CHAPTER 3

PMBLDC MOTOR DRIVES

3.1 General

In permanent magnet motors, the field is generated by permanent magnets mounted on the rotor, and the rotating field is generated by means of stator windings, survey chart of PMBLDC motor drives and improvements are shown in Figure 3.1. A permanent magnet rotor field can be of two shapes, sinusoidal and trapezoidal. The motors have a sinusoidal rotor field, and hence a sinusoidal back-emf as shown in Figure 3.2. It behaves like synchronous ac machines and is usually called Permanent Magnet Synchronous Machine (PMSM). For a brushless dc (BLDC) motor, the back-emf is trapezoidal as shown in Figure 3.3.

Figure 3.1 Survey Chart of PMBLDC Motor drives and Improvements
The brushless dc motor is actually a permanent magnet ac motor whose torque-current characteristics are similar to dc motor. Instead of commutating
the armature current using brushes, electronic commutation is used. This eliminates the problems associated with the brush and the commutator segments, thereby making a BLDC more rugged as compared to a dc motor. BLDC is a modified PMSM motor; with the modification being that the back-emf is trapezoidal instead of being sinusoidal as in the case of PMSM. The “commutation region” of the back-emf of a BLDC motor should be as small as possible, while at the same time it should not be so narrow as to make it difficult to commutate a phase of that motor when driven by a Current Source Inverter. The flat constant portion of the back-emf should be 120° for a smooth torque production.

The position of the rotor can be sensed by using an optical position sensors and its associated logic. Optical position sensors consist of phototransistors (sensitive to light), revolving shutters, and a light source, or even Hall effect position sensors. Generally named as Hall_A, Hall_B, and Hall_C, each having a lag of 120° with respect to the earlier one. Three hall position sensors are used to determine the position of the rotor field. These particular Hall position sensors, based on Hall effect principle, generate a TTL compatible output. Depending on the back-emf, signal is generated and rotor position is sensed.

A conventional BLDC drive is illustrated in Figure 3.4. It consists of a dc voltage supplied by a rectifier arrangement, a dc link capacitor for energy storage, a Voltage Source Inverter (VSI) consisting of transistor switches, and finally, the three-phase output of the inverter is supplied to the motor. For rotor position sensing, either a Hall position sensor or an optical shutter arrangement is used along with some sort of microcontroller/microprocessor.
3.2 Permanent Magnet Brushless DC Motor

As the flux distribution in a PM brushless dc motor is trapezoidal, that is non sinusoidal flux distribution; it is prudent to derive a model of the PMBLDC motor in phase variables. Here the assumptions made include induced currents in the rotor neglected due to stator harmonic fields and also the iron and stray losses. The motor is considered to have three phases, even the procedure supports for multi phases.

The BLDC motor model is explained as, the electromagnetic torque, $T_{em}$ is linearly proportional to the armature current $i_a$. Whereas $T_{em} = K_T i_a$, where $K_T$ is the torque constant.

The back-emf in a BLDC motor is linearly proportional to the rotational speed of the shaft. The back-emf is proportional to the speed of the motor and its direction is given by Fleming’s right hand rule. Considering that in a magnetic field of intensity $B$, a conductor of length $l$ on the edge of rotor of radius $r$ is
rotating at an angular velocity of $\omega$ radians per second. Then the speed of the conductor is given by

$$\text{Velocity (v)} = \omega \times r. \quad (3.1)$$

The emf $e$ generated in that conductor is given by

$$e = \omega rBl. \quad (3.2)$$

Conventionally the number of conductors in an electrical machine is given by $Z$, and if the number of conductors in series is $\frac{Z}{2}$, the series back-emf is given by $e$, as

$$e = \omega m rBl \frac{Z}{2} \quad (3.3)$$

In terms of the magnetic flux,

$$e = K_E \omega_m \text{ where } K_E \text{ is the back emf constant.}$$

The model of a BLDC consisting of three phases is explained by means of equations, since there is no neutral used, the sum of the three phase currents must add up to zero.

$$i_a + i_b + i_c = 0 \quad (3.4)$$

$$i_a + i_b = -i_c \quad (3.5)$$
Considering all the three phases following equations are used to model the two pole three phase BLDC motor.

\[
\begin{pmatrix}
v_a \\
v_b \\
v_c
\end{pmatrix} =
\begin{pmatrix}
R_a & 0 & 0 \\
0 & R_b & 0 \\
0 & 0 & R_c
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix}
+ \frac{d}{dt}
\begin{pmatrix}
L_{a} & L_{ba} & L_{ca} & i_a \\
L_{ab} & L_{b} & L_{cb} & i_b \\
L_{ac} & L_{bc} & L_{c} & i_c
\end{pmatrix}
\begin{pmatrix}
i_a \\
i_b \\
i_c
\end{pmatrix}
+ \begin{pmatrix}
e_a \\
e_b \\
e_c
\end{pmatrix}
\tag{3.6}
\]

If the permanent magnet inducing the rotor field is in the shape of an arc, it requires that the inductances be independent of the rotor position, hence

\[L_a = L_b = L_c = L_p\]  \tag{3.7}

Considering the symmetry of the above matrix in addition to independence w.r.t the rotor position,

\[L_{ab} = L_{ba} = L_{bc} = L_{cb} = L_{ca} = L_{ac} = M\] \tag{3.8}

Above equation reduces to

\[
\begin{pmatrix}
v_a \\
v_b \\
v_c
\end{pmatrix} =
\begin{pmatrix}
R_a & 0 & 0 \\
0 & R_b & 0 \\
0 & 0 & R_c
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix}
+ \frac{d}{dt}
\begin{pmatrix}
M & M & M \\
M & L_p & M \\
M & M & L_p
\end{pmatrix}
\begin{pmatrix}
i_a \\
i_b \\
i_c
\end{pmatrix}
+ \begin{pmatrix}
e_a \\
e_b \\
e_c
\end{pmatrix}
\tag{3.9}
\]

From above two equations we get
\[
\begin{pmatrix}
  v_a \\
  v_b \\
  v_c
\end{pmatrix}
= \begin{pmatrix}
  R_a & 0 & 0 \\
  0 & R_b & 0 \\
  0 & 0 & R_c
\end{pmatrix}
\begin{pmatrix}
  Lp - M & 0 & 0 \\
  0 & Lp - M & 0 \\
  0 & 0 & Lp - M
\end{pmatrix}
\begin{pmatrix}
  i_a \\
  i_b \\
  i_c
\end{pmatrix} + \begin{pmatrix}
  i_a \\
  i_b \\
  i_c
\end{pmatrix}
\]

\[
\frac{d}{dt} \begin{pmatrix}
  i_a \\
  i_b \\
  i_c
\end{pmatrix} + \begin{pmatrix}
  e_a \\
  e_b \\
  e_c
\end{pmatrix}
\] (3.10)

Rearranging the equations, we have obtained equations in a form suitable for simulation.

Following the efficient modelling for a brushless DC motor drive, as advised by Luk and Lee (1994) there arises the desirability of cost efficient simulation of the system at the design stage. The proposed mathematical model, developed in the de facto industry standard MATLAB environment, allows design engineers a quick investigation into the performance of the system when variations such as load or sampling rate of the digital controller occur. A user-friendly interface to the input of simulation parameters has been incorporated. The modular approach adopted facilitates program maintenance and further development. Some simulation and validating results are included. Since the practical implementations will usually involve such frame of transformation and other real time computations, a delay in outputting the actuation signal is incurred. Such delays are therefore included in the model.

The BLDC motor drive model offers an efficient and user friendly environment to examine implementation aspects encountered in the design of such drive systems. The software allows the user to trade off implementation details of the drive system at the design stage and is particularly useful for cost-critical projects. Since it runs on the platform of the industry accepted MATLAB simulation package, high portability and good software support are assured in the future. The package is both a viable tool for designing BLDC motor control systems and has been used as an invaluable teaching tool.
3.2.1 Dynamic behavior of BLDC motor using finite element analysis

Finite element method has long been used for deriving the motor model’s lumped parameters, the prediction and optimization of the system’s behaviour is often performed using a circuit simulation software. New and powerful features, namely the coupling of circuit equations to the finite element solution and the integration of the rotor motion within the solving process, open new ways for modern finite element software to directly model the drive system’s dynamic behaviour.

Moving air-gap technique and coupling with external circuits deal with multiple static positions, constant speed and mechanical coupling. The external coupling effects are also considered. Stator no load voltage, flux density harmonics and related rotor positions are also analysed. Apart from cogging torque, stator phase inductances involving both the effects of self and mutual inductances are studied. From the work it is possible to use a FEM technique to obtain a direct prediction of a motor’s dynamic behaviour. It produces best results and shows circuit simulation for dynamic studies. The FEM direct prediction of the dynamic behaviour of brushless DC motors must take into account the rotor motion and the drive and electrical control circuits.

3.2.2 Power converter topology a review

Cost minimization of the permanent magnet brushless dc motor drive is of immense interest to the industry at present, due to the opening up of a large number of applications to variable-speed operation. The designed converter topology is same as “C dump” as used in switched reluctance motor. This topology uses more than one switch per phase for operation but less than two switches per phase that is with n+1 switches for n-phase machines.
In this work it is reviewed for four quadrant operation. The C-dump converter for a three-phase system, shown in Figure 3.5, is considered for this work. It has four power switches and four power diodes, with one of each for each phase winding and one set for energy recovery from the capacitor. Since the phase has only one switch, the current in it could only be unidirectional and, hence, it is very much similar to the half-wave-converter-driven PMBLDC in operation. It can be able to perform both motoring and regenerative operation successfully. Design guidelines for the C-Dump topology include a close watch on DC link voltage, phase switches, phase diodes, energy recovery chopper and capacitor. The drawback from C-Dump topology is that it has twice the copper loss as compared to full wave inverter and it improves the switching losses.

The next method of converter design sown in Figure 3.6 includes same as n+1 switches for n phase machine but a switch T is made common with a diode D, inductor L and capacitor C form a step down chopper power stage. The chopper power stage varies the input DC source voltage to the machine.
windings. Since there is one switch per phase makes unidirectional and similar to a half wave converter driven PMBLDC motor. Here also both motoring and regenerative operation is done successfully.

![Image of a new n+1 Switch Topology]

**Figure 3.6 A new n+1 Switch Topology**

The drive system has feedback control over the phase currents, discrete rotor position signal and rotor speed signals. Poor utilization of the machine is due to half wave operation which results in larger self inductance and also the torque response is not up to the mark in comparison to full wave converter fed drive.

### 3.2.3 Reduced part converter topology

The reduced part converter topology results in cascade type and unified type. Under cascaded type as shown in Figure 3.7, a separate PWM converter for power factor correction and the PWM inverter for speed control are connected in series with a large DC link capacitor. The two static power converters are operated and controlled separately. Here the required number of switches can be reduced which leads to reduced part converters.
Figure 3.7 Cascaded type PWM system

But whereas in the Unified type as shown in Figure 3.8, conventional concepts of PWM converter and inverter are merged together and the same converter handles the functions of PWM converter (power factor correction) and PWM inverter (motor control) at the same time. Input inductor used in PWM can be neglected and the motor inductor is used and this makes an added advantage.

Figure 3.8 Unified type PWM System

While the above framework gives details of reduced part converters for a three phase machine, whereas a generalized design procedure is made for Multiphase as two-phase as shown in Figure 3.9, three-phase, four-phases as
shown in Figure 3.10 and five-phase Machines. The design is carried out by back EMF and the winding distribution.

Figure 3.9 Reduced Two Switch Configuration

Figure 3.10 Reduced Four switch Configuration

3.2.4 Generalized design methodology for n-phase BLDC motors

Therefore, for n-phase BLDC motor, 2n number of switches is needed. In order to minimize the number of switches, the current profiles should be
modified to the sum of phase current which is equal to zero. The converter can be designed as even n-phase BLDC motors where n number of switches is required along with split dc-link capacitors. Odd n-phase BLDC motors where 2n-2 numbers of switches are required along with split dc-link capacitors.

Following the reduced part converters current source inverters are suggested where it is explained with three phase BLDC motor as shown in Figure 3.11, an ac-dc converter and a three phase inverter containing six SCR’s. A microcontroller or a digital signal processor will be used to control the overall system. The proposed system is fault tolerant due to the current regulated nature, where it can even withstand a solid short circuit at its output terminals. When comparing with the existing drives, the new topology reduces cost by 30%. Since all the switches used in the output three-phase inverter is current commutated, this drive has much lower switching losses than the conventional PWM drive. It uses the Buck-Boost converter technology for successful converter design of BLDC motor Drive.

![Cuk Converter fed BLDC motor drive.](image)

**Figure 3.11 Cuk Converter fed BLDC motor drive.**
3.2.5 Transformer based resonant soft DC link inverter for BLDC Motor Drive System.

Soft switching inverter based on transformer generates dc link voltage notches. During chopping switches undergo commutation that guarantees all switches are working in zero voltage switching condition. The operation principle and control scheme of the inverters are analyzed for the successful operation of the drive of all the operating regions.

![Figure 3.12 Structure of the resonant DC link inverter for BLDC drive systems](image)

The resonant circuit as shown in Figure 3.12 consists of three auxiliary switches, one transformer and one resonant capacitor. The auxiliary switches are controlled at certain instant to obtain the resonance between transformer and capacitor. Thus the DC link voltage reaches zero temporarily (voltage notch) and the main switches of the inverter get ZVS condition for
commutation. In this design all switches work under soft-switching condition, so their power losses are small. Simple auxiliary switches are used for control scheme this reduces the voltage stresses, dv/dt and di/dt. This makes further reduction in the electromagnetic interference.

Discussing about the speed control of PMBLDC motor drive centre’s around a new control scheme to the conventional PMBLDC motor, aimed at improving control system robustness via complete decoupling of the design and performance of the control loops that ensures robustness by minimizing the mutual influence among the speed and current control loops. This robust decoupling control scheme would be applicable to both static and dynamic aspects.

3.2.6 Sensorless Techniques

Some of the sensorless techniques have been introduced and developed based on the reduction in cost of the entire drive system as well as reducing the complexity of the system. Here the commutation signals are extracted directly from the specific average line to line voltages with simple RC circuits and comparators. By this the common mode interferences and noises are reduced and it leads to easy interface with the cost effective commercial Hall Effect sensors based commutation integrated circuits. This technique leads to elimination of the motor neutral voltage, elimination of the fixed phase shift circuit and insensitive to the back emf waveform and also it proves a cost effective system.

Even sensorless control techniques used Field Programmable Logic Array (FPGA). In this method also cost is reduced by switch device count, cost of control, and saving of hall sensor. The position information is
estimated from the crossings of voltage waveforms in floating phases, and a low cost FPGA is utilized to implement the control action. It results in smooth motor operation in all the regions and controlling of torque ripples.

EMF Detection technique is introduced which provides a wide range of control for BLDC drives. It can be capable of handling both low and high duty-ratio control. The zero crossing point of back-emf which is used for generating proper commutation control of inverter is calculated by sampling the voltage of floating phase. It leads to absence of current and position sensors. By reducing both the position and current sensors, a cost effective system is introduced and complexity in the drive control circuit is reduced to a large extent.

3.3 Chapter Summary

Many areas in the associated design and development of permanent magnet brushless DC motor drives have been covered by the study; much is to emerge from the areas of control algorithms, drive design, sensorless techniques and speed control.
CHAPTER 4

BUCK CONVERTER FED PMBLDC DRIVE SYSTEM WITH AND WITHOUT SNUBBER

4.1 Buck Converter

Buck Converter is also known as a step down converter. The buck converter as shown in Figure 4.1, consists of dc input voltage source, controlled switch (MOSFET), diode D, filter inductor L, filter capacitor C and Load resistance R.

Figure 4.1 Simulation of Basic Buck Converter Circuit.

Figure 4.2 shows the input DC voltage which is applied to the buck converter. The switching pulse applied to the buck converter is shown in
Figure 4.3, the output current of the buck converter is shown in Figure 4.4 and output voltage of the buck converter is shown in Figure 4.5.

Figure 4.2 Input D.C voltage of the Buck Converter

Figure 4.3 Switching Pulse for Buck Converter.

Figure 4.4 Output Current of the Buck Converter.
The first assumption is that the inductor current for any period of time leads to continuous Conduction mode (CCM). When the switch (MOSFET) ‘S’ is on state the diode D is reverse biased. Similarly when the switch S is off, the diode conducts to support continuous current in the inductor. The relationship between the input voltage, output voltage and the switch duty ratio D can be desired from the inductor voltage waveform. It can be seen that output voltage is always smaller than input voltage. The converter can operate in both continuous current mode and also in discontinuous current mode. Generally continuous current mode is taken for discussion.

This work proposes the buck converter for PMBLDC drive system.

Figure 4.5 Output Voltage of the Buck Converter.

Figure 4.6 Structure of Buck converter fed PMBLDC Drive System.
The structure of the PMBLDC motor drive system as shown in Figure 4.6 has an A.C. source, where the A.C. supply is fed to the rectifier circuit through the power factor correction block where it has L & C elements used for Power factor correction. Then rectifier is used to convert the available A.C. source into D.C. source and then it is fed to the Buck Converter, where depending upon the motor need, a constant input voltage is provided and then it is connected with the inverter and finally supply is fed to the PMBLDC motor.

4.2 Simulation Results

The Simulink model of the closed loop controlled buck converter fed PMBLDC drive is shown in Figure 4.7. Here 48V DC is stepped down to 24V DC using a buck converter. The output of the buck converter is filtered using pi-filter. The output of the pi-filter is applied to the three phase inverter. The inverter produces three phase voltage required by the PMBLDC motor. The technical specifications of the drive systems are as follows

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>48 V DC</td>
</tr>
<tr>
<td>Buck output voltage</td>
<td>24 V DC</td>
</tr>
<tr>
<td>Pulse width to Buck MOSFET</td>
<td>0.5 duty cycle (50%)</td>
</tr>
<tr>
<td>( T_{off} )</td>
<td>50%</td>
</tr>
<tr>
<td>Pulse width (33%) to</td>
<td></td>
</tr>
<tr>
<td>Inverter MOSFET</td>
<td>120° mode of operation..</td>
</tr>
</tbody>
</table>

**Parameters of BLDC Motor**

The inverter is a MOSFET bridge.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance ( R_s )</td>
<td>2.8750 ohms</td>
</tr>
<tr>
<td>Stator Inductance ( L_s )</td>
<td>8.5e-3 Henrys</td>
</tr>
<tr>
<td>Flux induced by magnets</td>
<td>0.175 Weber</td>
</tr>
<tr>
<td>Back EMF Flat area</td>
<td>120 degrees</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.8x10^{-3} Kg.m^2</td>
</tr>
</tbody>
</table>
Friction factor : $1 \times 10^{-3}$ N.m.s
Pole pairs : 4

Stator windings are connected in star to an internal neutral point.

Figure 4.7 Simulink Diagram of the Closed Loop Controlled Buck Converter fed PMBLDC Drive System

The actual speed is measured and it is compared to the reference speed. The error is given to the PI Controller. The output of the PI controller is one of the inputs to the comparator. The other input is high frequency triangular wave. The output of the comparator controls the pulse width applied to the buck MOSFET. The pulses that are given to the MOSFETS 1, 3 and 5 are shown in Figure 4.8.
D.C. input voltage is shown in Figure 4.9 and its value is 48 volts. Phase voltages of the three phase inverter are shown in Figure 4.10. The voltages are displaced by 120°. Three phase currents drawn by the motor are shown in Figure 4.11. The back emfs in the three phases are shown in Figure 4.12. The response of the speed is shown in Figure 4.13. The speed settles at 130 rpm, which is equal to the set value.
Figure 4.10 Phase voltages of the Inverter

Figure 4.11 Output Currents of the Inverter
Figure 4.12 Back EMF Waveforms

Figure 4.13 Rotor Speed in rpm
4.3 Snubber Circuit

Snubbers are used in electrical systems to reduce the transient across the device while switching ON/OFF the device. While having a transient this may cause electromagnetic disturbance which in turn creates interference with nearby circuits. The snubber prevents this undesired voltage by conducting transient current around the device.

Semiconductor switch turns on from 10µs to 100µs. At that time the voltage across them falls and the current through the switch rises. These extremely large and fast edges create massive amount of trouble, as a result semiconductor switch may actually burns itself and the EMI contaminates the entire power distribution system. The solution is to add a few components to snub these transients, slowing them or diverting them while protecting the power system from interference. In general snubbers used for load line shaping, to reduce switching losses, reduces turn off dv/dt, controllable working current is much greater, device heating is minimized, reduces the peak power and average power dissipate, power dissipation is avoided, reduces voltage transients.

Snubber circuit basically consists of a series connected resistor and capacitor placed in shunt with semiconductor switch. Generally snubbers to slow the rate of rise of this current. Inductor opposes a change of current, so placing an inductor in series with the semiconductor switch as shown in Figure 4.14.

\[ V_L = L \frac{di}{dt} \]  \hspace{1cm} (4.1)
\[ L = \frac{V_t}{\frac{di}{dt}} \quad (4.2) \]

So, \( V_L \) is the line peak voltage, \( \frac{di}{dt} \) is a specification given by the manufacturer.

\[ L > \frac{V_{P, line}}{\frac{di}{dt \ spec}} \quad (4.3) \]

**Figure 4.14 Basic series Snubber Circuit**

Between main terminal of a semiconductor switch and its gate is a considerable parasitic capacitance as shown in Figure 4.15. Any noise on the line is coupled into the semiconductor switch and through this capacitance to the gate; it turns on the semiconductor switch. It is quite possible that the switch can be fired by the noise even without a gating pulse.
Figure 4.15 Snubber Circuit Showing Parasitic Capacitance

To reduce the noise around the semiconductor switches, the capacitor is large enough to divert the energy from the parasitic anode to gate capacitance. As a result, we have to choose a capacitor that assures the response to a step is slowed below that critical rate of rise of voltage. Voltage across a snubbing capacitance cannot change instantaneously; instead, it rises exponentially as $C_{\text{snub}}$ charges through $R_{\text{load}}$. This is shown in Figure 4.16.

$$C_{\text{snub}} = \frac{V_{p\text{noise}}}{R_{\text{load}}} \times \frac{dv}{dt} \quad (4.4)$$

Fig 4.16 Snubber Circuit with snubber Capacitor.
For simplicity the value of the snubber resistance and snubber capacitance can be calculated by using the formulae:

\[ R = 2 \cdot \delta \sqrt{\frac{L}{C}} \]  \hspace{1cm} (4.5)

and

\[ C = L \left( \frac{I_r}{K \cdot V_s} \right)^2 \]  \hspace{1cm} (4.6)

The values are as follows:

a. Snubber Resistance \( R_{\text{snub}} = 0.4 \) ohms
b. Snubber Capacitance \( C_{\text{snub}} = 5 \mu \) farads
c. The optimum damping factor \( \delta = 0.4 \)
d. The optimum current factor \( K = 0.75 \)
e. Recovery current of diode \( I_r = 20 \) amps
f. Source voltage is \( V_s = 230 \) volts
g. Circuit Inductance \( L = 1.25 \mu \) Henrys

Figure 4.17 Structure of Buck converter fed PMBLDC Drive System with Snubber.

The structure of the PMBLDC motor drive system with snubber circuit as shown in Figure 4.17 has an A.C. source, where the A.C. supply is fed to the
rectifier circuit through the power factor correction block where it has L & C elements used for Power factor correction. Then rectifier is used to convert the available A.C. source in to D.C. source and then it is fed to the Buck Converter, where depending upon the motor need, a constant input voltage is provided and then it is connected with the inverter where the snubber circuit is connected which gives smooth transition between the switches and finally supply is fed to the PMBLDC motor.

4.4 Simulation Results of Buck Converter with and without snubber

Closed loop system is simulated using Matlab/Simulink. The simulink model of closed loop controlled buck converter fed PMBLDC drive system without and with snubber is shown in Figure 4.18 and Figure 4.23. Here 48V DC is stepped down to 24V DC using a buck converter. The output of buck converter is filtered using pi-filter. The output of the pi-filter is applied to the three phase inverter, the inverter produces three phase voltage required by the PMBLDC motor. The technical specifications of the drive systems are as follows

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>48 V DC</td>
</tr>
<tr>
<td>Buck output voltage</td>
<td>24 V DC</td>
</tr>
<tr>
<td>Pulse width to Buck MOSFET</td>
<td>0.5 duty cycle (50%)</td>
</tr>
<tr>
<td>( T_{\text{off}} )</td>
<td>50%</td>
</tr>
<tr>
<td>Pulse width (33%) to Inverter MOSFET</td>
<td>120° mode of operation.</td>
</tr>
</tbody>
</table>

**Parameters of BLDC Motor.**

The inverter is a MOSFET bridge.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance ( R_s )</td>
<td>2.8750 ohms</td>
</tr>
<tr>
<td>Stator Inductance ( L_s )</td>
<td>8.5e-3 Henrys</td>
</tr>
<tr>
<td>Flux induced by magnets</td>
<td>0.175 Weber's</td>
</tr>
</tbody>
</table>
Back EMF Flat area : 120 degrees
Inertia : $0.8 \times 10^3$
Friction factor : $1 \times 10^{-3}$
Pole pairs : 4

Stator windings are connected in star to an internal neutral point.

Figure 4.18 Simulink Diagram of the Closed Loop Controlled Buck Converter fed PMBLDC drive System without Snubber

The actual speed is measured and it is compared with the reference speed and the error is given to the PI Controller. The output of the PI controller is one of the inputs to the comparator. The other input is high frequency triangular wave. The output of the comparator controls the pulse width applied to the buck MOSFET. The pulses given to the MOSFETS 1, 3 and 5 are shown in Figure 4.19
Figure 4.19 Triggering Pulses

D.C.input voltage is shown in Figure 4.20 and its value is 48 volts. Phase voltages of the three phase inverter are shown in Figure 4.21. The voltages are displaced by 120°. Three phase currents drawn by the motor are shown in Figure 4.22. The simulink diagram of the closed loop controlled buck converter fed PMBLDC drive system with snubber is shown in Figure 4.23. The phase voltages and current outputs are shown in Figure 4.24 and 4.25. The inverter phase voltages without and with snubber is shown in Figure 4.26 and Figure 4.27 shows Inverter output current without snubber and with snubber.
Figure 4.21 Phase voltages of the Inverter

Figure 4.22 Output Currents of Inverter
Figure 4.23 Simulink Diagram of the Closed Loop Controlled Buck Converter fed PMBLDC drive System System with Snubber.

Figure 4.24 Phase voltages of the Inverter with the Snubber
Figure 4.25 Output Currents of the Inverter with the Snubber

Figure 4.26 Inverter phase voltages without snubber and with snubber
Figure 4.27 Inverter output current without snubber and with snubber

The currents are balanced and they are displaced by 120°. The comparison of voltage and current spikes with and without snubber are given in Table 4.1. The height of the spike is reduced by introducing the snubber.
Table 4.1 Comparison of Buck Converter with and Without Snubber

<table>
<thead>
<tr>
<th>Buck Converter</th>
<th>Voltage Spike (Volts)</th>
<th>Current Spike (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Snubber</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>With Snubber</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4.5 Chapter Summary

Closed loop controlled PMBLDC drive system is simulated using MATLAB/SIMULINK and the above results were derived. Buck converter is proposed to reduce the input voltage to the required value. Closed loop Buck controlled PMBLDC drive systems with and without snubber is modeled and simulated using MATLAB/SIMULINK and the results are presented. This drive system has advantages of reduced switching losses. With the presence of snubber circuit the voltage spikes are reduced by 72% and current spikes are reduced by 33%, which in turn improves the output response.