University of Anbar
College of Engineering
Dept. of Electrical Engineering

DC Machine II
Dr. Settar S. Keream

CHAPTER 10
BRUSHLESS DC MOTORS

10.1 Introduction

Conventional dc motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance-free motors were realized. These motors are now known as brushless dc motors.

In this chapter, the basic structures, drive circuits, fundamental principles, steady state characteristics, and applications of brushless dc motors will be discussed.

10.2 Structures and Drive Circuits

10.2.1 Basic structures

The construction of modern brushless motors is very similar to the ac motor, known as the permanent magnet synchronous motor. Fig.1 illustrates the structure of a typical three-phase brushless dc motor. The stator windings are similar to those in a polyphase ac motor, and the rotor is composed of one or more permanent magnets. Brushless dc motors are different from ac synchronous motors in that the former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches as shown in Fig.2. The most common position/pole sensor is the Hall element, but some motors use optical sensors.

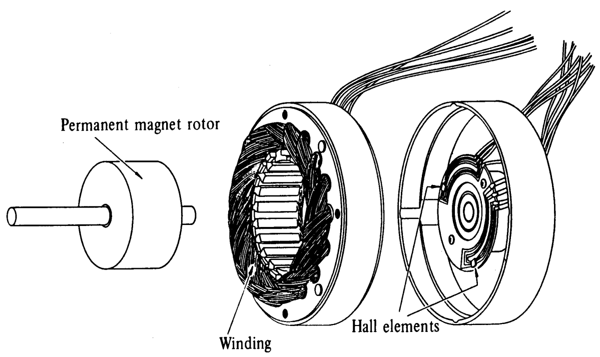


Fig.10.1 Disassembled view of a brushless dc

Although the most orthodox and efficient motors are three-phase, two-phase brushless dc motors are also

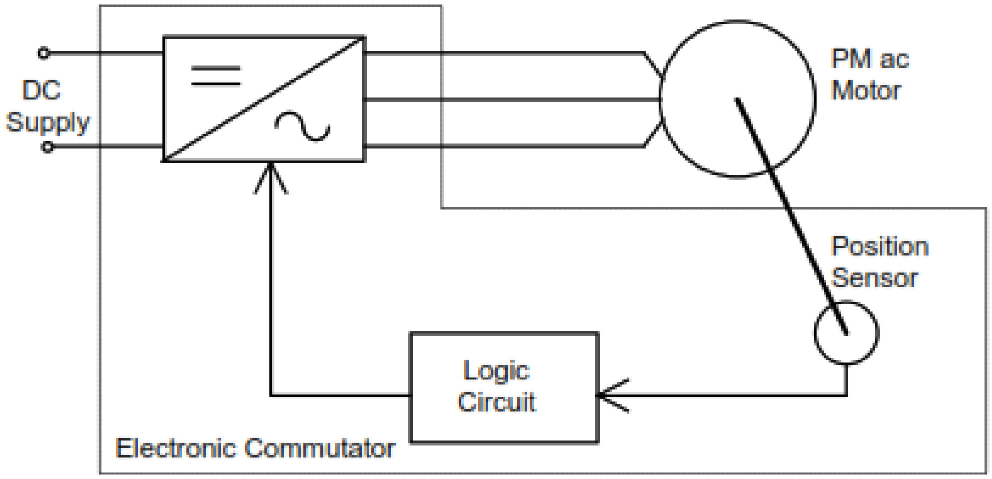


Fig.10.2 Brushless dc motor = Permanent magnet ac motor + Electronic commutator

very commonly used for the simple construction and drive circuits. Fig.3 shows the cross section of a two-phase motor having auxiliary salient poles.

10.2.2 Comparison of conventional and brushless dc motors

Although it is said that brushless dc motors and conventional dc motors are similar in their static characteristics, they actually have remarkable differences in some aspects. When we compare both motors in terms of present-day technology, a discussion of their differences rather than their similarities can be more helpful in understanding their proper applications. Table 1 compares the advantages and disadvantages of these two types of motors. When we discuss the functions of electrical motors, we should not forget the significance of windings and commutation.

Commutation refers to the process which converts the input direct current to alternating current and properly distributes it to each winding in the armature. In a conventional dc motor, commutation is undertaken by brushes and commutator; in contrast, in a brushless dc motor it is done by using semiconductor devices such as transistors.

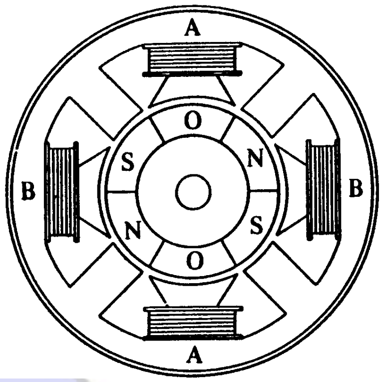
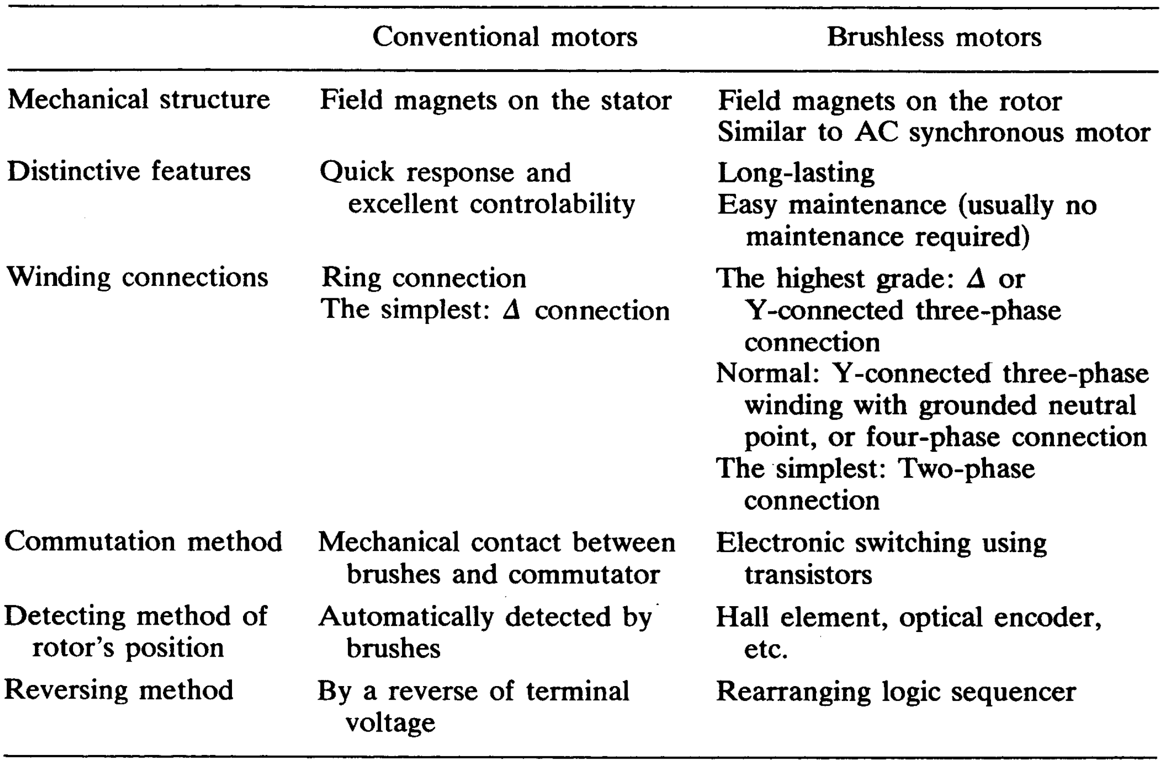


Fig.10.3 Two-phase motor having auxiliary salient poles (from Ref.[1] p95 Fig.5.22)

10.3 Drive Circuits

10.3.1 Unipolar Drive

Table 1. Comparison of conventional and brushless DC motors



	Conventional motors	Brushless motors
Mechanical structure	Field magnets on the stator	Field magnets on the rotor Similar to AC synchronous motor
Distinctive features	Quick response and excellent controlability	Long-lasting Easy maintenance (usually no maintenance required)
Winding connections	Ring connection The simplest: Δ connection	The highest grade: Δ or Y-connected three-phase connection Normal: Y-connected three-phase winding with grounded neutral point, or four-phase connection The simplest: Two-phase connection
Commutation method	Mechanical contact between brushes and commutator	Electronic switching using transistors
Detecting method of rotor's position	Automatically detected by brushes	Hall element, optical encoder, etc.
Reversing method	By a reverse of terminal voltage	Rearranging logic sequencer

Fig.4 illustrates a simple three-phase unipolar-operated motor that uses optical sensors (phototransistors) as position detectors. Three phototransistors PT1, PT2, and PT3 are placed on the end-plate at 120o intervals, and are exposed to light in sequence through a revolving shutter coupled to the motor shaft.

As shown in Fig.4, the north pole of the rotor now faces the salient pole P2 of the stator, and the phototransistor PT1 detects the light and turns transistor Tr1 on. In this state, the south pole which is created at the salient pole P1 by the electrical current flowing through the winding W1 is attracting the north pole of the rotor to move it in the direction of the arrow. When the north pole comes to the position to face the salient pole P1, the shutter, which is coupled to the shaft, will shade PT1, and PT2 will be exposed to the light and a current will flow through the transistor Tr2. When a current flow through the winding W2, and creates a south pole on salient pole P2, then the north pole in the rotor will revolve in the direction of the arrow and face the salient pole P2. At this moment, the shutter shades PT2, and the phototransistor PT3 is exposed to the light. These actions steer the current from the winding W2 to W3. Thus, salient pole P2 is de- energized, while the salient pole P3 is energized and creates the south pole. Hence the north pole on the rotor further travels from P2 to P3 without stopping. By repeating such a switching action in sequence given in Fig.5, the permanent magnet rotor revolves continuously.

10.3.2 Bipolar Drive

When a three-phase (brushless) motor is driven by a three-phase bridge circuit, the efficiency, which is the ratio of the mechanical output power to the electrical input power, is the highest, since in this drive an alternating current flow through each winding as an ac motor. This drive is often referred to as 'bipolar drive'. Here, 'bipolar' means that a winding is alternatively energised in the south and north poles.

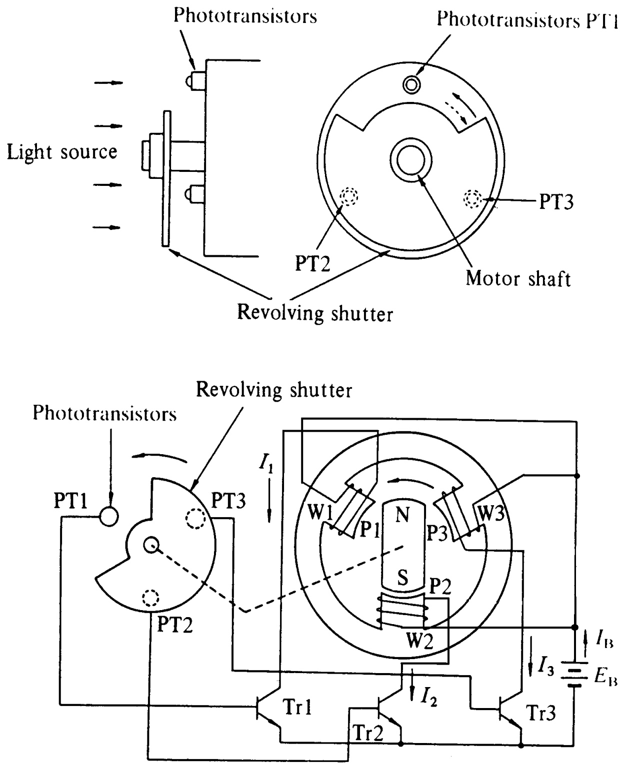


Fig.10.4 Three-phase unipolar-driven brushless dc motor (from Ref. [1] p59

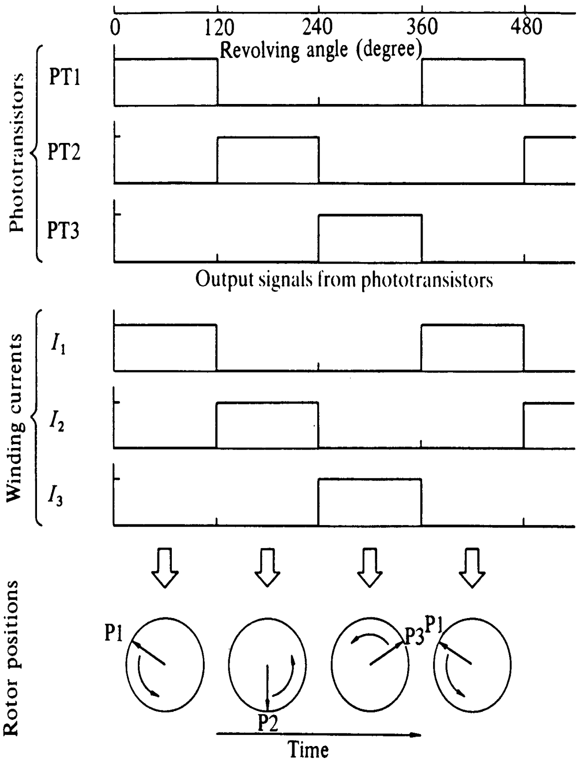


Fig.10.5 Switching sequence and rotation of stator's magnetic field (from Ref. [1] p60 Fig.4.3)

We shall now survey the principle of the three-phase bridge circuit of Fig.6. Here too, we use the optical method for detecting the rotor position; six phototransistors are placed on the end-plate at equal intervals.

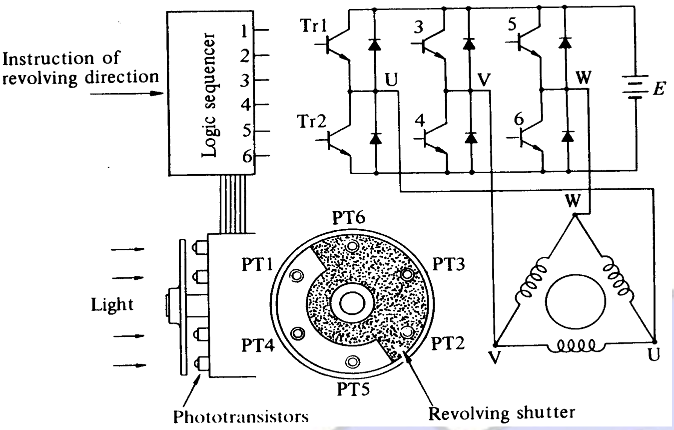


Fig.10.6 Three phase bipolar-driven brushless motor (from Ref. [1] p61, Fig.4.4)

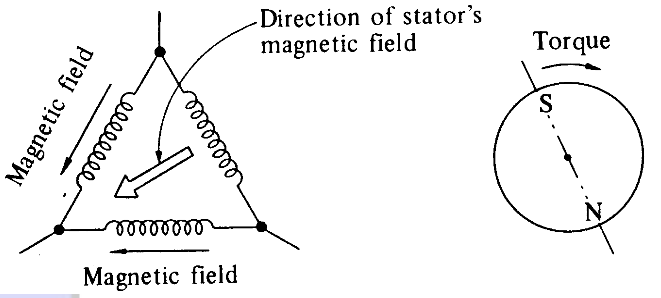


Fig.10.7 Stator's magnetic field in the shutter state of Fig.6, and the direction of torque (from Ref. [1] p62, Fig.4.5)

ON-OFF sequence	1	2	3	4	5	6
Tr 1	0	1	1	1	0	0
2	1	0	0	0	1	1
3	1	1	0	0	0	1
4	0	0	1	1	1	0
5	0	0	0	1	1	1
6	1	1	1	0	0	0

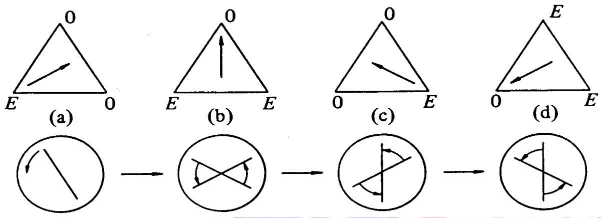


Fig.10.9 Counter-clockwise revolutions of the stator's magnetic field and rotor (from Ref. [1] p63 Fig.4.7)

Tr 1	1	1	1	0	0	0
2	0	0	0	1	1	1
3	0	0	1	1	1	0
4	1	1	0	0	0	1
5	1	0	0	0	1	1
6	0	1	1	1	0	0

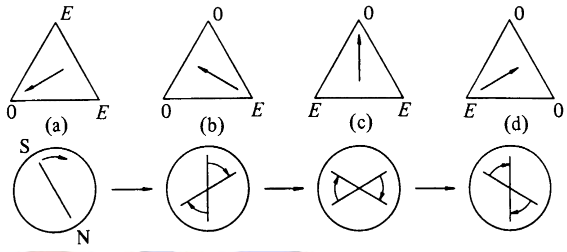
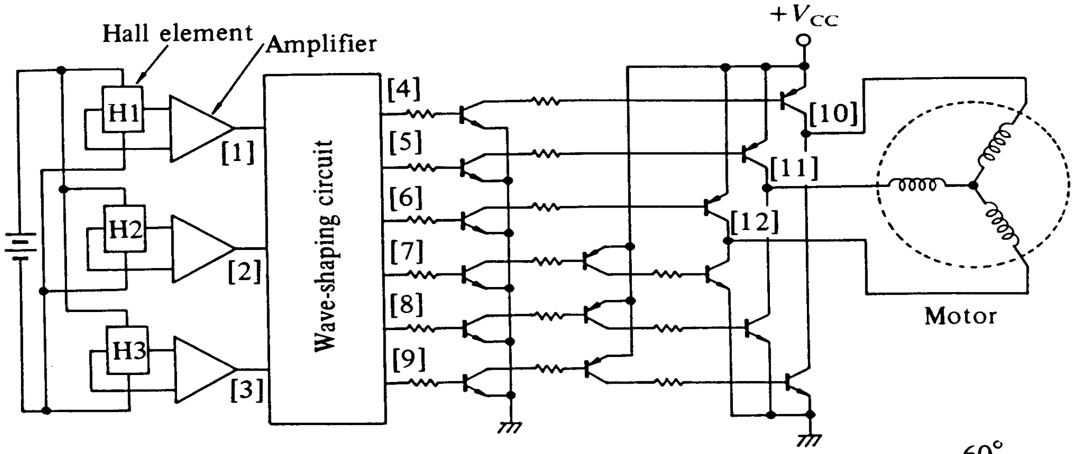


Fig.10.8 Clockwise revolutions of the stator's magnetic field and rotor (from Ref. [1] p63 Fig.4.6)

Since a shutter is coupled to the shaft, these photo elements are exposed in sequence to the light emitted from a lamp placed in the left of the figure. Now the problem is the relation between the ON/OFF state of the transistors and the light detecting phototransistors. The simplest relation is set when the logic sequencer is arranged in such a way that when a phototransistor marked with a certain number is exposed to light, the transistor of the same number turns ON. Fig.6 shows that electrical currents flow through Tr1, Tr4, and Tr5, and terminals U and W have the battery voltage, while terminal V has zero potential. In this state, a current will flow from terminal U to V, and another current from W to V as illustrated in Fig.7. We may assume that the solid arrows in this figure indicate the directions of the magnetic fields generated by the currents in each phase. The fat arrow in the centre is the resultant magnetic field in the stator. The rotational direction may be reversed by arranging the logic sequencer in such a way that when a photodetector marked with a certain number is exposed to light, the transistor of the same number is turned OFF. On the other hand, when a phototransistor is not exposed to light, the transistor of the same number is turned ON.

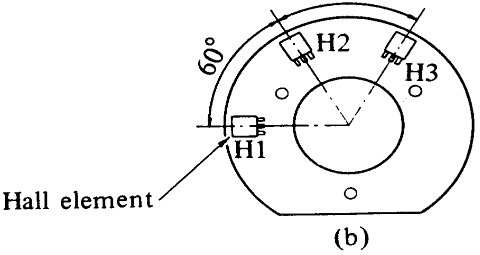
In the positional state of Fig.6, Tr2, 3, and 6 are ON, and the battery voltage E appears at terminal V, while U and W have zero electric potential. Then, as shown in Fig.9(a), the magnetic field in the stator is reversed, and the rotor's torque is counter-clockwise. After the motor revolves about 30°, Tr2 turns OFF and Tr1 ON. At this point, the field has revolved 60° and becomes as shown in (b). As the rotor produces another counter-clockwise torque, the counter-clockwise motion continues and the field becomes as shown in (c). This action is replaced in the sequence of (a)-(b)-(c)-(d) to produce a continuous counter-clockwise motion.

The motor discussed above has -connected windings, but it may also have Y-connected windings. Fig.10(a) shows a practical circuit which is used in a laser-beam printer or a hard-disc drive. As shown in Fig.10(b), three Hall elements are placed at intervals of 60° for detection of the rotor's magnetic poles. Because this motor has four magnetic poles, a mechanical angle of 60° corresponds to an electrical angle of 120°.



(a)

Fig.10.10 Practical circuit for a three-phase bipolar-driven motor, and arrangement of Hall elements (from Ref.[1] p80 Fig.5.1)



(b)

10.4 Equivalent Circuit and General Equations

The per phase equivalent circuit is shown in Fig.11 as following, where λ_m is the flux linkage of stator winding per phase due to the permanent magnet.

For steady state conditions, assuming *v* and e are sinusoidal at frequency ω, the equivalent circuit becomes the one shown in Fig.12, where X= ω L, and V, I, E, and λ_m are phasors with rms amplitudes. The steady state circuit equation can be written as