UNIVERSITY OF TECHNOLOGY, SYDNEY
FACULTY OF ENGINEERING

48531 Electromechanical Systems

Brushless DC Motors

Topics to cover:

1. Introduction

2. Structures & Drive Circuits

3. Equivalent Circuit

4. Performance

Introduction

- Why Brushless ?

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***.

Brushless DC motors are widely used in applications such as laser printers, floppy and hard disk drives, robotic drives and machine tools, etc.

Introduction

- Why Brushless ? (Cont.)

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

Introduction

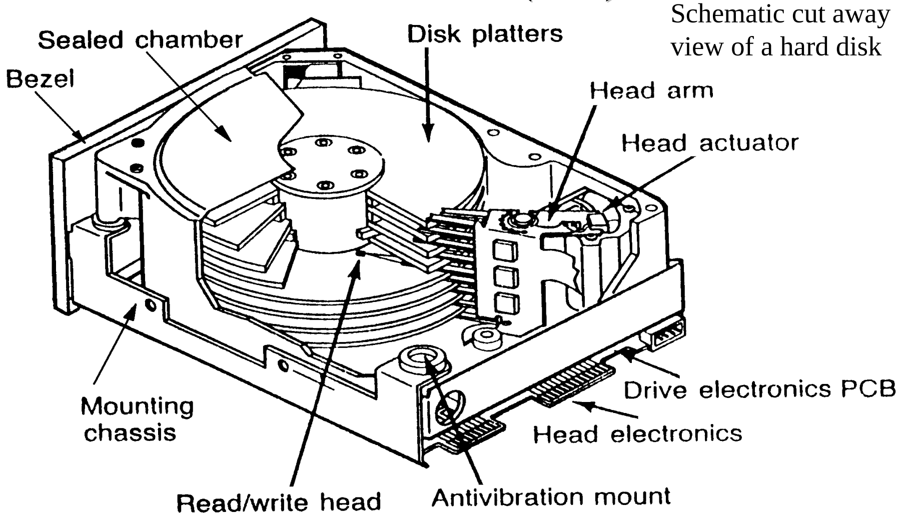
- Hard Disk Drives

In a hard disk drive, a brushless DC motor is used to drive the spindle.

Introduction

- Hard Disk Drives (Cont.)

Schematic cut away view of a hard disk



Introduction

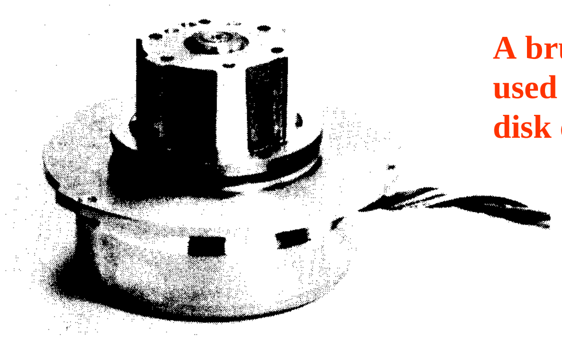
- Hard Disk Drives (Cont.)

Comparison of an AC synchronous motor and a brushless DC motor for an 8-inch hard disk drive (Major advantages: ***smaller and more efficient***)

	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

Introduction

- Hard Disk Drives (Cont.)



A brushless DC motor used for 8-inch hard disk drives

Introduction

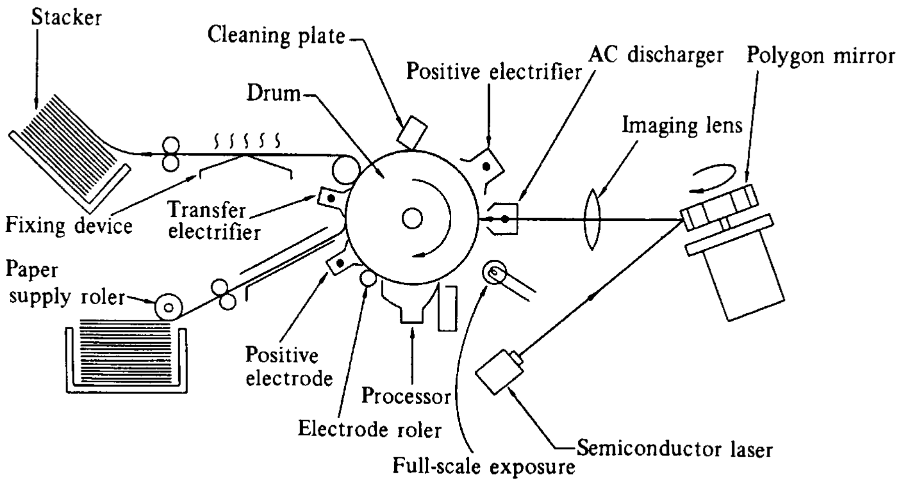
- Hard Disk Drives (Cont.)

Characteristics of a three phase unipolar motor designed for the spindle drive in a hard disk drive

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

Introduction

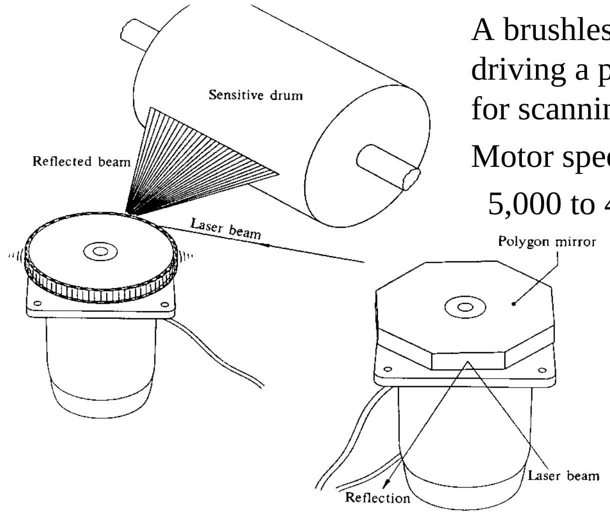
- Laser Printers



Schematic view of principles of laser printers

Introduction

- Laser Printers (Cont.)



A brushless DC motor driving a polygon mirror for scanning laser beams

Motor speed:

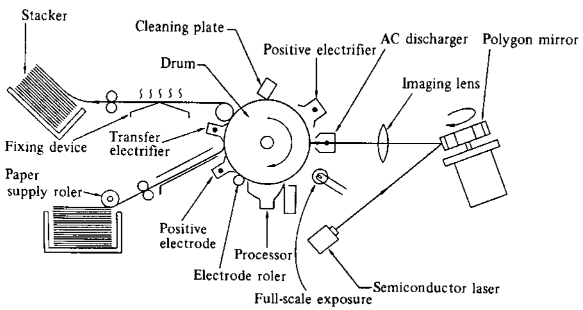
5,000 to 40,000 rev/min

Introduction

- Laser Printers (Cont.)

Procedure:

(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.

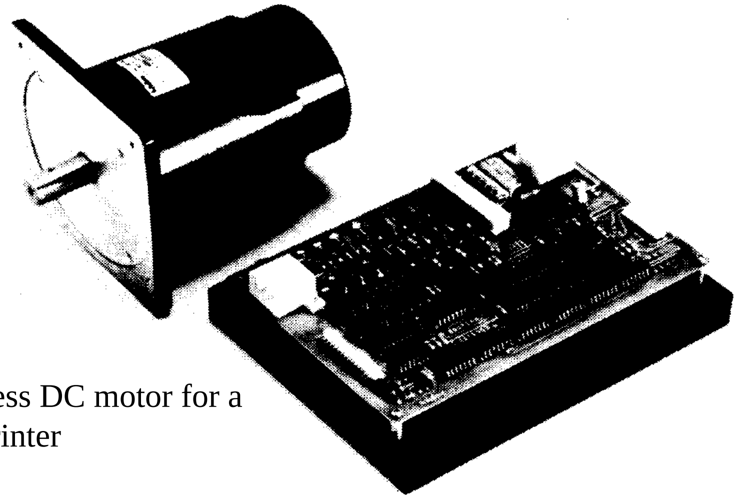


(2) The developed image is then transferred to normal paper and fixed using heat and pressure.

(3) The latent image is eliminated.

Introduction

- Laser Printers (Cont.)



Brushless DC motor for a laser printer

Introduction

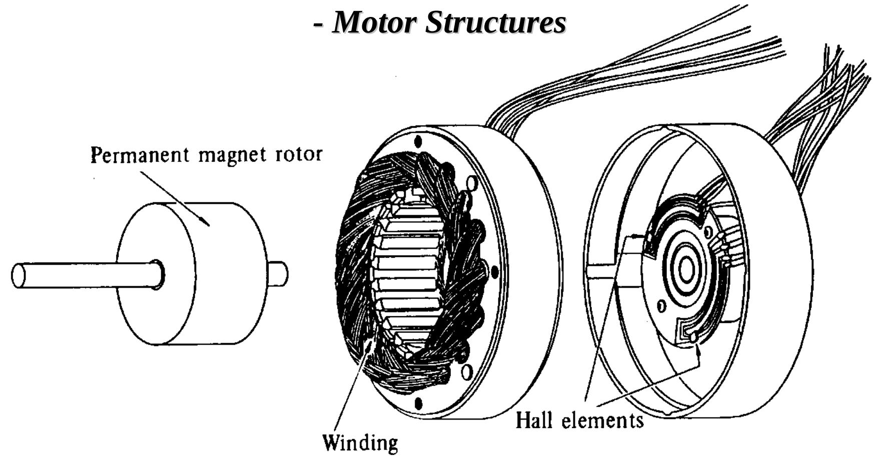
- Laser Printers (Cont.)

Characteristics of three-phase bipolar type brushless motors

Item	Manufacturer Model	Nippon Densan Corporation 09PF8E4036
Voltage	V	±24±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

Structures and Drive Circuits

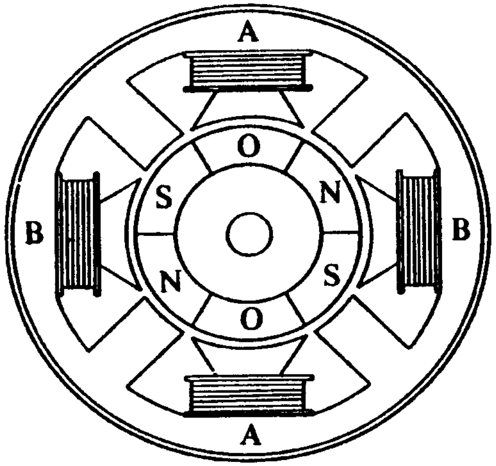
- Motor Structures



Disassembled view of a three phase brushless DC motor

Structures and Drive Circuits

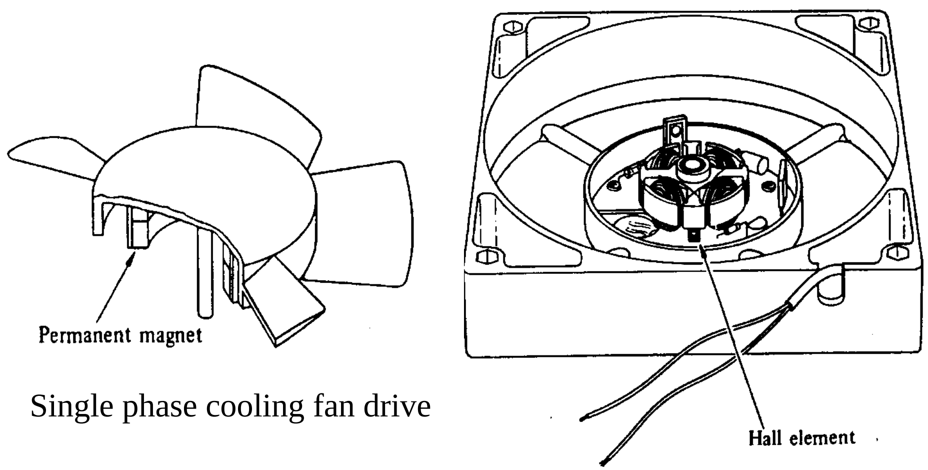
- Motor Structures (Cont.)



Two-phase motor having auxiliary salient poles

Structures and Drive Circuits

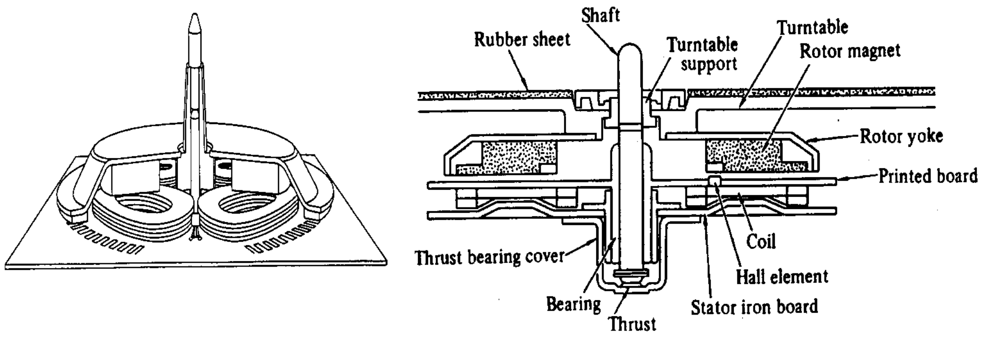
- Motor Structures (Cont.)



Single phase cooling fan drive

Structures and Drive Circuits

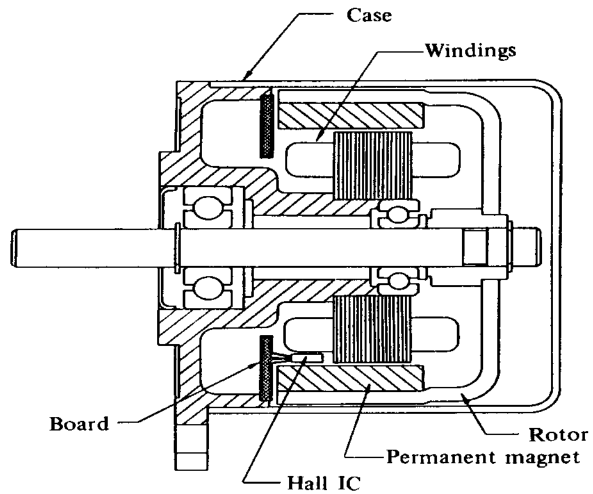
- Motor Structures (Cont.)



Cutaway view of a brushless DC motor used to drive a turntable in a record player

Structures and Drive Circuits

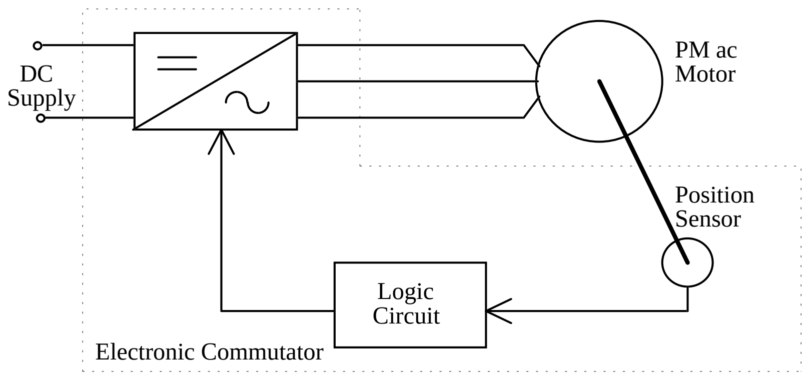
- Motor Structures (Cont.)



Outer rotor three phase permanent magnet brushless DC motor

Structures and Drive Circuits

- System Block Diagram



Brushless DC motor =

Permanent magnet AC motor + Electronic commutator

Structures and Drive Circuits

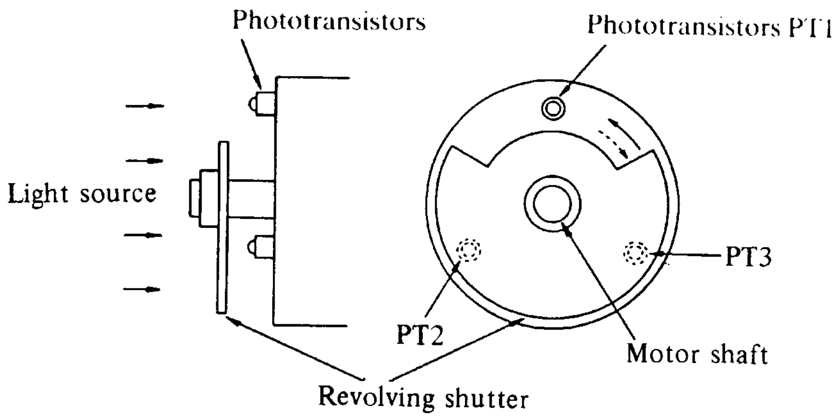
- Position Sensors

Commonly used position sensors are:

- Phototransistors and photodiodes
- Hall elements
- Pulse encoders
- Variable Differential Transformers

Structures and Drive Circuits

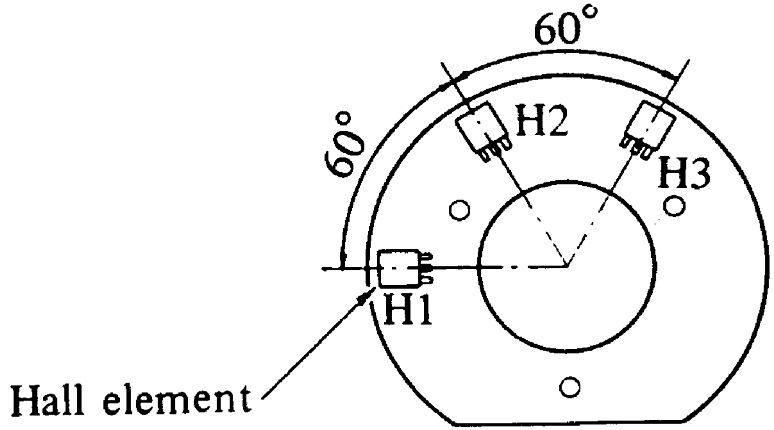
- Position Sensors (Cont.)



Phototransistor position sensor

Structures and Drive Circuits

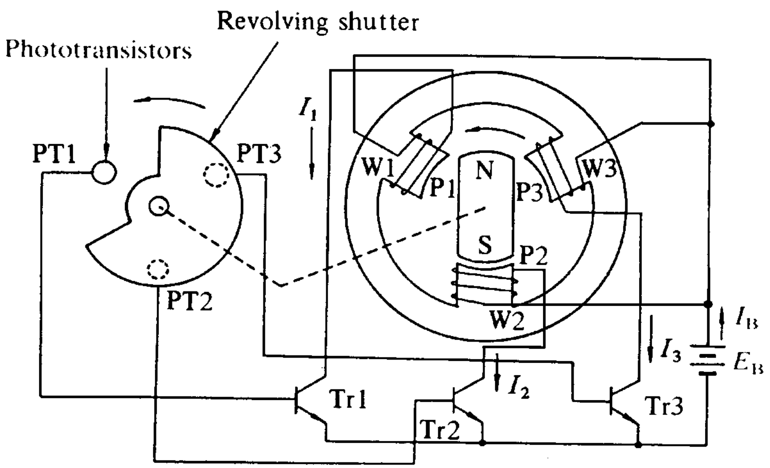
- Position Sensors (Cont.)



Hall element position sensor

Structures and Drive Circuits

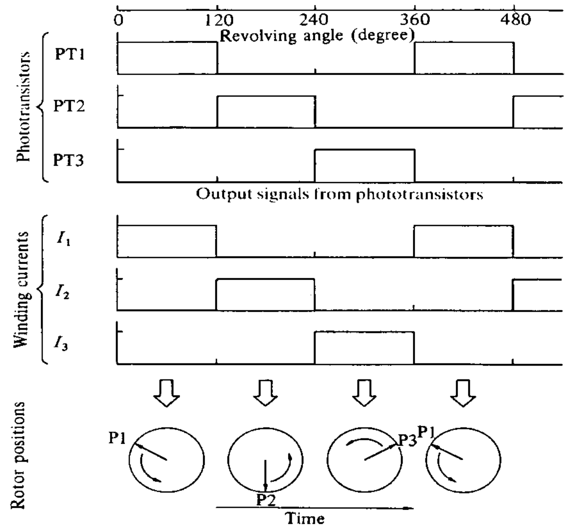
- Unipolar Drive Circuit



Three-phase unipolar-driven brushless DC motor

Structures and Drive Circuits

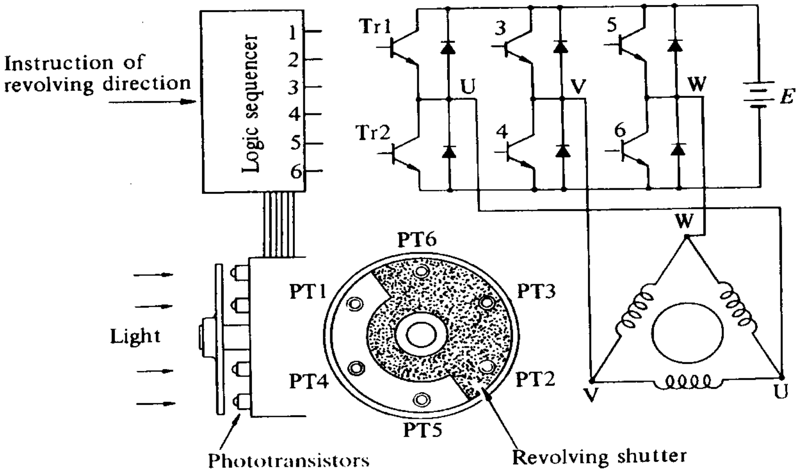
- Unipolar Drive Circuit (Cont.)



Switching sequence and rotation of stator magnetic field

Structures and Drive Circuits

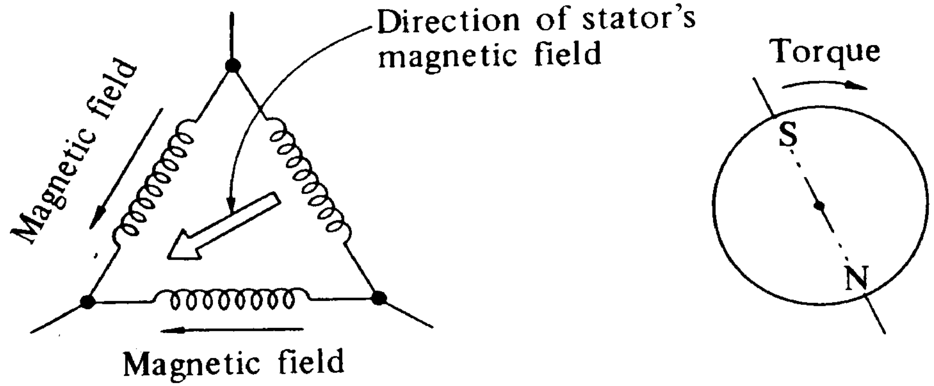
- Bipolar Drive Circuits



Three phase bipolar driven brushless DC motor

Structures and Drive Circuits

- Bipolar Drive Circuits (Cont.)

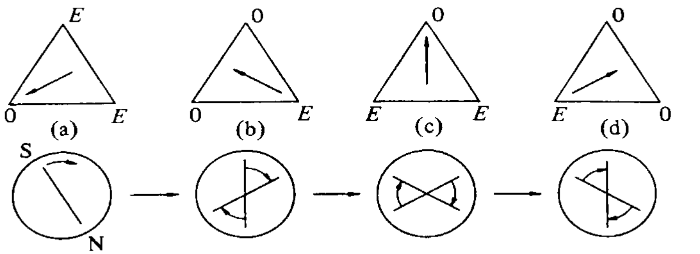


Directions of stator magnetic field and torque

Structures and Drive Circuits

- Bipolar Drive Circuits (Cont.)

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

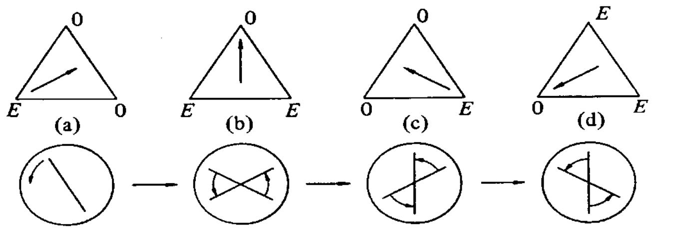


Clockwise revolutions of stator field and rotor

Structures and Drive Circuits

- Bipolar Drive Circuits (Cont.)

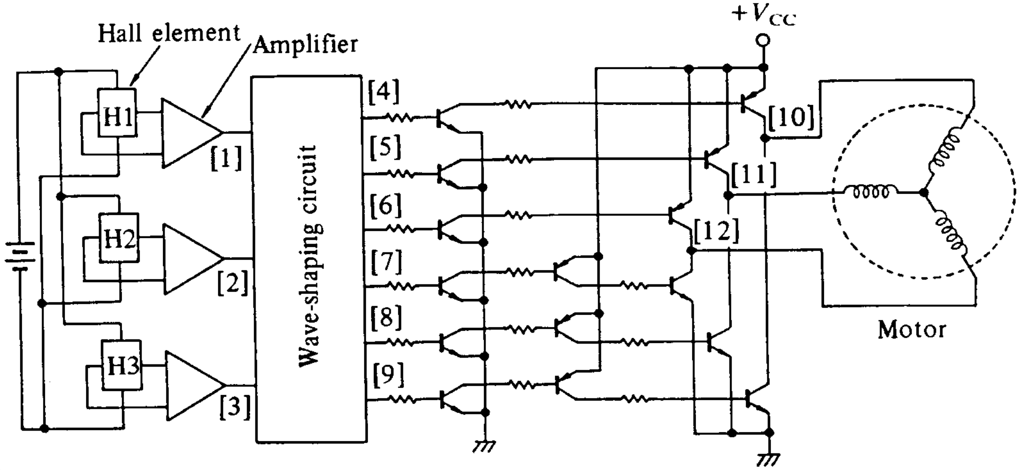
ON-OFF sequence	1	2	3	4	5	6
Tr 1	0	1	1	1	0	0
2	1	0	0	0	1	1
3	1	1	0	0	0	1
4	0	0	1	1	1	0
5	0	0	0	1	1	1
6	1	1	1	0	0	0



Counter clockwise revolutions of stator field and rotor

Structures and Drive Circuits

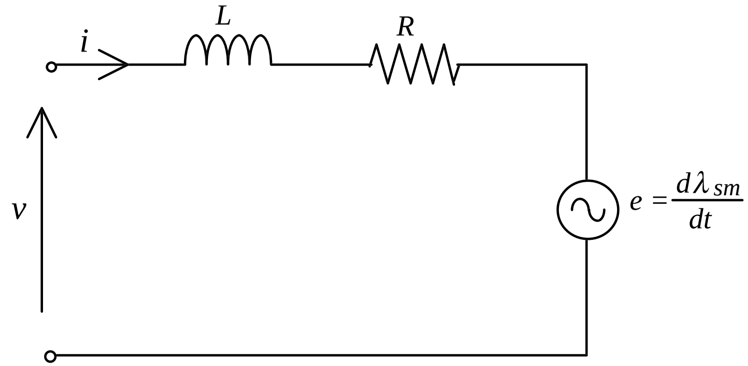
- Bipolar Drive Circuits (Cont.)



Three phase bipolar driven brushless DC motor

Mathematical Model

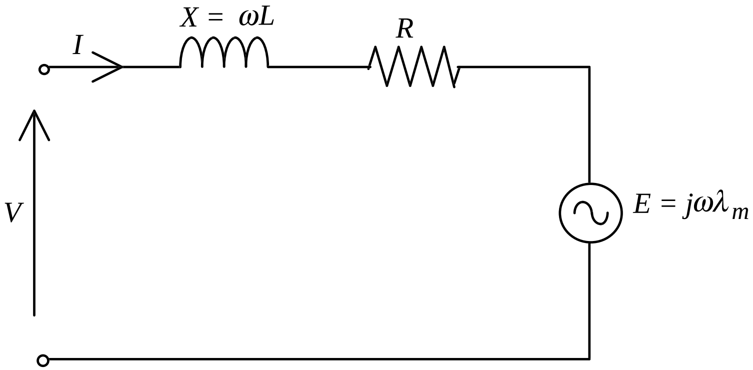
- Dynamic Equivalent Circuit



Dynamic per phase equivalent circuit of brushless DC motors

Mathematical Model

- Steady State Equivalent Circuit



Steady state per phase equivalent circuit of brushless DC motors

Mathematical Model

- Electrical Circuit Equation

The steady state circuit equation for a brushless DC motor is

$$\boxed{V = (R + j\omega L)I + E}$$

where $\boxed{E = j\omega\lambda_m}$ is the induced *emf* in stator winding by the magnets,

$\omega = 2\pi f$ the angular frequency of excitation, and λ_m the flux linkage of the stator winding due to the magnets.

Using the ***position feedback***, the phase angle of the terminal voltage *V* can be controlled to be the same as that of the induced *emf E*, i.e.

$$\varphi_V = \varphi_E$$

By proper design, the reactance of the stator winding can be much smaller than the resistance within the speed range, i.e.

$$R >> \omega L$$

Therefore, $\boxed{V = E + RI}$

Mathematical Model

- Emf and Torque

Assume the flux linkage of the stator winding due to the magnets varies with time sinusoidally: $\boxed{\lambda_{sm} = \sqrt{2}\lambda_m \sin \omega t}$

The induced *emf* then can be calculated by

$$\boxed{e = \frac{d\lambda_{sm}}{dt} = \sqrt{2}\omega\lambda_m \cos \omega t = \sqrt{2}E \cos \omega t}$$

where $\boxed{E = \omega\lambda_m = \frac{p}{2}\omega_r\lambda_m}$ is the *rms* value of the *emf*.

The electromagnetic power must balance the internal mechanical power, or $\boxed{P_{em} = m|E\|I| = T_{em}\omega_r}$ where *m* is the no. of phases.

Therefore,

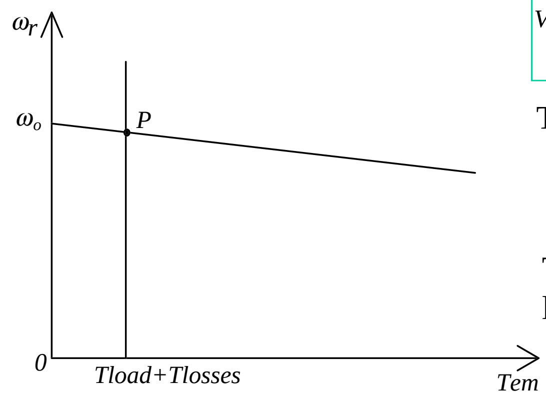
$$\boxed{T_{em} = \frac{P_{em}}{\omega_r} = \frac{m|E\|I|}{\omega_r} = \frac{mp}{2}\lambda_m I}$$

Performce

- Torque/Speed Curve

Substituting the *emf* and torque expressions into the steady state circuit equation, we have

$$\boxed{V = E + RI = \frac{p}{2}\omega_r\lambda_m + \frac{R}{\frac{mp}{2}\lambda_m}T_{em}}$$



Therefore,

$$\boxed{\omega_r = \frac{V}{p\lambda_m/2} - \frac{R}{m\left(p\lambda_m/2\right)^2}T_{em}}$$

The operating point for a given load can be found by

$$\boxed{T_{em} = T_{load} + T_{losses}}$$

Performance

- Efficiency

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

$$\boxed{\eta = \frac{P_{out}}{P_{in}}}$$

where $\boxed{P_{out} = T_{load}\omega_r}$ and $\boxed{P_{in} = mVI}$

In terms of the power flow, we have

$$\boxed{P_{in} = P_{cu} + P_{Fe} + P_{mech} + P_{out}}$$

where $\boxed{P_{cu} = mRI^2}$

is the copper loss of the stator winding, and P_{Fe} and P_{mech} are the core loss and the mechanical loss due to friction and windage.