V = E + (R + jwL) I (10.1)

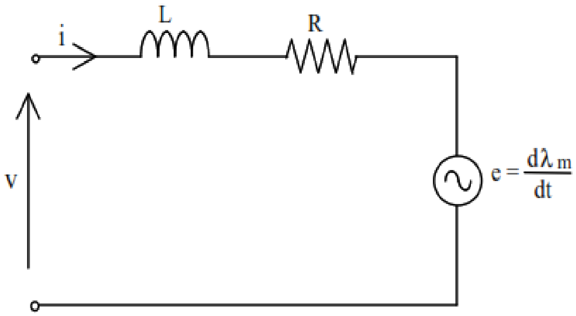

Fig.10.11 Dynamic per phase equivalent circuit of brushless dc

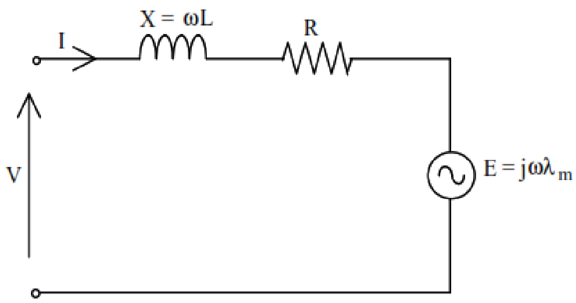

Fig.10.12 Steady state per phase equivalent circuit of brushless dc

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 $wL \ll R$, 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

$$P_{em} = m\,|E|\,|I| = mw|\lambda_m|\,|I| \qquad (10.2)$$

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

$$T_{em} = \frac{P_{em}}{w_r} = \frac{mw|\lambda_m|\,|I|}{w_r} \qquad (10.3)$$

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

$$T_{em} = \frac{mP|\lambda_m|\,|I|}{2} \qquad (10.4)$$

The actual shaft output torque is

$$T_{load} = T_{em} - T_{losses} \qquad (10.5)$$

where T_{losses} is the total torque due to friction, windage, and iron losses. Dropping the amplitude (modulus) signs, we have

$$T_{em} = \frac{mP}{2}\lambda_m I \qquad (10.6)$$

and in terms of rotor speed

$$E = \frac{P}{2}\lambda_m w_r \qquad (10.7)$$

10.5 Performance of Brushless DC Motors

10.5.1 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

$$V = E + RI \quad (10.8)$$

Substituting relations of $E\sim w_r$ and $T\sim I$, we obtain

$$V = \frac{P}{2}\lambda_m w_r + \frac{2R}{mp\lambda_m}T_{em} \quad (10.9)$$

So

$$w_r = \frac{V}{p\lambda_m/_2} - \frac{R}{m(^{p\lambda_m}/_2)^2}T_{em} \quad (10.10)$$

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

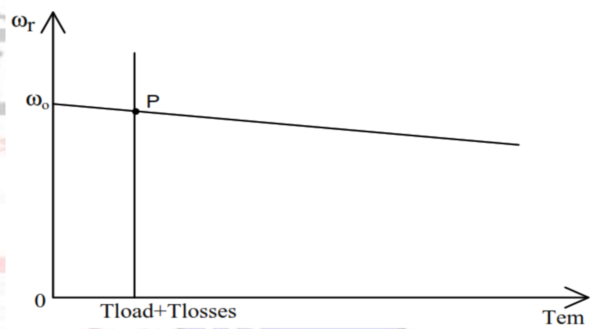

Fig.10.13 *T~w* curve of a brushless dc motor with a constant voltage supply

10.5.2 Efficiency

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

$$\zeta = \frac{P_{out}}{P_{in}} \quad (10.11)$$

where $P_{in} = mVI$, and $P_{out} = T_{load}\, w_r$. In term of the power flow

$$P_{in} = P_{cu} + P_{Fe} + P_{mec} + P_{out} \quad (10.12)$$

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.

10.6 Applications

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

10.6.1 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:

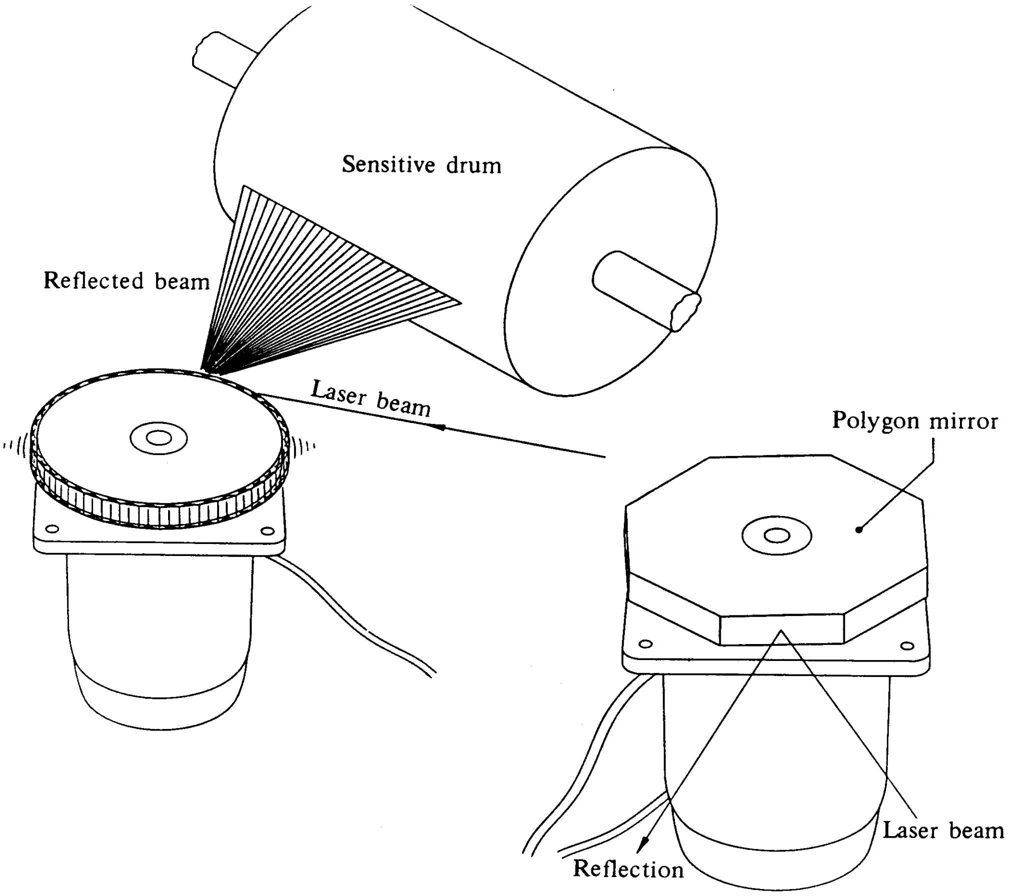

Fig.10.14 Role of motors for laser printers; (right) a brushless dc motor driving a polygon mirror, and (above) how to scan laser beams (from Ref. [1] p82 Fig.5.3)

(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.

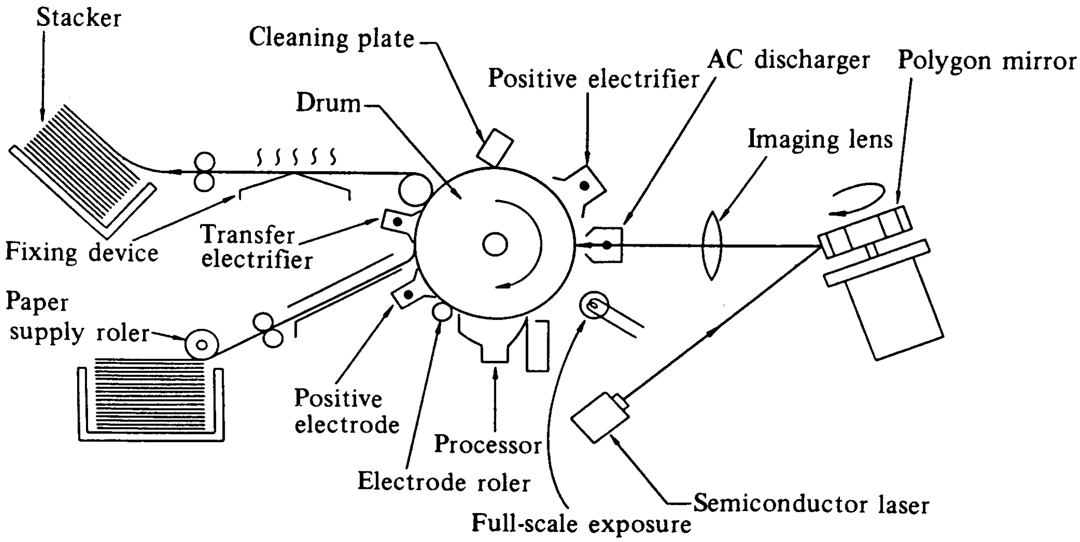

Fig.10.15 Principles of laser printers (from Ref. [1] p82 Fig.5.4)

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

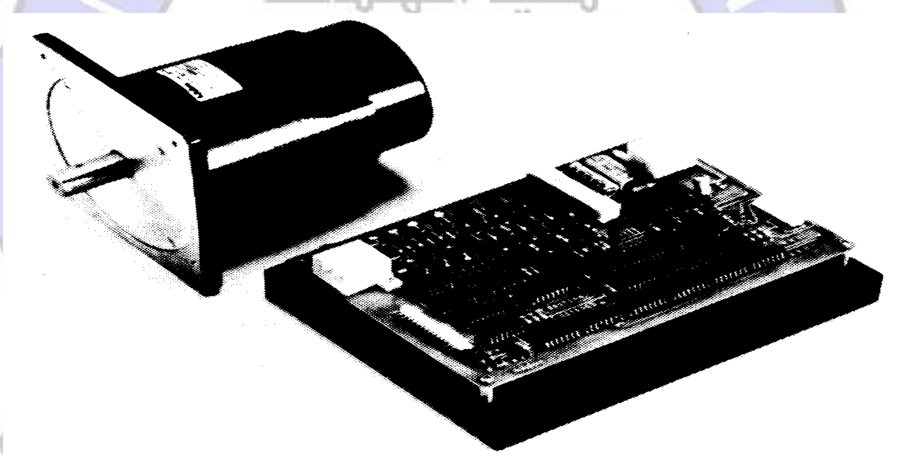

Fig.10.16 Brushless dc motor for a laser printer (from Ref. [1] p83 Fig.5.5

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

10.6.2 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.

	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

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

Item	Manufacturer	Nippon Densan Corporation	
	Model	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

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

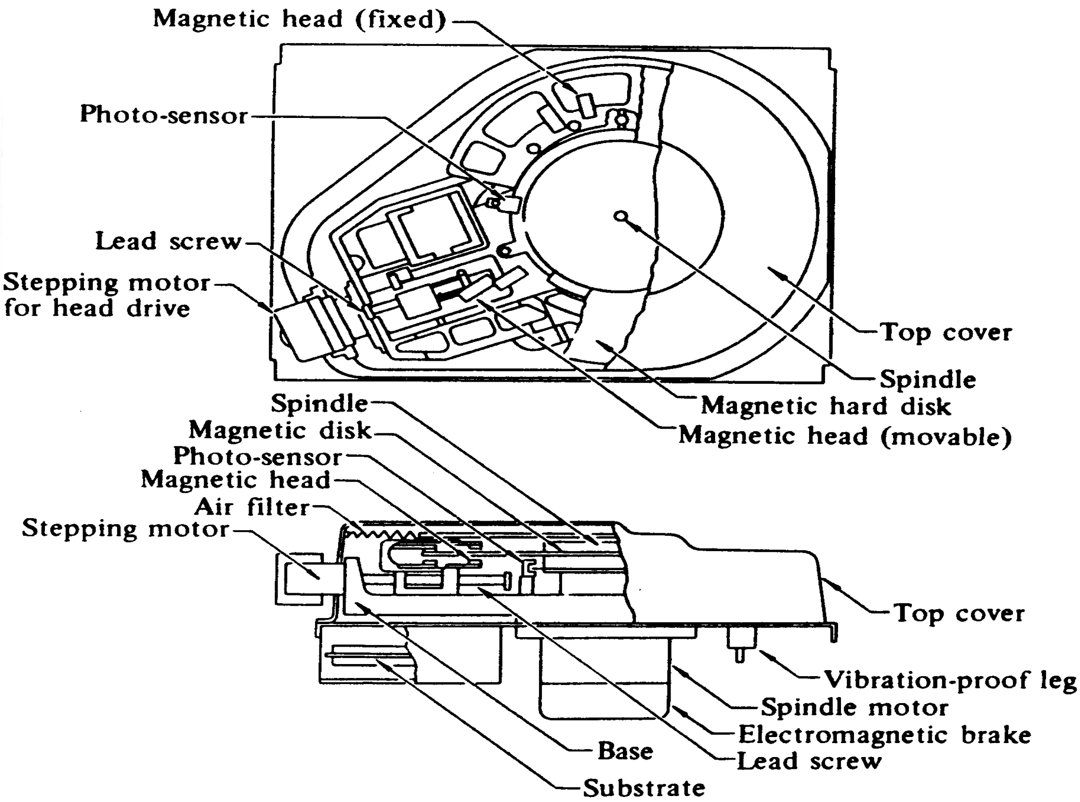

Fig.10.17 An example of hard disk drive (single disk type) (from Ref. [1] p86 Fig.5.9).

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).

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

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in a ha…

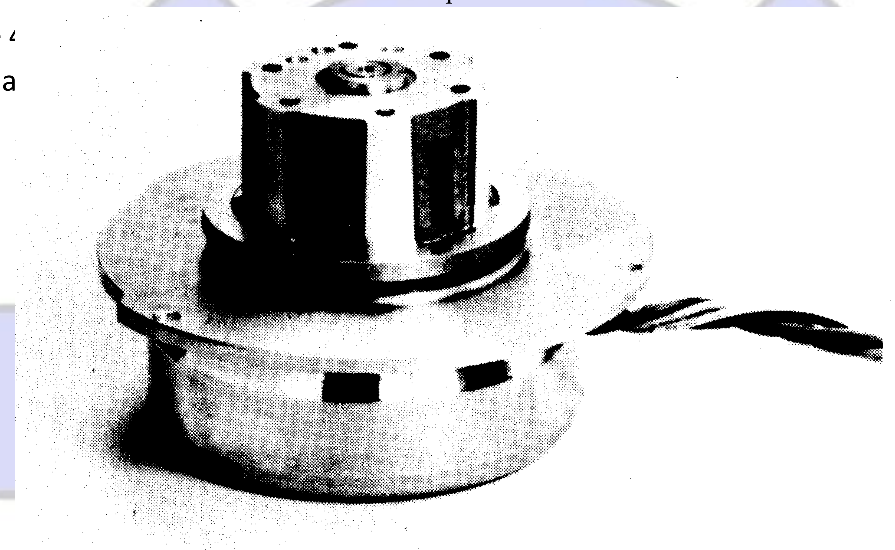

Fig.10.18 A brushless dc motor used for 8-inch hard disk drives (from Ref. [1] p87 Fig.5.10)

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 ;

(d) the supply frequency at 1000 rpm;