_s \) is therefore exactly proportional to the primary current at any moment.
This secondary current \( I_s \) can be passed through a measuring resistance \( R_M \). The
measuring voltage \( V_M \) at the terminals of this measuring resistance \( R_M \) is therefore also
exactly proportional to the primary current \( I_p \). The measuring resistance \( (R_M) \) of the
current sensor circuit and the voltage \( (V_A) \) required for the power supply are calculated
using various design equations and specifications data provided by the current sensor
manufacturer. The current sensor used in this work is TELCON make HTP 25 model.

The secondary circuit current \( (I_S) \) is calculated as

\[
N_p I_p = N_s I_s \tag{3.22}
\]

Where \( I_p \) is the primary current to be measured and \( N_p/N_s \) is the turns ratio of the
current sensor provided in the data sheet.

The measuring resistance \( (R_M) \) is calculated as,

\[
R_M = \frac{V_M}{I_S} \tag{3.23}
\]

Where \( V_M \) is the required output voltage from the sensor for maximum input current
\( (I_p) \).

The power supply voltage \( (V_A) \) required for desired \( V_M \) can be obtained as

\[
V_A \geq (e + V_S + V_M) \tag{3.24}
\]
Where $V_S \approx I_S R_S$ is the voltage drop across the secondary winding, the values of secondary winding resistance ($R_S$) and voltage drop ($e$) across output transistor and protection diode are obtained from the current sensor’s datasheet. Fig. 3.7 shows the developed hardware circuit for current sensor using HTP 25 (HTP 25, 2000).

### 3.5.2 Development of Signal Conditioning Circuit for Voltage Sensors

The schematic diagram and equivalent circuit of the voltage sensor are shown in Fig. 3.8. The voltage sensor (LV-25 P, 2012) used in this work is LEM make, LV 25-P as shown in Fig. 3.9. The measuring resistance ($R_M$) of the voltage sensor circuit and the voltage ($V_A$) required for the power supply are calculated using various design equations and specification data, provided by the voltage sensor manufacturer.

![Fig. 3.8 Voltage sensor schematic diagram and its equivalent circuit](image)

The primary circuit current ($I_P$) should be kept at nominal current rating ($I_{PN}$) of the sensor which can be controlled by external resistance ($R_E$). For measurement of a voltage $V_P$ the total resistance $R$ is calculated as,

$$R = \frac{V_S}{I_{PN}}$$  \hspace{1cm} (3.25)

The required value of external resistance ($R_E$) and its power rating ($P_{RE}$) are obtained as,

$$R_E = R - R_P$$  \hspace{1cm} (3.26)

$$P_{RE} = I_E^2 R_E$$  \hspace{1cm} (3.27)

where $R_P$ is the primary resistance of the voltage sensor given in its datasheet.

The secondary circuit current ($I_S$) is calculated as,
\[ N_P I_P = N_S I_S \]  
(3.28)

where \( N_P/N_S \) is the turns ratio of the current sensor given in its data sheet.

![Image of a circuit board](image)

Fig. 3.9 Developed signal conditioning circuit for voltage sensor

The measuring resistance \( (R_M) \) is calculated as,

\[ R_M = V_M/I_S \]  
(3.29)

where \( V_M \) is the desired output voltage from the sensor for maximum input current \( (I_P) \).

The supply voltage \( (V_A) \) required for desired \( V_M \) can be obtained as,

\[ V_A \geq (e + V_S + V_M) \]  
(3.30)

where \( V_S \) \((\approx I_S R_S)\) is the voltage drop across the secondary winding, the values of secondary winding resistance \( (R_S) \) and voltage drop \( (e) \) across output transistor and protection diode are obtained from the current sensor’s datasheet.

### 3.5.3 Hardware Implementation of DBR-DC Link Capacitor-VSI fed PMBLDC Motor

Fig. 3.10 shows the developed hardware prototype of a PMBLDC motor drive which uses a VSI along with a single-phase DBR and a DC link capacitor. The PMBLDC motor used for hardware implementation is a 1.1 kw rated motor with 2.2 Nm rated torque with DC link voltage 310 volt (detailed data given in Appendix). The shaft of the PMBLDC motor is coupled with a separately excited DC generator for application of mechanical load in terms of equivalent electrical load as shown in Fig. 3.11. The developed hardware is operated for various load settings at different speeds of
the PMBLDC motor without any control by simply applying DC voltage at VSI input terminals to observe the performance of the PMBLDC motor drive in a wide range of speed and voltage. The speed of the PMBLDC motor is controlled by varying the DC link voltage of the VSI, and the VSI is switched at natural commutation instants (electronic commutation of the PMBLDC motor) for low switching losses.

![Developed test set up of PMBLDC motor drive](image1) ![PMBLDC motor coupled with separately excited DC generator for application of mechanical load in terms of equivalent electrical load](image2)

### 3.6 RESULTS AND DISCUSSION

The obtained results of simulation as well as hardware implementation of a conventional PMBLDC motor drive under various operating conditions such as starting, loading, free running at basic motor load are depicted in Fig. 3.12 to check the performance of the drive without any control. A single phase AC source is used to feed the VSI through a DBR and a DC link capacitor. Fig. 3.12 shows the steady state simulated results for the PMBLDC motor drive at 1500 rpm under basic motor load. Basic motor load consist of motor’s own inertial load, the coupling motor weight and inertia load which is approximately 0.3 Nm. The source current shown is a peaky current and therefore rich in harmonics with poor power factor. Fig. 3.13 shows the FFT analysis of source current depicting the high value of THD. Simulated results are validated on the hardware for various operating
conditions. The hardware results are recorded using a power analyzer (Fluke make) and a four channel mixed signal oscilloscope (MSO- Agilent make) to demonstrate operation of various components of the PMBLDC motor drive simultaneously.

![Graph](image1)

**Fig. 3.12** Simulated performance of the PMBLDC motor drive at 1500 rpm, under basic load condition

![Graph](image2)

**Fig. 3.13** FFT analysis of input AC at 1500 rpm under light load condition

### 3.6.1 Performance of PMBLDC Motor Drive during Starting

For the performance of the PMBLDC motor drive during starting, DC link voltage is increased slowly so that the speed of PMBLDC motor is increased in such a manner that the source and motor current remains within the specified limit. It can be observed from Fig. 3.14, that during speed up, motor draws high current and thereafter the current reduces to its no load value. It is observed in the hardware results that as the motor speed up, the frequency of the motor current increases.
3.6.2 Performance of PMBLDC Motor Drive under Basic Motor Load

Figs. 3.15-3.16 show the steady state simulated and experimental performance of the PMBLDC motor drive at 1200 rpm with basic motor load applied on the PMBLDC motor shaft. The current drawn by motor is 1 A at 72 volt DC link voltage to maintain 1200 rpm.

3.6.3 Performance of PMBLDC Motor Drive with Load

The simulated and hardware performance of the PMBLDC motor drive under light load condition is shown in Figs. at 1500 rpm. Figs show the steady state results at 1500 rpm with 95 volt DC link voltage. Moreover, motor speed is maintained up to 1500 rpm under loading condition while observing the increase in current and voltage at
DC link. Figs. 3.18-3.19 show that motor draws around 2 A current to maintain the speed during steady state condition.

3.6.4 Power Quality Performance of PMBLDC Motor Drive

The obtained results show that the power quality at AC mains of the PMBLDC motor drive remains poor with all loads and operating conditions due to charging current of the DC link capacitor. The performance of the PMBLDC motor drive in terms of power quality is simulated and shown in Figs. 3.19-3.20 which are validated on the hardware as shown in Figs. 3.21-3.22. It is observed that the value of total harmonic distortion (THD) at AC mains current is very high and is not acceptable as per international power quality standards. A very low value of PF (around 0.72) and high value of crest factor (CF) is shown during wide range of speed.
Table 3.2 given below shows the required DC link voltage to maintain the desired speed in RPM under basic motor load condition. Fig. 3.23 depicts the speed versus DC link voltage plot that shows the linear relationship between the two.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Speed</th>
<th>DC link voltage at basic motor load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>100 rpm</td>
<td>10 volt</td>
</tr>
<tr>
<td>2.</td>
<td>200 rpm</td>
<td>15 volt</td>
</tr>
<tr>
<td>3.</td>
<td>300 rpm</td>
<td>20 volt</td>
</tr>
<tr>
<td>4.</td>
<td>400 rpm</td>
<td>25 volt</td>
</tr>
<tr>
<td>5.</td>
<td>500 rpm</td>
<td>31 volt</td>
</tr>
<tr>
<td>6.</td>
<td>600 rpm</td>
<td>36 volt</td>
</tr>
<tr>
<td>7.</td>
<td>700 rpm</td>
<td>42 volt</td>
</tr>
<tr>
<td>8.</td>
<td>750 rpm</td>
<td>44 volt</td>
</tr>
<tr>
<td>9.</td>
<td>800 rpm</td>
<td>46.5 volt</td>
</tr>
<tr>
<td>10.</td>
<td>900 rpm</td>
<td>52 volt</td>
</tr>
<tr>
<td>11.</td>
<td>1000 rpm</td>
<td>57.5 volt</td>
</tr>
<tr>
<td>12.</td>
<td>1100 rpm</td>
<td>62 volt</td>
</tr>
<tr>
<td>13.</td>
<td>1200 rpm</td>
<td>68 volt</td>
</tr>
<tr>
<td>14.</td>
<td>1250 rpm</td>
<td>70 volt</td>
</tr>
<tr>
<td>15.</td>
<td>1300 rpm</td>
<td>73 volt</td>
</tr>
<tr>
<td>16.</td>
<td>1400 rpm</td>
<td>80.7 volt</td>
</tr>
<tr>
<td>17.</td>
<td>1500 rpm</td>
<td>86.5 volt</td>
</tr>
</tbody>
</table>
3.7 CONCLUSIONS

Detailed modelling of various components of a PMBLDCM drive has been carried out and the developed model is simulated in MATLAB-SIMULINK environment for a 1.1 kW, 2.2 Nm rated torque PMBLDC motor. The simulated performance of the PMBLDCM drive is validated on a test setup developed in the laboratory. Simulated performance of the PMBLDCMD presented under different operating conditions such as starting, on basic motor load and under loading condition. The simulated performance of the PMBLDCMD is validated under similar operating conditions on the test set up developed in the laboratory. It can be concluded from the presented results that the simulated results closely match with the test results under various operating conditions. Test results validate the developed simulation model of the PMBLDCMD. However, to reduce the volume of PMBLDCM, position sensorless control of PMBLDC motor is potential area for further investigation. Various methods for position sensorless control has been reported in the literature however the technology is not matured up to commercial level.
As most of the PMBLDCM applications are operated from utility mains therefore the power quality indices of the PMBLDCMD are of serious concern and need suitable mitigation techniques to control power quality problems at AC mains.

Hence to obtain a complete PMBLDCM drive there is a requirement of power factor correction (PFC) converter at front end, and a position sensorless controlled PMBLDCMD. Moreover reduction of sensors for control of the PMBLDCMD shall also be taken up as a potential area for further investigation.