Module 7

Electrical Machine Drives

Lesson 35

Electrical Actuators: BLDC Motor Drives

Instructional Objectives

After learning the lesson students should be able to

A. Define the Structure of a PM BLDC Motor.

B. Describe the principle of operation of a PM BLDC motor.

C. Understand Closed Loop Control of a BLDC Drive.

D. Name applications of BLDC Motor.

Introduction

Brushless DC motors, rather surprisingly, is a kind of permanent magnate synchronous motor. Permanent magnet synchronous motors are classified on the basis of the wave shape of their induce emf, i.e, sinusoidal and trapezoidal. The sinusoidal type is known as permanent magnet synchronous motor; the trapezoidal type goes under the name of PM Brushless dc (BLDC) machine. Permanent magnet (PM) DC brushed and brushless motors incorporate a combination of PM and electromagnetic fields to produce torque (or force) resulting in motion. This is done in the DC motor by a PM stator and a wound armature or rotor. Current in the DC motor is automatically switched to different windings by means of a commutator and brushes to create continuous motion. In a **brushless motor**, the rotor incorporates the magnets, and the stator contains the windings. As the name suggests brushes are absent and hence in this case, commutation is implemented electronically with a drive amplifier that uses semiconductor switches to change current in the windings based on rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor.

Advantage of Permanent Magnet Brushless DC Motor

BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- Faster dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

Structure of Permanent Magnet Brushless DC Motor

BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Here we focus on 3-phase motors.

Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery (as shown in Figure 2). Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous interconnected coils, with one or more coils are placed in the stator slots. Each of these windings are distributed over the stator periphery to form an even numbers of poles. As their names indicate, the trapezoidal motor gives a back trapezoidal EMF as shown in Figure 35.1.

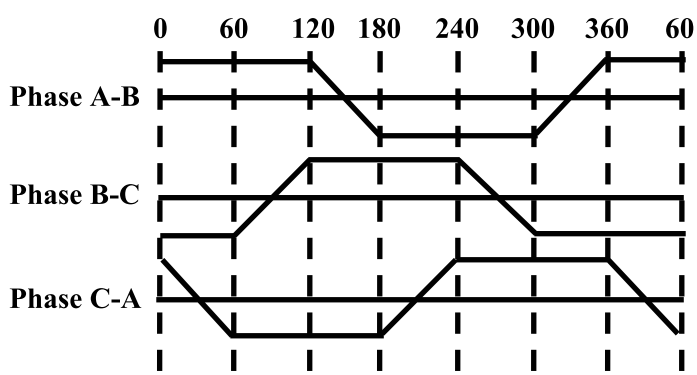

Fig. 35.1 Voltage phase diagram of a 3-phase BLDC motor.

In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings. Depending upon the power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volts, or less voltage rated motors are used in automotive, robotics, small arm movements and so on. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

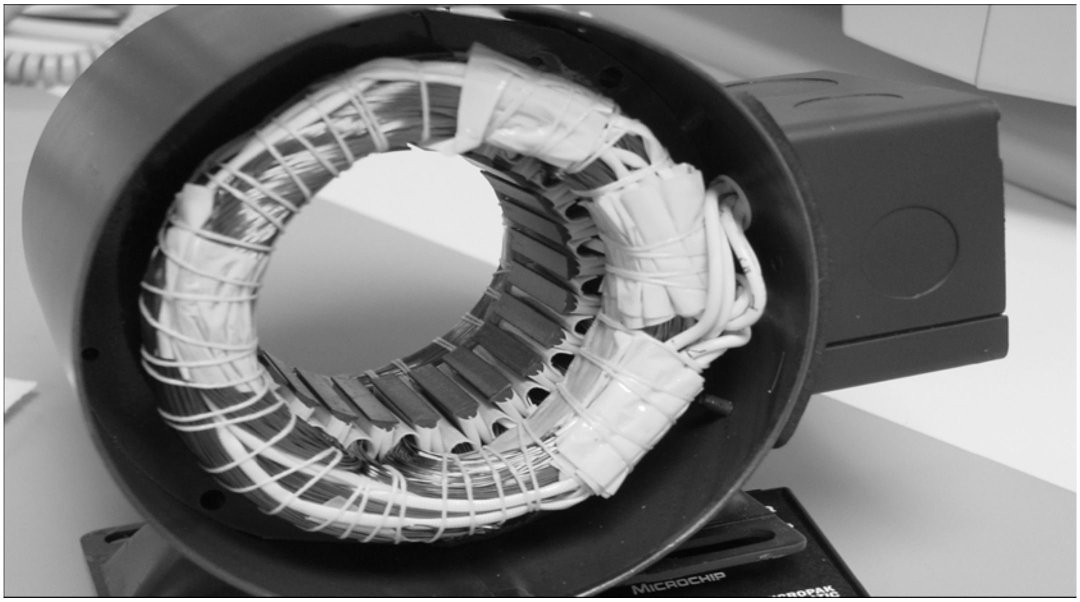

Fig. 35.2 Cross-sectional View of the BLDC motor stator.

Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets were traditionally used to make the permanent magnet pole pieces. For new design rare earth alloy magnets are almost universal. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables using a smaller rotor and stator for the same torque. Accordingly, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Figure 35.3 shows cross sections of different arrangements of magnets in a rotor.

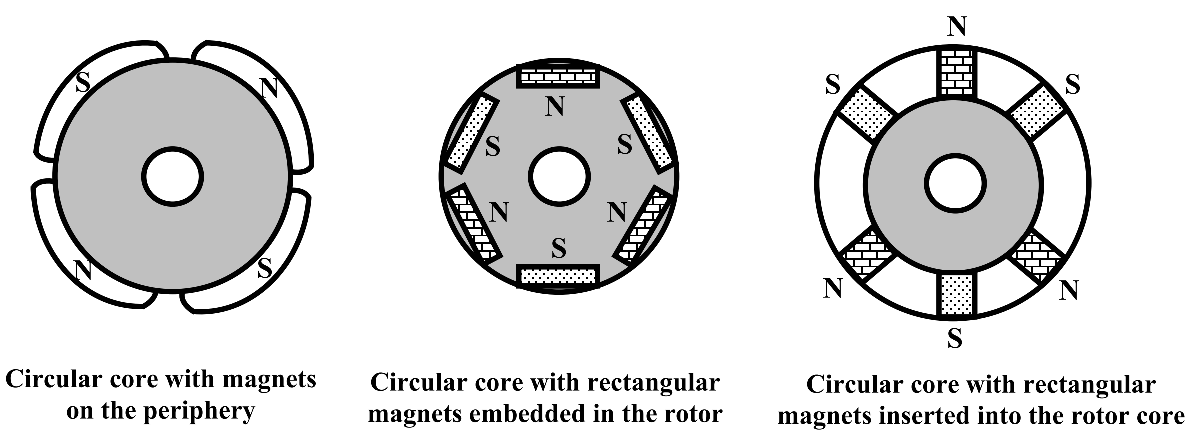

Fig. 35.3 Cross-sections of different rotor cores.

Hall Sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

Principle of operation and dynamic model of a BLDC Motor

The coupled circuit equations of the stator windings in terms of motor electrical constants are

$$v_{an} = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_a$$

$$v_{bn} = R_b i_b + \frac{d}{dt}(L_{ab} i_a + L_{bb} i_b + L_{cb} i_c) + e_b$$

$$v_{cn} = R_c i_c + \frac{d}{dt}(L_{ac} i_a + L_{bc} i_b + L_{cc} i_c) + e_c$$

$$R_a = R_b = R_c = R$$

$$L_{aa} = L_{bb} = L_{cc} = L_s$$

$$L_{ba} = L_{ab} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M$$

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Since, $i_a + i_b + i_c = 0$, and with $(L_s - M) = L$, we have,

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

where,

R : Stator resistance per phase, assumed to be equal for all phases

L_s : Stator inductance per phase, assumed to be equal for all phases.

M : Mutual inductance between the phases.

i_a, i_b, i_c : Stator current/phase.

The instantaneous induced emfs can be written as given in equation (35.1), (35.2) and (35.3).

$$e_a = f_a(\theta_r)\lambda_p \omega_m \qquad (35.1)$$

$$e_b = f_b(\theta_r)\lambda_p \omega_m \qquad (35.2)$$

$$e_c = f_c(\theta_r)\lambda_p \omega_m \tag{35.3}$$

where, ω_m is the rotor mechanical speed and θ_r is the rotor electrical position.

The machine is represented in the figure 35.4 by a three-phase equivalent circuit, where each phase consists of stator resistance R_s, equivalent self inductance L_s, and a trapezoidal CEMF wave in series. Figure 5 shows the phase diagram of V_{an}, V_{bn}, V_{cn}.

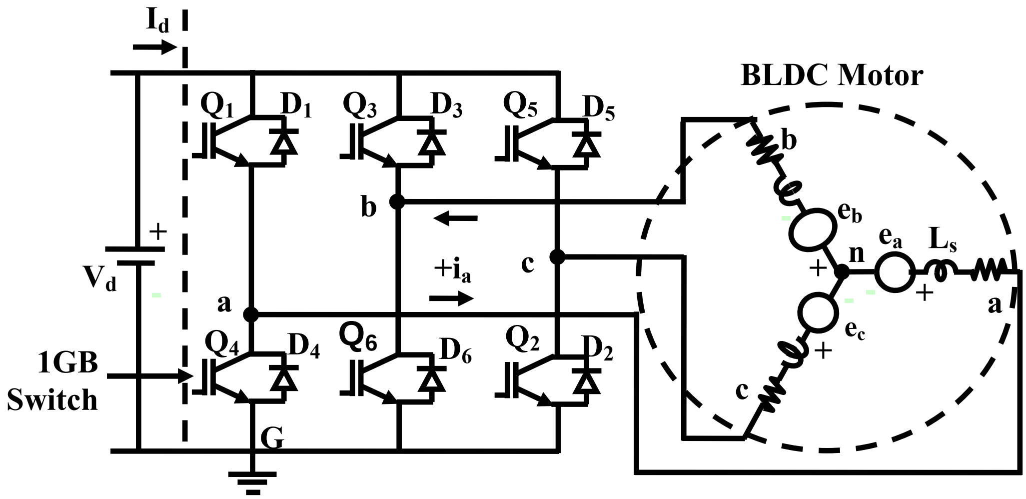

Fig. 35.4 A 3-phase Equivalent Circuit of BLDC motor.

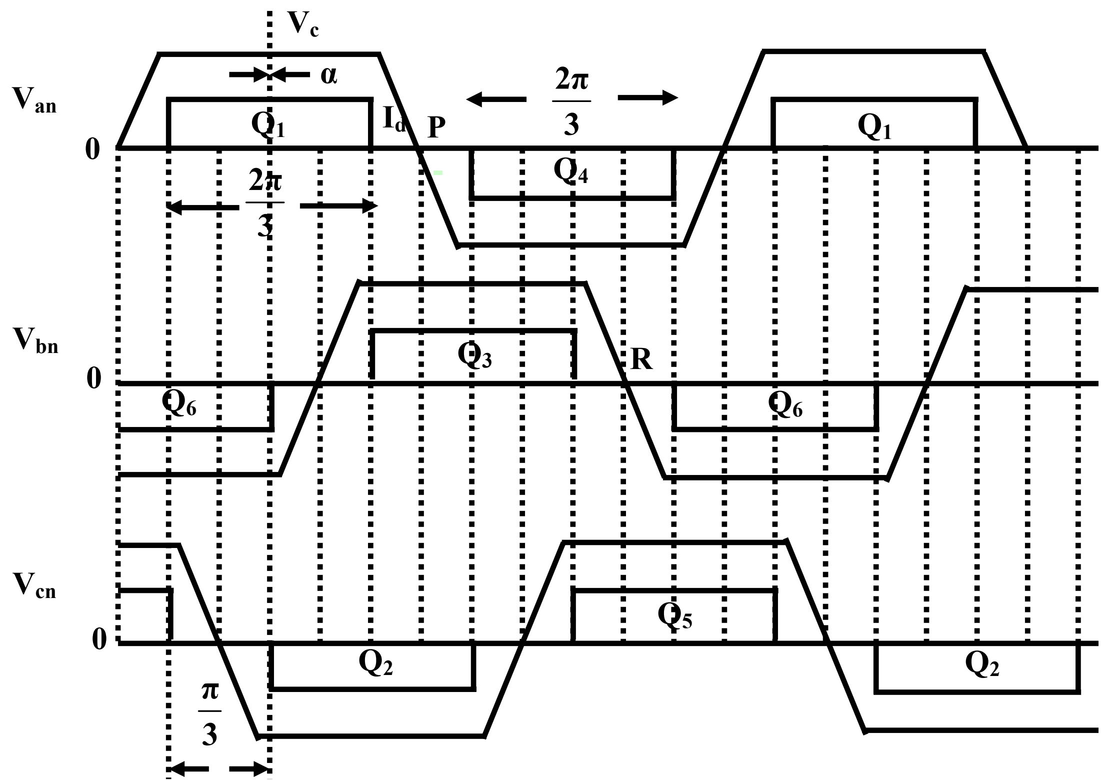

Fig. 35.5 An Illustration of 3-phase switching sequence.

The spatial orientations of the stator MMF vector, under different switching phases of the inverter are shown below in figure 6. Therefore under a cyclic switching scheme one has a rotating stator MMF vector. If the switching can be synchronized with the rotor position, then an approximately fixed angle between the stator flux and the rotor flux can be maintained, while both rotate around the rotor axis. This is similar to the case of the DC motor, where the commutator brush arrangement maintains a fixed spatial direction of the armature flux aligned with the field flux, which is also fixed in space by construction. This is precisely what the inverter switching sequence shown in Fig.5 achieves. The switching instants of the individual transistor switches, $Q_1 - Q_6$ with respect to the trapezoidal emf wave is shown in the figure. Note that the emf wave is synchronized with the rotor. So switching the stator phases synchronously with the emf wave make the stator and rotor mmfs rotate in synchronism. Thus, the inverter acts like an electronic commutator that receives switching logical pulses from the rotor position sensor. This is why a BLDC drive is also commonly known as an electronically commutated motor (ECM).

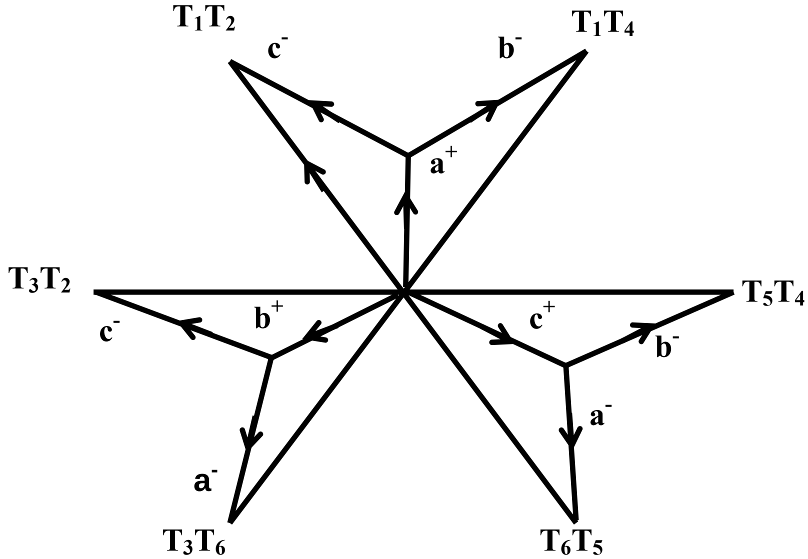

Fig. 35.6 Phasor diagram of stator MMF vector.

The torque equation is given as,

$$T_e = \lambda_p [\, f_a(\theta_r)\, i_a + f_b(\theta_r)\, i_b + f_c(\theta_r)\, i_c \,]$$

The equation of motion for simple system is,

$$T_e = J \frac{d\omega_m}{dt} + T_l + B\omega_m$$

where, J is the inertia of the motor and B is the friction coefficient.

$$\Rightarrow \frac{d\omega_m}{dt} = \frac{1}{J}(T_e - T_l - B\omega_m) \qquad (35.4)$$

The relation between angular velocity and angular position (electrical) is given by

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \qquad (35.5)$$

where, P is the number of rotor poles. The state variable (θ_r), rotor position, is required to have the function $f_a(\theta_r)$, which is given as the trapezoidal function :

$$
\begin{aligned}
f_a(\theta_r) &= 1 && 0 < \theta_r < \pi/3 \\
&= \left(\frac{\pi}{2} - \theta_r\right) * \frac{6}{\pi} && \pi/3 < \theta_r < 2\pi/3 \\
&= -1 && 2\pi/3 < \theta_r < \pi \\
&= -1 && \pi < \theta_r < 4\pi/3 \\
&= \left(\theta_r - 3 * \frac{\pi}{2}\right) * \frac{6}{\pi} && 4\pi/3 < \theta_r < 5\pi/3 \\
&= 1 && 5\pi/3 < \theta_r < 2\pi
\end{aligned}
$$

Similarly

$$f_b(\theta_r) = f_a\left(\theta_r + 2\frac{\pi}{3}\right)$$

$$f_c(\theta_r) = f_a(\theta_r - 2\frac{\pi}{3})$$

The induced emfs do not have sharp corners, as is shown in trapezoidal functions, but rounded edges. The emfs are the result of the flux linkages derivatives, and the flux linkages are continuous functions. Fringing also makes the flux density functions smooth with no abrupt edges. It is significant to observe that the phase-voltage equation is identical to the armature-voltage equation of a dc machine.

Points to Ponder: 1

A. *Why is a BLDC motor called a dc motor?*
B. *Why does a BLDC motor come with an integrated hall sensor?*
C. *Can you name other purposes which Hall sensors serve in BLDC drives?*

Closed Loop Control of PM BLDC Drive

Figure 35.7 represents a position control scheme for PM BLDC motor. For this control scheme speed and position sensors are assumed to be Tachogenerator and LVDT (Linear Variable Differential Transformer). As seen in the figure, there are three loops; the outermost loop called the position loop, the second loop is the speed loop and the innermost loop called the current control loop.

The position of the rotor is compared with the reference value, and the rotor position error is amplified through a PD controller. The output of the PD controller is then used as the speed reference command. Based on the speed reference and the speed feedback from a tachogenerator, a PI speed controller generates the torque references, from which, in turn, phase current references are generated.

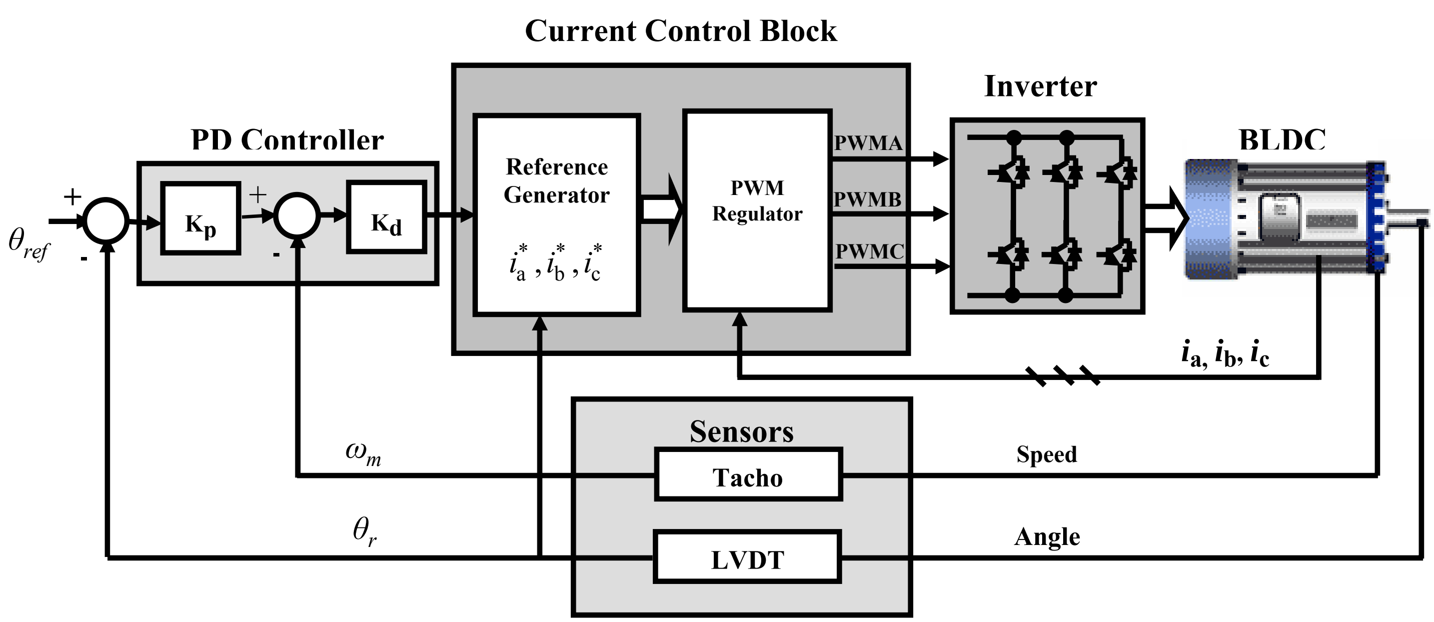

Fig. 35.7 Position Controlled PMBDCM drive scheme

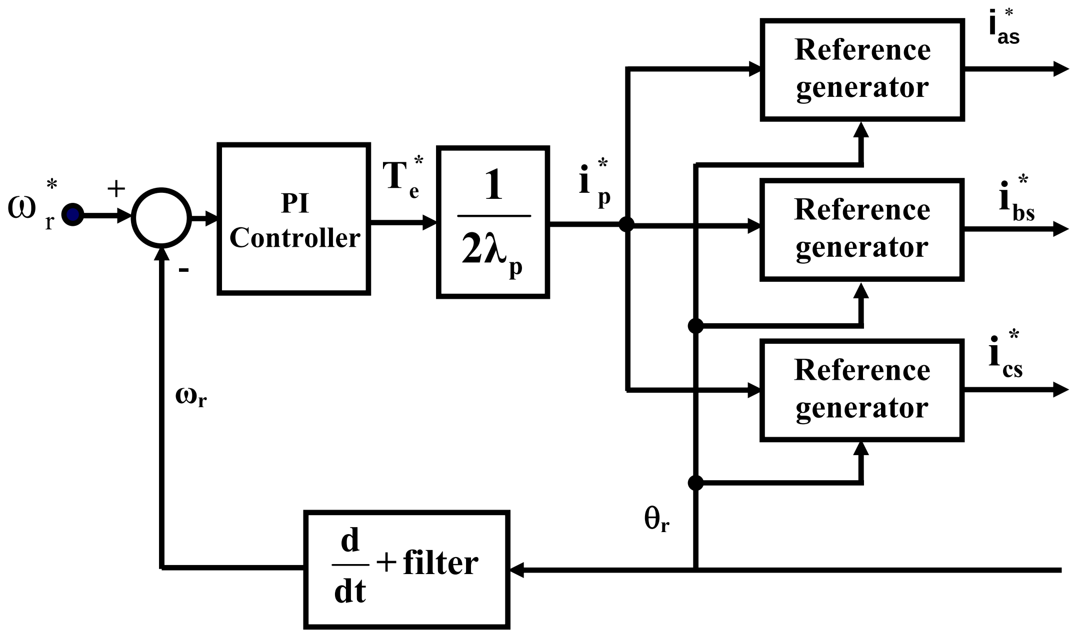

Fig. 35.8 Block Diagram Representation of speed controlled BLDC drive.

The phase current magnitude i_p* command is positive for motoring but negative for regeneration. This signal is then enabled with appropriate polarity to the respective phases with the help of decoder output. The actual phase currents track the command currents by hysteresis-band current control. At any instant, two phase currents are enabled, one with positive polarity and another with negative polarity. Consider, for example, the motoring mode time duration when phase a positive current $+i_a$* and phase b negative current $-i_b$* commands are enabled by the decoder. Devices Q_1 in phase a and Q_6 in phase b are turned on simultaneously to increase $+i_a$ and $-i_b$ respectively. When the currents (equal in magnitude) tend to exceed the hysteresis band, Q_6 is turned off. The decaying freewheeling current will flow then through D_3 and Q_1.In this case, three upper devices (Q_1, Q_3, and Q_5) of the inverter are turned on sequentially in the middle of the respective positive voltage half-cycles, whereas the lower devices (Q_4, Q_6, and Q_2) are chopped in sequence for $2\pi/3$ angles in respective negative voltage half-cycles with the help of a decoder for controlling the current *ip**.

Points to Ponder: 2

A. *Why is a PD controller used in the position loop ?*
B. *Explain how the current control loop works*

Typical BLDC Motor Applications

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors. Out of these, we can categorize the type of BLDC motor control into three major types:

• Constant load
• Varying loads
• Positioning applications

Applications with Constant Loads

These are the types of applications where variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

Applications with Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand a high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers and compressors are good examples. In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolvers are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Computer Numeric Controlled (CNC) machines are a good example of this. Process controls, machinery controls and conveyer controls have plenty of applications in this category.

Points to Ponder: 3

A. *What are the reasons behind the popularity of BLDC motors over dc motors for servo applications?*
B. *Name application areas where a BLDC motor drive is preferable over an ac drive.*

Lesson Summary

In this lesson, the following topics related to PM BLDC motor have been discussed.

A. Advantages of PM BLDC Motor.

B. Structure of PM BLDC Motor.
C. Principle of operation and dynamic model of a BLDC Motor.
D. Closed Loop Control of PM BLDC Drive.
E. Applications of Typical BLDC Motor.

Answers, Remarks and Hints to Points to Ponder

Points to Ponder: 1

A. *Why is a BLDC motor called a dc motor?*

Ans: Because in a BLDC motor the stator and the rotor fluxed maintain a constant angle, although both are rotating in space. This is similar to the dc motor, but in the dc motor, both the armature and the field flux are stationary in space.

B. *Why does a BLDC motor come with an integrated hall sensor?*

Ans: Because, to maintain a constant angle difference between the stator and the rotor flux, the stator current has to be switched from winding to winding depending on the rotor position. So the rotor position is sensed in all BLDC motors, by the Hall sensors.

C. *Can you name other purposes which Hall sensors serve in BLDC drives?*

Ans: Hall sensors are also used in many drives to sense stator current to implement a current loop for fast torque control.

Points to Ponder: 2

A. *Why is a PD controller used in the position loop ?*

Ans: Since the velocity to position dynamics already contains an integral dynamics, no integrator needs to be introduced n the controller for achieving zero steady state error. Thus, to improve the control bandwidth, only a PD controller is used.

B. *Explain how the current control loop works.*

Ans: As explained for dc motors in an earlier lesson, switching the supply across the BLDC motor makes the current increase linearly, since the back emf, being proportional to speed can be assumed to remain constant. When the current crosses upper trip point of a hysteresis block set around the current set point, the supply is switched off, making the current free wheel through one transistor and one diode, and reduce linearly. Again, when the current crosses the lower trip point, the supply is switched on. Thus, the current oscillates at the PWM switching frequency around the current set point.

Points to Ponder: 3

A. *What are the reasons behind the popularity of BLDC motors over dc motors for servo applications?*

Ans: Higher torque to weight ratio, due to rare earth magnets which have less weight and have much higher operating flux density limits. This leads to faster dynamic response. Also, the lack of brushes and commutators reduce maintenance problems.

B. *Name application areas where a BLDC motor drive is preferable over an ac drive.*

Ans: Most control applications are examples, such as, CNC control, Avionic controls etc.

Source:http://www.nptel.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Industrial%20Automation%20control/pdf/L-35(SM)%20(IA&C)%20((EE)NPTEL).pdf