Chapter 12. Brushless DC Motors

Topics to cover:

1. *Structures and Drive Circuits*
2. *Equivalent Circuit*
3. *Performance*
4. *Applications*

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 realised. 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.

Structures and Drive Circuits

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.

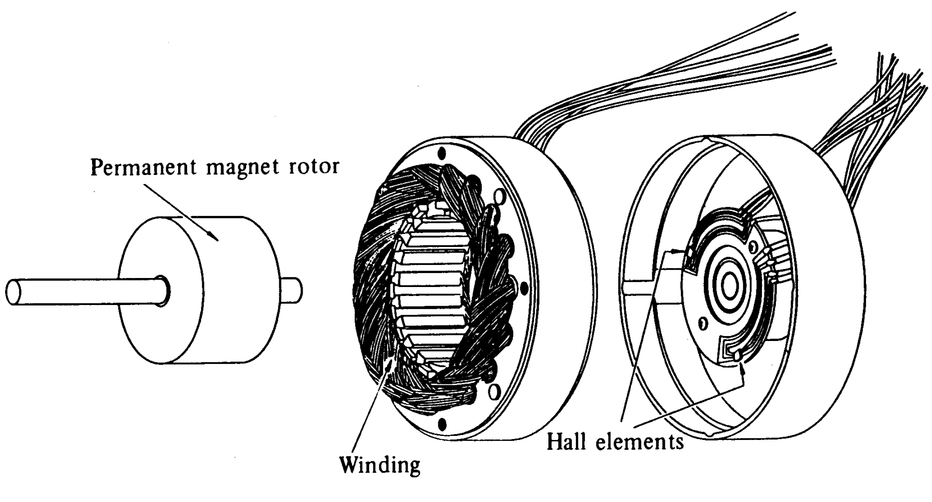

Fig.1 Disassembled view of a brushless dc motor (from Ref.[1] p58 Fig.4.1)

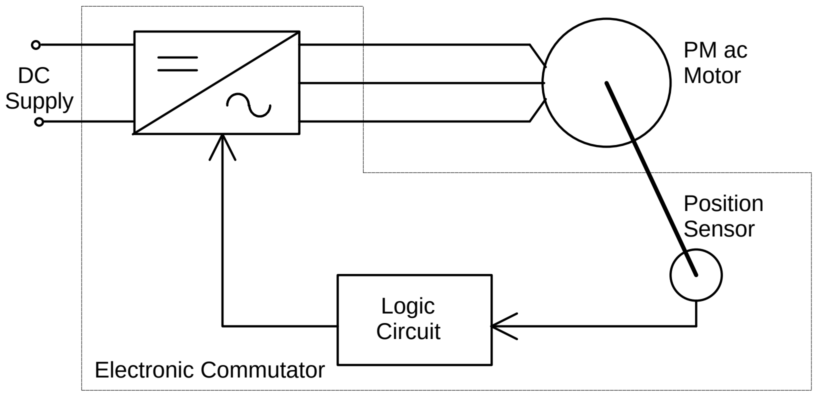

Fig.2 Brushless dc motor = Permanent magnet ac motor + Electronic commutator

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

Comparison of conventional and brushless dc motors

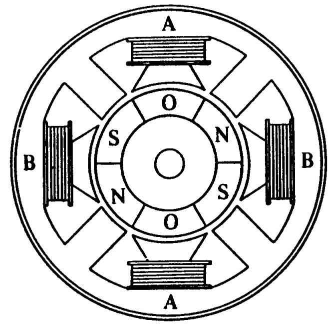

Fig.3 Two-phase motor having auxiliary salient poles (from Ref.[1] p95 Fig.5.22)

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.

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

Drive circuits

(1) Unipolar drive

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 120^{o} 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 flows 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.

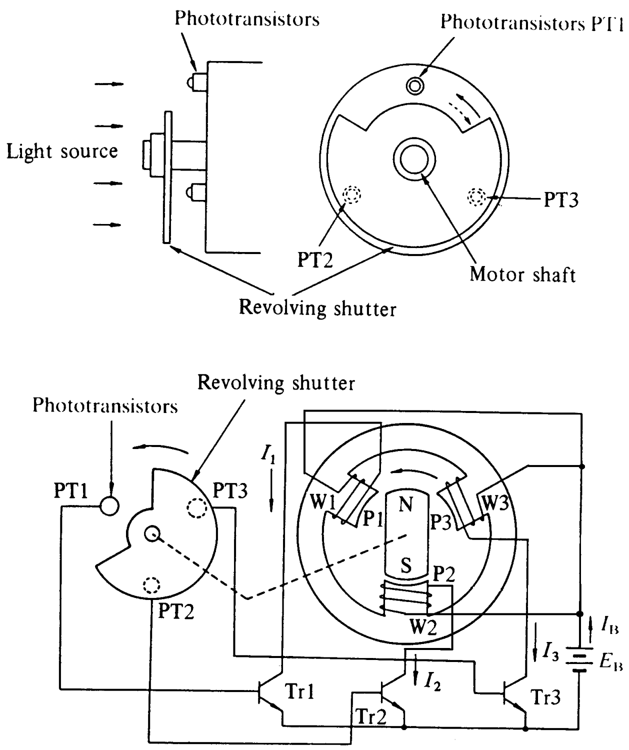

Fig.4 Three-phase unipolar-driven brushless dc motor
(from Ref.[1] p59 Fig.4.2 with winding directions swapped)

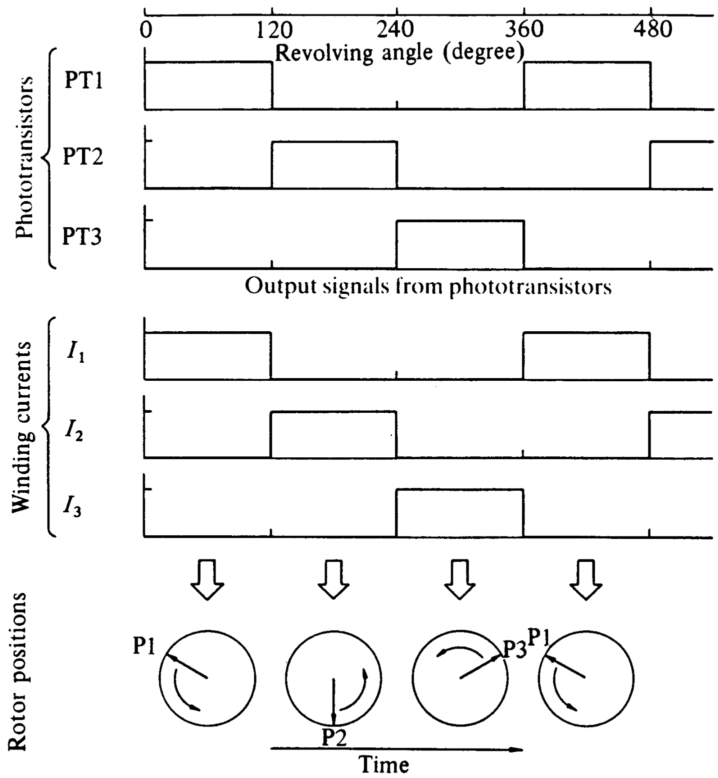

Fig.5 Switching sequence and rotation of stator's magnetic field (from Ref.[1] p60 Fig.4.3)

(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 flows 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.

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. 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.

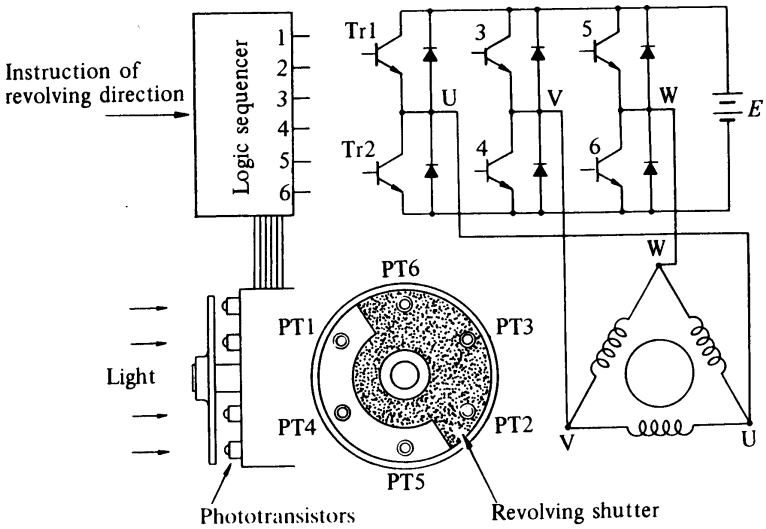

Fig.6 Three phase bipolar-driven brushless motor (from Ref.[1] p61, Fig.4.4)

The rotor is placed in such a position that the field flux will have a 90^{O} angle with respect to the stator's magnetic field as shown in Fig.7. In such a state a clockwise torque will be produced on the rotor. After it revolves through about 30^{O}, PT5 is turned OFF and PT6 ON which makes the stator's magnetic pole revolve 60^{O} clockwise. Thus when the rotor's south pole gets near, the stator's south pole goes away further to create a continuous clockwise rotation. The ON-OFF sequence and the rotation of the transistor are shown in Fig.8.

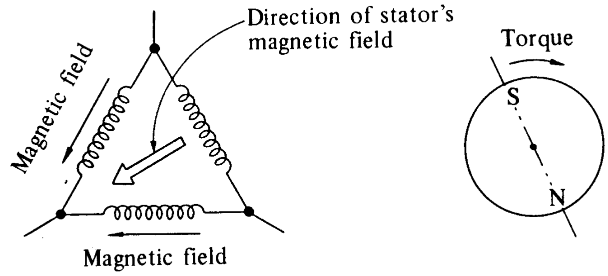

Fig.7 Stator's magnetic field in the shutter state of Fig.6, and the direction of torque (from Ref.[1] p62, Fig.4.5)

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

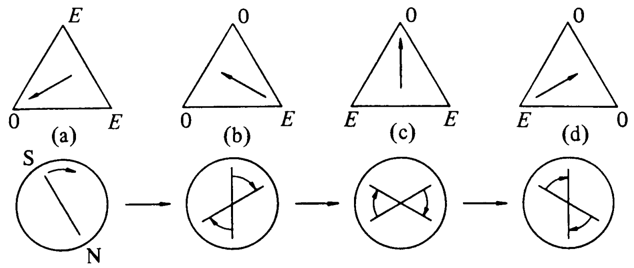

Fig.8 Clockwise revolutions of the stator's magnetic field and rotor (from Ref.[1] p63 Fig.4.6)

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^{o}, Tr2 turns OFF and Tr1 ON. At this point, the field has revolved 60^{o} 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.

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

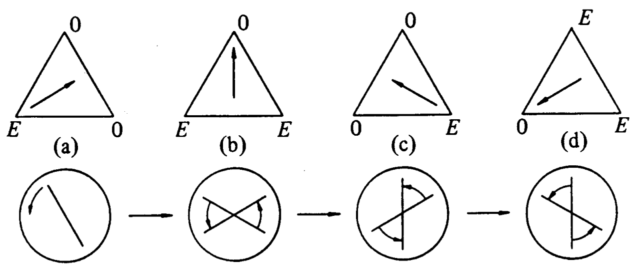

Fig.9 Counter-clockwise revolutions of the stator's magnetic field and rotor (from Ref.[1] p63 Fig.4.7)

The motor discussed above has Δ-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^{o} for detection of the rotor's magnetic poles. Because this motor has four magnetic poles, a mechanical angle of 60^{o} corresponds to an electrical angle of 120^{o}.

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=ωL, and V, I, E, and λ_m are phasors with rms amplitudes. The steady state circuit equation can be written as

$$V = E + (R + jwL) I \qquad (1)$$

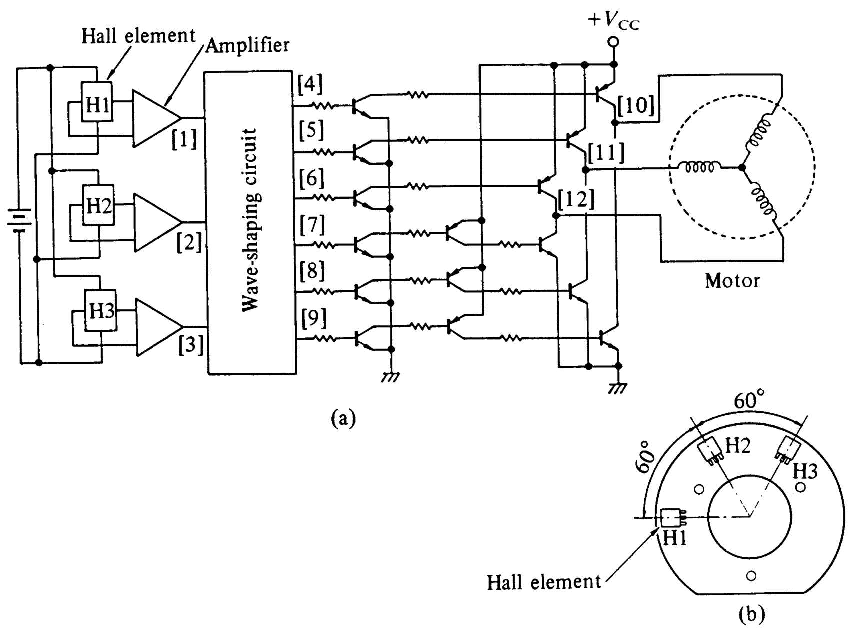

Fig.10 Practical circuit for a three-phase bipolar-driven motor, and arrangement of Hall elements (from Ref.[1] p80 Fig.5.1)

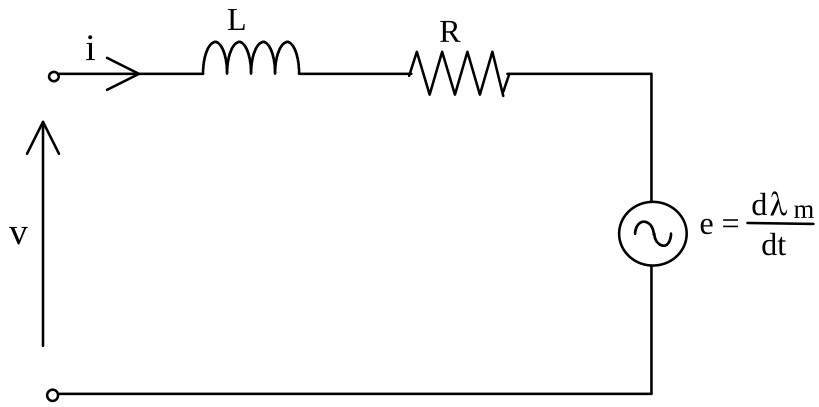

Fig.11 Dynamic per phase equivalent circuit of brushless dc motors

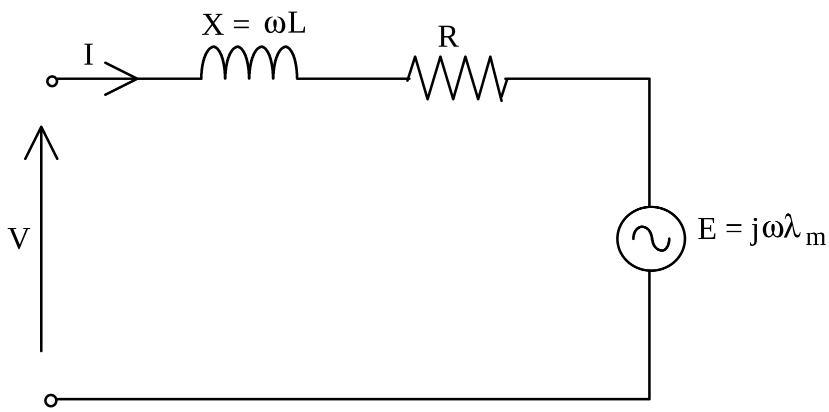

Fig.12 Steady state per phase equivalent circuit of brushless dc motors

For a maximum mechanical power at a given speed, *I* and *E* are in phase. This also gives maximum torque/ampere (minimum current/Nm). A brushless dc motor has position feedback from the rotor via Hall devices, optical devices, encoder etc. to keep a particular angle between *V* and *E*, since *E* is in phase with rotor position, and *V* is determined by the inverter supply to the motor. Assuming that $wL<<R$, when I is in phase with E, V will also be in phase with E. Thus the circuit can be analyzed using magnitudes of E, V, and I as if it were a dc circuit.

But first note that when E and I are in phase, the motor mechanical power output (before friction, windage, and iron losses) i.e. the electromagnetic output power is

$$P_{em} = m\,|E|\,|I| = mw\,|l_m|\,|I| \qquad (2)$$

where m is the number of phases, $|E|$, $|I|$, and $|\lambda_m|$ are the amplitudes of phasor E, I, and λ_m, and the electromagnetic torque is

$$T_{em} = \frac{P_{em}}{w_r} = \frac{mw\,|l_m||I|}{w_r} \qquad (3)$$

where $w_r = 2w/p$ is the rotor speed in Rad/s, and p the number of poles.

$$\therefore\ T_{em} = \frac{mp}{2}\,|l_m|\,|I| \qquad (4)$$

The actual shaft output torque is

$$T_{load} = T_{em} - T_{losses} \qquad (5)$$

where T_{losses} is the total torque due to friction, windage, and iron losses.

Dropping the amplitude (modulus) signs, we have

$$T_{em} = \frac{mp}{2}\,l_m\,I \qquad (6)$$

and in terms of rotor speed

$$E = \frac{p}{2}\,w_r\,l_m \qquad (7)$$

Performance of Brushless DC Motors

Speed-Torque (T~w) curve

Still assuming $wL<<R$ and position feed back keeps V and E (and hence I) in phase, the voltage equation can be simplified in algebraic form as

$$V = E + RI \qquad (8)$$

Substituting relations of E~w_r and T~I, we obtain

$$V = \frac{p}{2} w_r l_m + \frac{2R}{mp l_m} T_{em} \qquad (9)$$

and

$$\therefore \; w_r = \frac{V}{p l_m/2} - \frac{R}{m(p l_m/2)^2} T_{em} \qquad (10)$$

The corresponding T~w curve is shown in Fig.13 for a constant voltage.

Efficiency

Efficiency is defined as the ratio of output power and input power, i.e.

$$h = \frac{P_{out}}{P_{in}} \qquad (11)$$

where $P_{in} = mVI$, and $P_{out} = T_{load} w_r$.

In term of the power flow,

$$P_{in} = P_{cu} + P_{Fe} + P_{mec} + P_{out} \qquad (12)$$

where $P_{cu} = mRI^2$ is the copper loss due to winding resistance, P_{Fe} the iron loss due to hysteresis and eddy currents, and P_{mec} the mechanical loss due to windage and friction.

Applications

Brushless dc motors are widely used in various applications. Two examples of them are illustrated in the following.

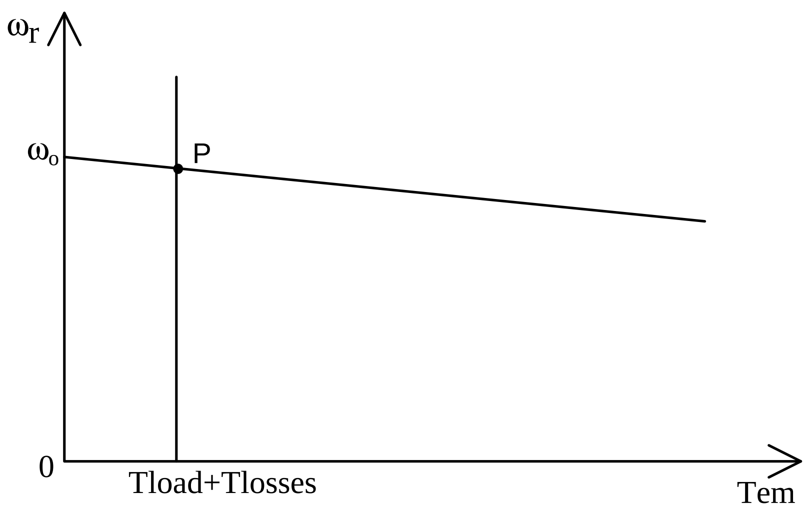

Fig.13 *T~w* curve of a brushless dc motor with a constant voltage supply

Laser printer

In a laser printer, a polygon mirror is coupled directly to the motor shaft and its speed is controlled very accurately in the range from 5000 to 40,000 rpm. When an intensity-modulated laser beam strikes the revolving polygon mirror, the reflected beam travels in different direction according to the position of the rotor at that moment. Therefore, this reflected beam can be used for scanning as shown in Fig.14. How an image is produced is explained, using Fig.15 and the following statements:

(1) The drum has a photoconductive layer (e.g. Cds) on its surface, with photosensitivity of the layer being tuned to the wavelength of the laser. The latent image of the information to be printed formed on the drum surface by the laser and then developed by the attracted toner.

(2) The developed image is then transferred to normal paper and fixed using heat and pressure.

(3) The latent image is eliminated.

A recent brushless dc motor designed for a laser printer is shown in Fig.16, and its characteristic data are given in Table 2.

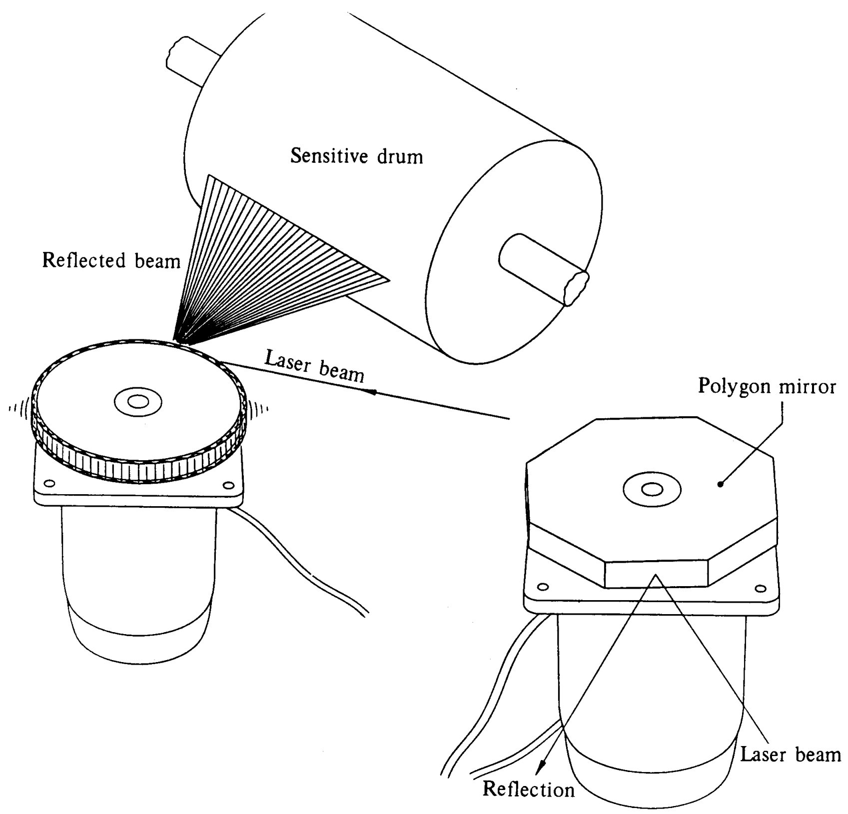

Fig.14 Role of motors for laser printers; (right) a brushless dc motor driving a polygon mirror, and (above) how to scan laser beams (from Ref.[1] p82 Fig.5.3)

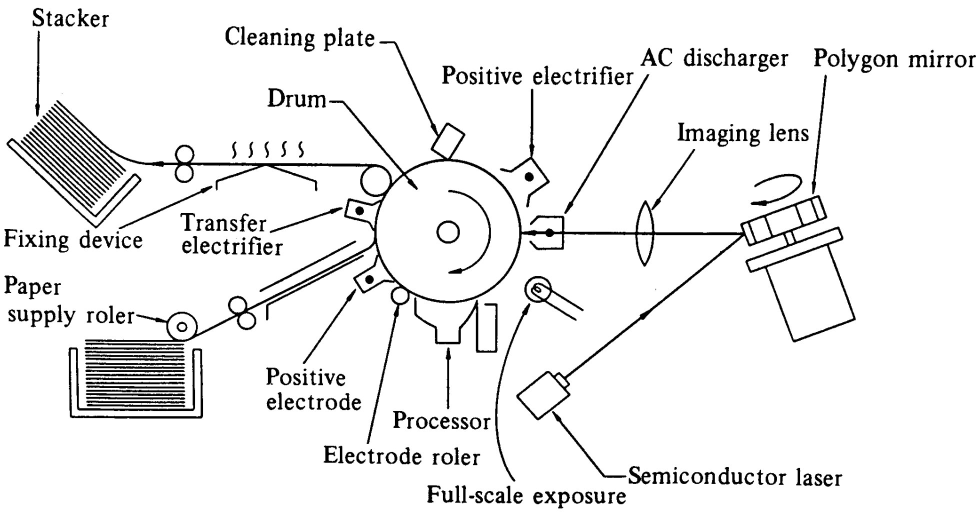

Fig.15 Principles of laser printers (from Ref.[1] p82 Fig.5.4)

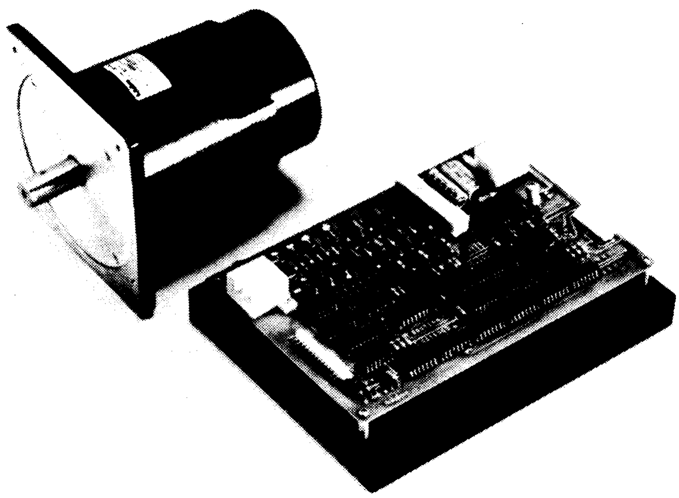

Fig.16 Brushless dc motor for a laser printer (from Ref.[1] p83 Fig.5.5

Table 2 Characteristics of three-phase bipolar type brushless motors

Item	Manufacturer Model	Nippon Densan Corporation 09PF8E4036
Voltage	V	$\pm 24 \pm 1.2$
Output	W	36
Rated torque	10^{-1} N m	0.294
Starting torque	10^{-1} N m	0.588
Starting time	s	3 (at non-inertial load)*
Rated speed	r.p.m.	6000, 9000, 12 000 selection
Rated current	A	3.5
Temperature	°C	5 ~ 45
Stability	per cent	±0.01
		Three-phase Δ connection

* A non-inertial load is a load applied by using a pulley and a weight

Hard disk drive

As the main secondary memory device of the computer, hard disks provide a far greater information storage capacity and shorter access time than either a magnetic tape or floppy disk. Formerly, ac synchronous motors were used as the spindle motor in floppy or hard disk drives. However, brushless dc motors which are smaller and more efficient have been developed for this application and have contributed to miniaturization and increase in memory capacity in computer systems. Table 3 compares a typical ac synchronous motor with a brushless dc motor when they are used as the spindle motor in an 8-inch hard disk drive. As is obvious from the table, the brushless dc motor is far superior to the ac synchronous motor. Although the brushless dc motor is a little complicated structurally because of the Hall elements or ICs mounted on the stator, and its circuit costs, the merits of the brushless dc motor far outweigh the drawbacks.

Table 3 Comparison of an ac synchronous motor and a brushless dc motor for an 8-inch hard disk drive

	AC synchronous motor	Brushless DC motor
Power supply: direct current, low voltage (for extension and interchangeability)	Inverter required	Direct current, low voltage (12–24 V)
Speed adjustment	Since speed depends on the frequency, regional adaptability is low	Adjustable independent of frequency
Adjustment of starting time	Adjustment not possible	Adjustment possible
Temperature rise	High	Low
Efficiency	Low (approx 30 per cent)	High (40–50 per cent)
Output to volume ratio	Small (bad)	Large (good)
Speed control	Fixed	Feedback control
Structure/cost	Simple, low cost	Slightly complicated, control circuit is not so expensive by the use of ICs

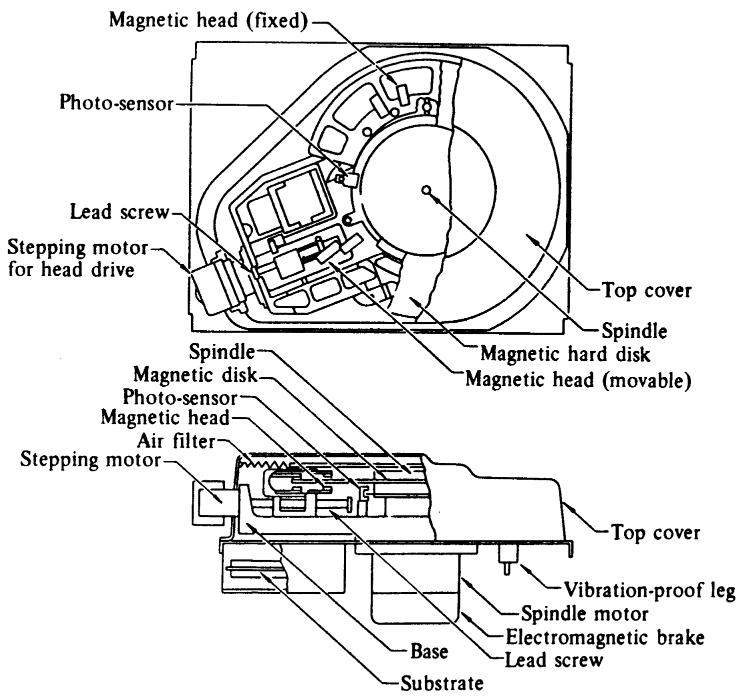

Fig.17 An example of hard disk drive (single disk type) (from Ref.[1] p86 Fig.5.9)

The hard disk drive works as follows (see Fig.17): The surface of the aluminium disk is coated with a film of magnetic material. Data is read/written by a magnetic head floating at a distance of about 0.5 μm from the disk surface due to the airflow caused by the rotating disk, and this maintains a constant gap. Therefore, when the disk is stopped or slowed down, the head may touch the disk and cause damage to the magnetic film. To prevent this, this spindle motor must satisfy strict conditions when starting the stopping.

Table 4 lists the basic characteristic data of brushless dc motors used in 8-inch hard disk drives (Fig.18).

Table 4 Characteristics of a three-phase unipolar motor designed for the spindle drive in a hard disk drive (from Ref.[1] p87 Table 5.3)

Item	Manufacturer / Model	Nippon Densan Corporation 09FH9C4018	09FH9C4022
Voltage	V	24±2.4	24±2.4
Output	W	18	22
Rated torque	10^{-1} N m	0.490	0.588
Starting torque	10^{-1} N m	1.47	1.96
Starting time	s	1.35	1.55
Rated speed	r.p.m.	3600	3600
Rated current	A	2.0	2.4
Temperature	°C	0 ~ 50	
Stability	per cent	±1.0	
Inertia	10^{-6} kg m^2	1380	1670
Braking method		Electromagnetic method	
Number of disks		2	4

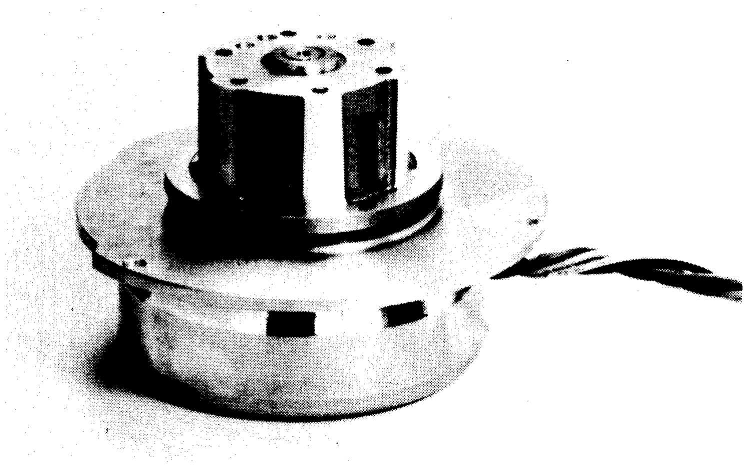

Fig.18 A brushless dc motor used for 8-inch hard disk drives (from Ref.[1] p87 Fig.5.10)

REFERENCES

[1] T. Kenjo, "Permanent magnet and brushless dc motors", Oxford, 1985
[2] T.J.E. Miller, "Brushless permanent magnet and reluctance motor drive", Oxford, 1989

EXERCISES

1. Describe the essential features of a brushless dc motor (alternatively called a self-synchronous motor).

2. What additional features would be required for a brushless dc servomotor with torque and position control?

3. Sketch the power circuit for a 3-phase brushless dc motor.

4. Calculate the supply frequency required for a twelve pole motor to rotate at
   (a) 360 rpm, and (b) 3600 rpm.

5. A brushless dc motor has 3 phases and 4 poles. The generated emf is 220 V rms sinusoidal at 1000 rpm (open circuit voltage when tested as generator with a drive motor). Calculate
   (a) the emf constant (V/Rad/s);
   (b) the torque constant (Nm/A) with optimum position feedback angle;
   (c) the speed/torque curve, if the resistance per phase is 4 Ω;
   (d) the supply frequency at 1000 rpm;
   (e) curves of input power, output power and efficiency against torque, assuming friction and iron losses are zero;
   (f) the frequency and speed at which $X=\omega L$ is equal to the resistance R, if the phase inductance is 5 mH;
   (g) what is the effect of (f) on the speed/torque curve i.e. the effect of $L>0$ and $\omega L>R$ as speed increases?

6. A brushless dc motor has 3 phases and 6 poles. The electromagnetic torque is 4 Nm with a current of 0.5 A rms. Friction and iron losses produce a constant retarding torque of 0.1 Nm. The resistance and inductance per phase are 70 Ω and 50 mH. Assume optimum position feedback. Calculate
   (a) the torque and emf constants;
   (b) the emf generated for a speed of 600 rpm;
   (c) the speed of the motor for a supply voltage of 200 V (ac rms per phase) with no external load;
   (d) the speed, current and efficiency for an external load of 4 Nm and a supply voltage of 200 V ac rms;
   (e) the supply frequency for (d), and check $\omega L<R$.