Review of DC motors and their selection in Mechatronics systems

Actuators

An actuator is a component of machines that is responsible for moving or controlling a mechanism or system. An actuator requires a control signal and source of energy. The control signal is relatively low energy and may be electric voltage or current, pneumatic or hydraulic pressure, or even human power.

Actuator System

An actuator system has four components:

1. **Electric Motor**
2. **Power Converter**
   - **Rectifiers**
   - **Choppers**
   - **Inverters**
   - **Cycloconverters**
3. **Controllers – matching the motor and power converter to meet the load requirements**
4. **Load**

Electric Motors

Electric motors presently used for speed control applications are:

1. DC excited

- Shunt
- Series
- Compound
- Separately excited
- Switched reluctance motors

2. AC Excited

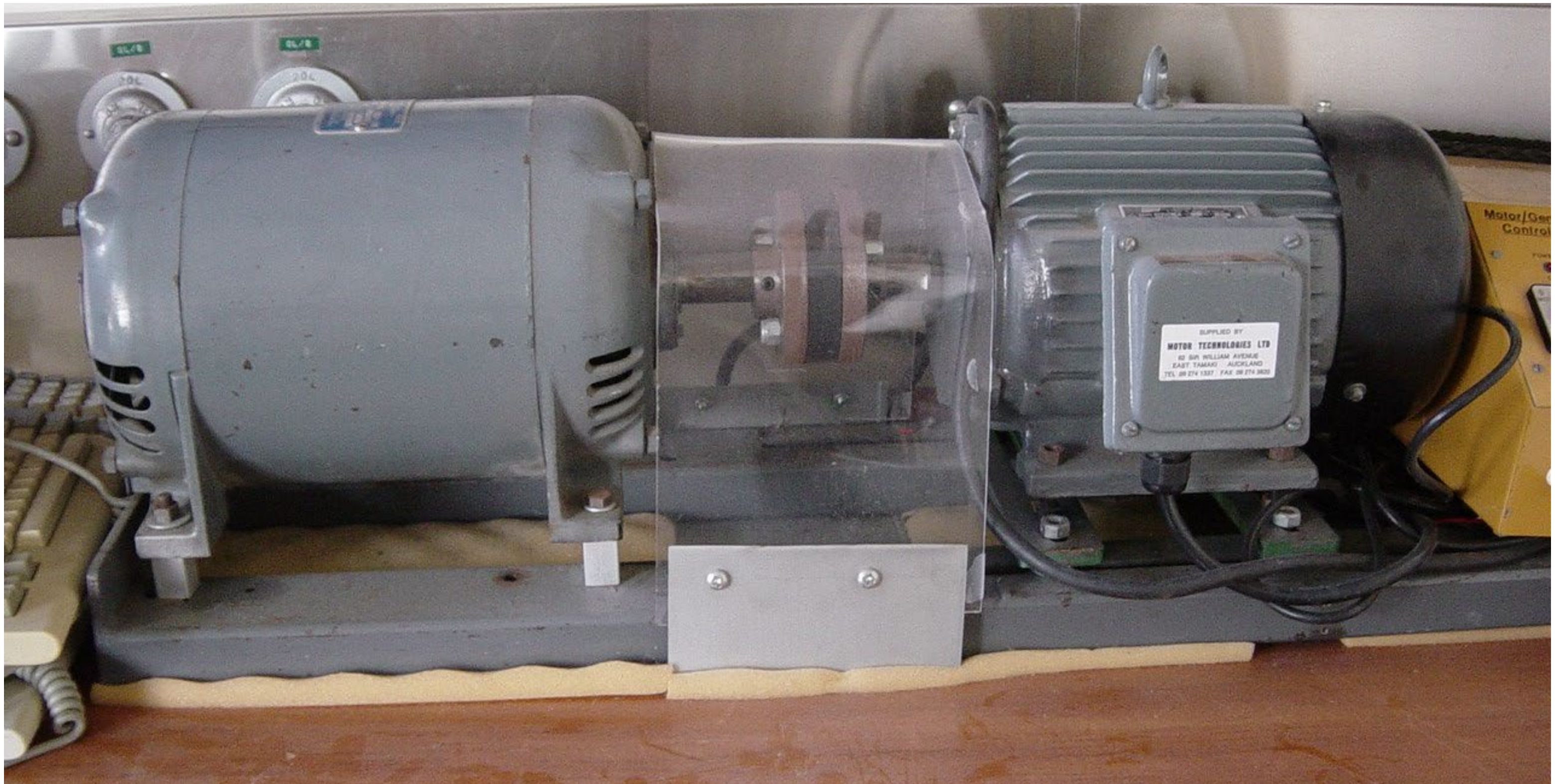
- Induction
- Wound rotor synchronous
- Permanent magnet synchronous
- Reluctance motors

Fundamental of rotating machines

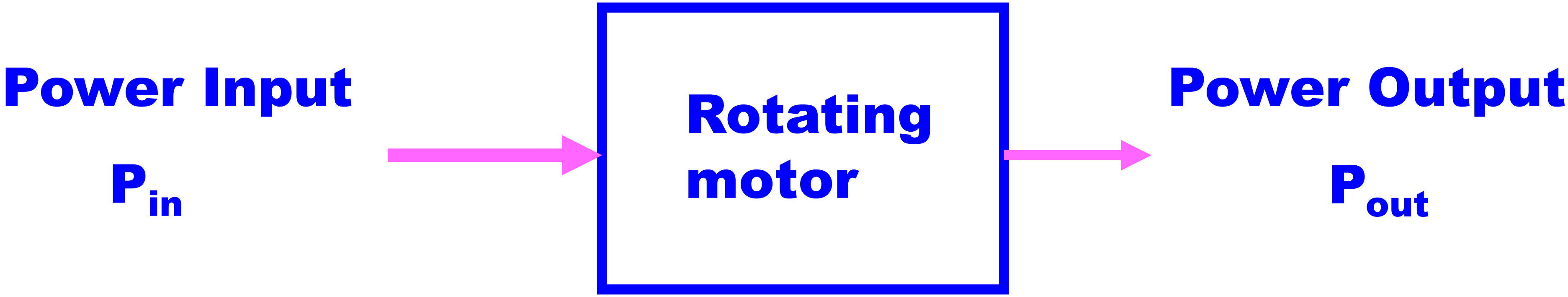
Energy converter

Input power → **Rotating machine** → **Output power**

Overview of motor construction



Power flow in rotating motors



Power output = Power input - Losses

Power input, $P_{in} = V_{in} I_{in}$ for a DC motor

$= V_{in} I_{in} \cos\phi$ for a single phase motor

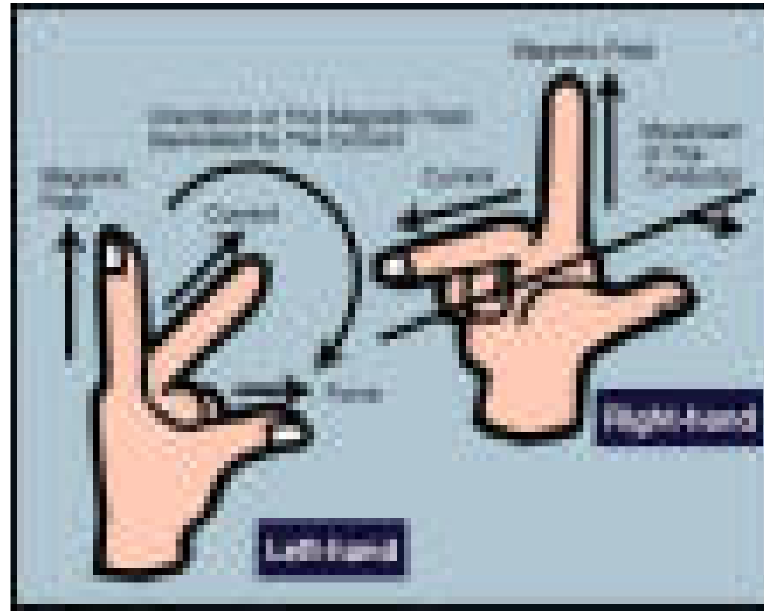
$= \sqrt{3} V_{in} I_{in} \cos\phi$ for a 3-phase motor

Note: ϕ is the phase angle between phase voltage and phase current

Power output, $T_{OUT} = \omega_m T_m = \frac{2\pi N T_m}{60}$; N is in RPM

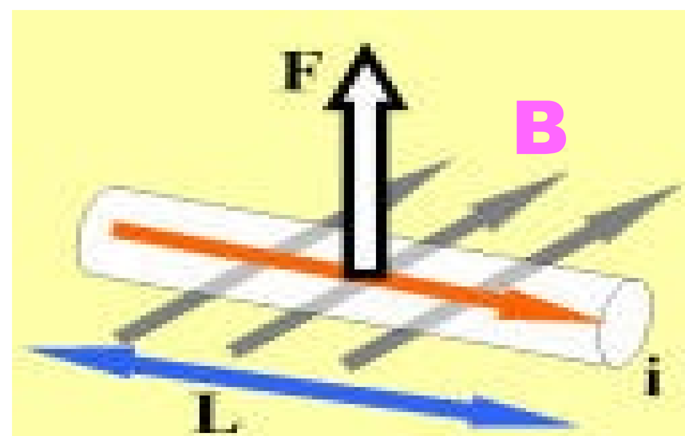
Efficiency $\eta = \frac{P_{out}}{P_{in}}$

Operating principle of rotating motors



Fleming's Left Hand Rule

$$F = i\,L \times B$$



F = BiL ; F is perpendicular to both B and I (L)

Force on a charge

Stationary charge in an electric field:

$$F = Q E$$

F - Force on charge Q

E - electric field intensity

Charge in motion or the moving charge in a magnetic field :

$$F = Q v \times B$$

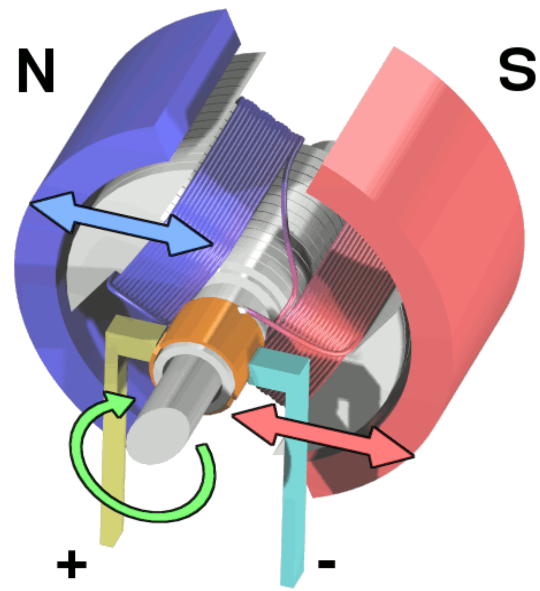
Combination of electric and magnetic field

$$F = Q(E + v \times B)$$

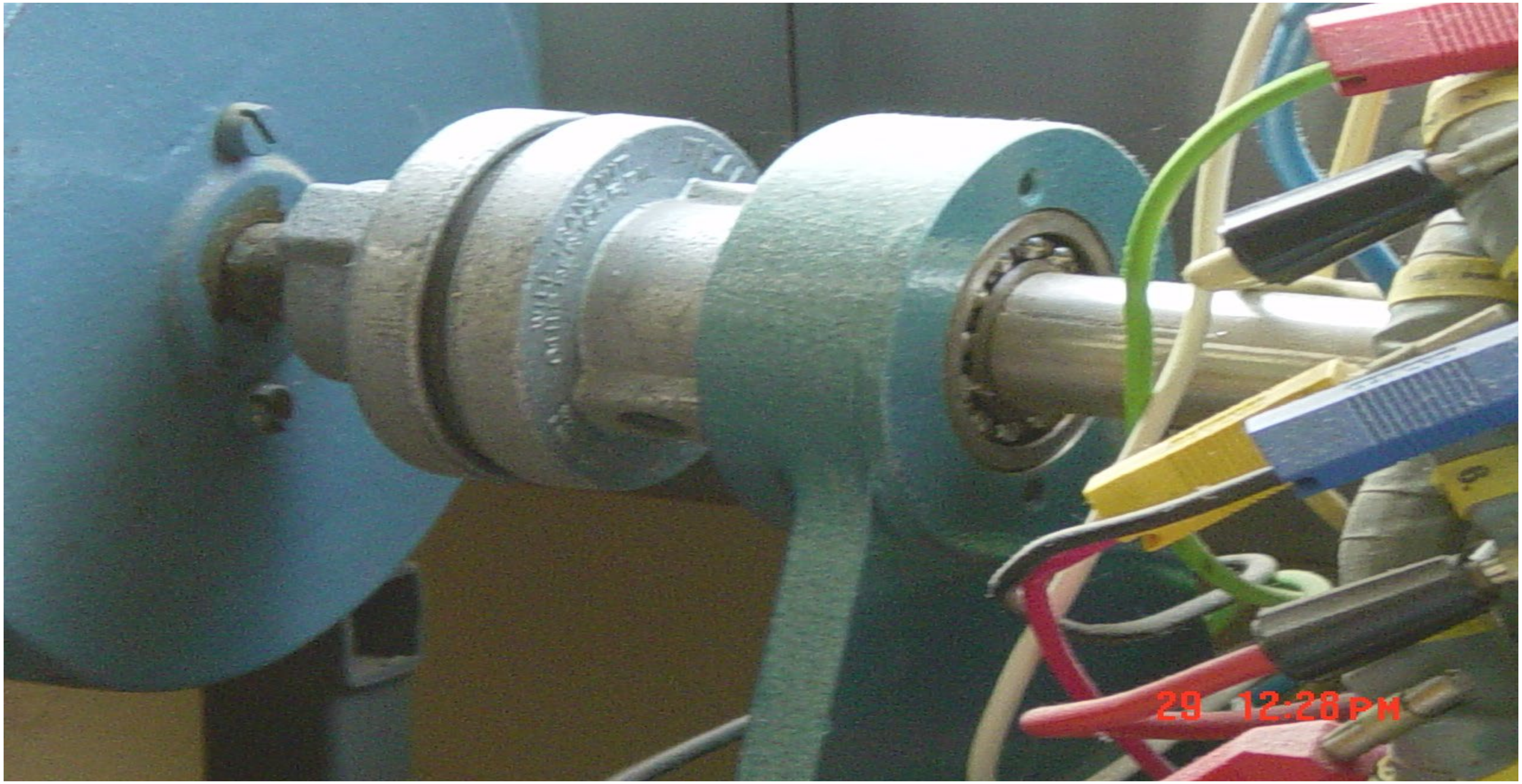
is known as Lorentz force equation

Brushed DC Motors Review

- A winding assembly (armature) within a stationary magnetic field
- Brushes and Commutators switch current to different windings in correct relation to the outer permanent magnet field.
- Pros:
- Electronic control is simple, no need to commutate in controller
- Requires only four power transistors
- Cons:
- A sensor is required for speed control
- The brushes and commutator create sparks and wear out
- Sparks limit peak power
- Heat in armature is difficult to remove
- Low power density



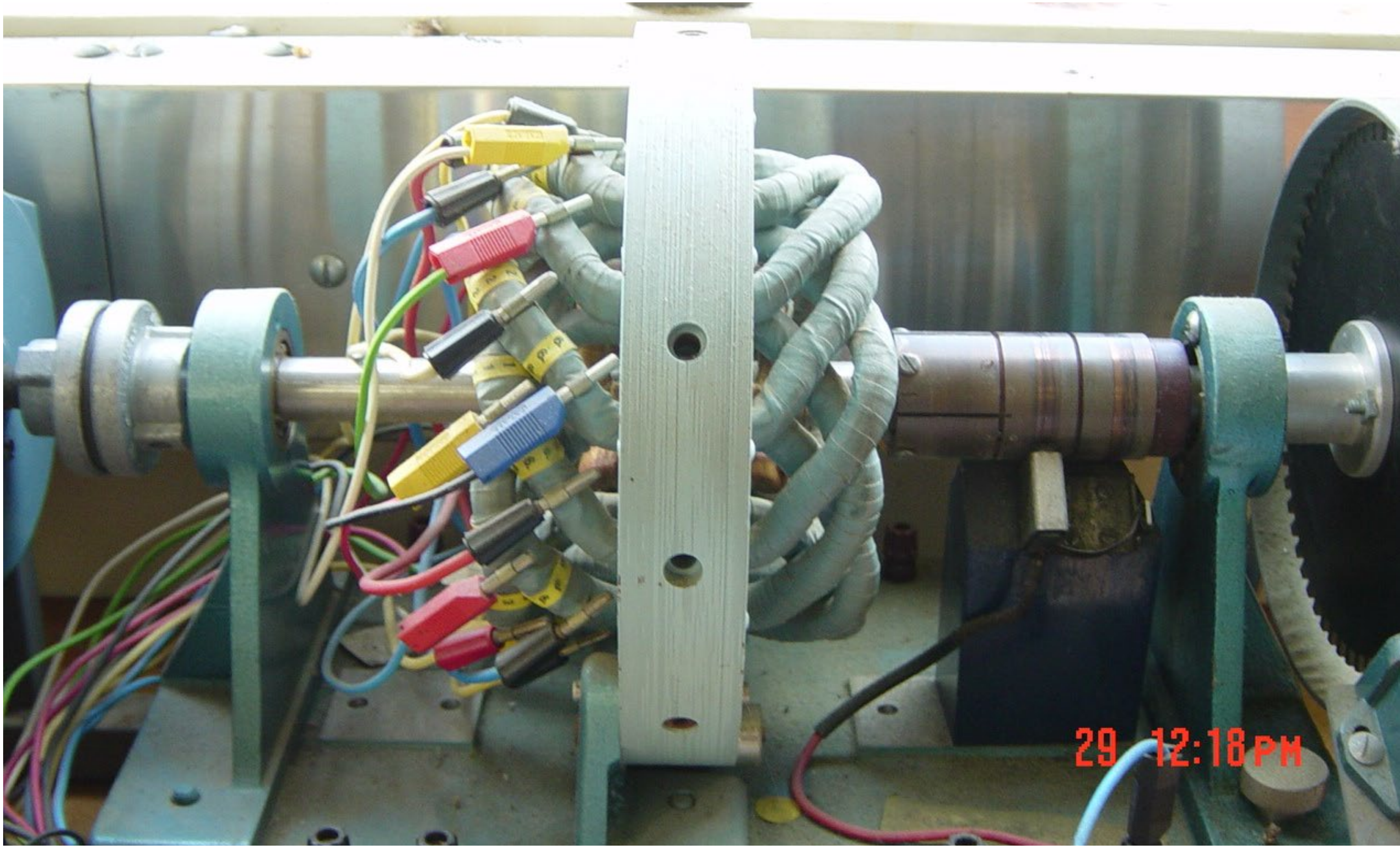
Mechanical bearing - Ball bearing



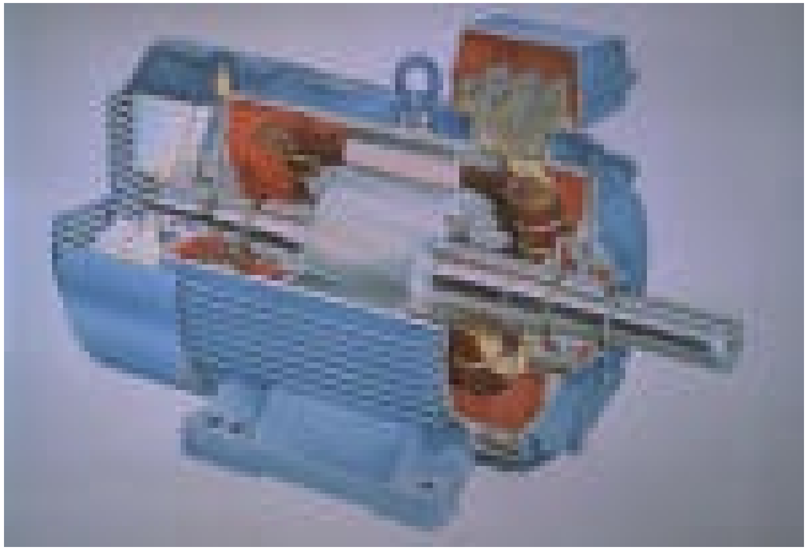
Wear and tear

Lubrication

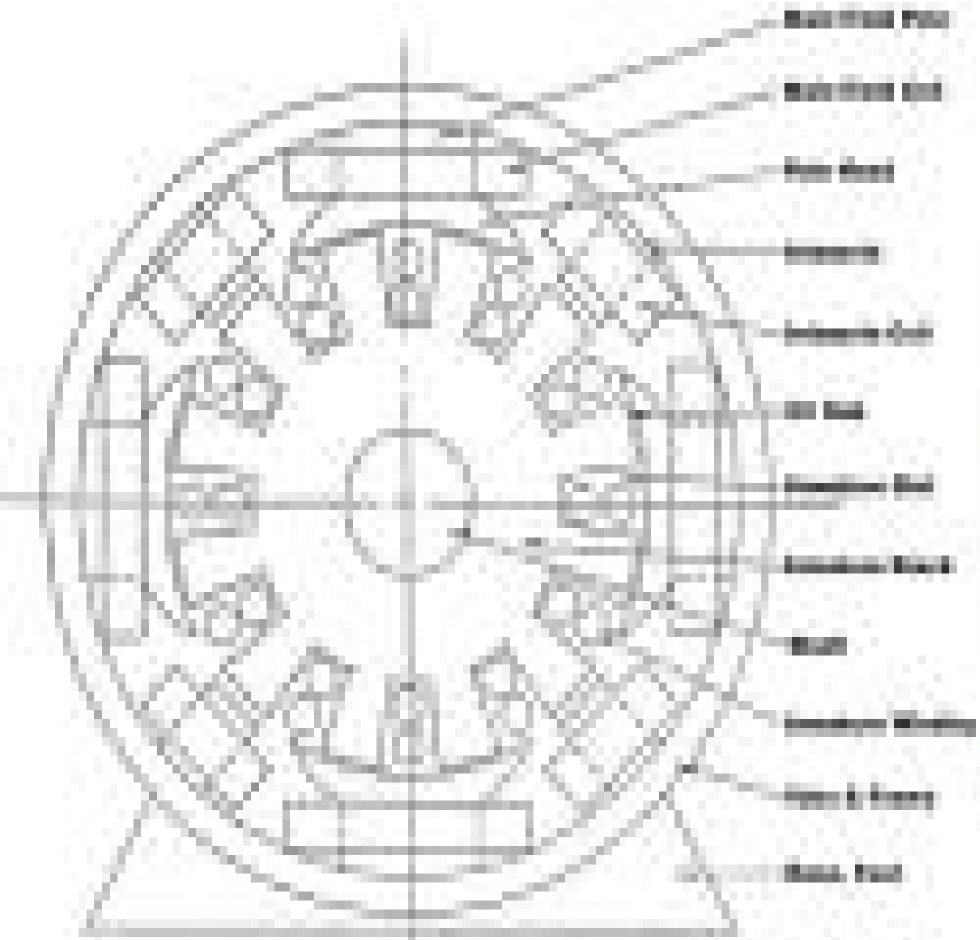
Typical stator winding, commutator and brush of a DC motor



Cross-sectional view of motor



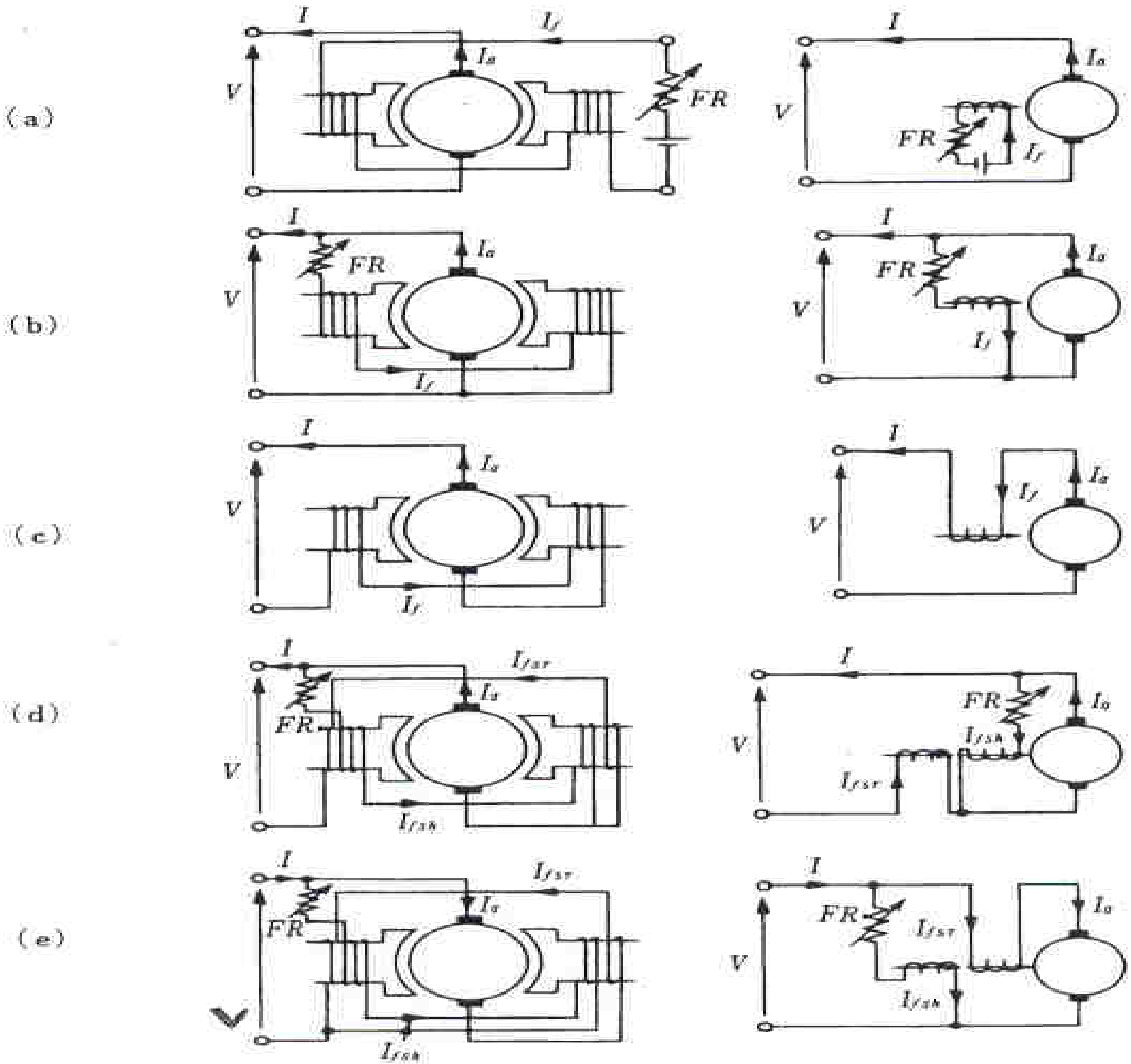
Laminations of rotating motor



(a) Pictorial view of laminations of dc motor

(b) Lamination of induction motor

Different connections of DC motors with field winding



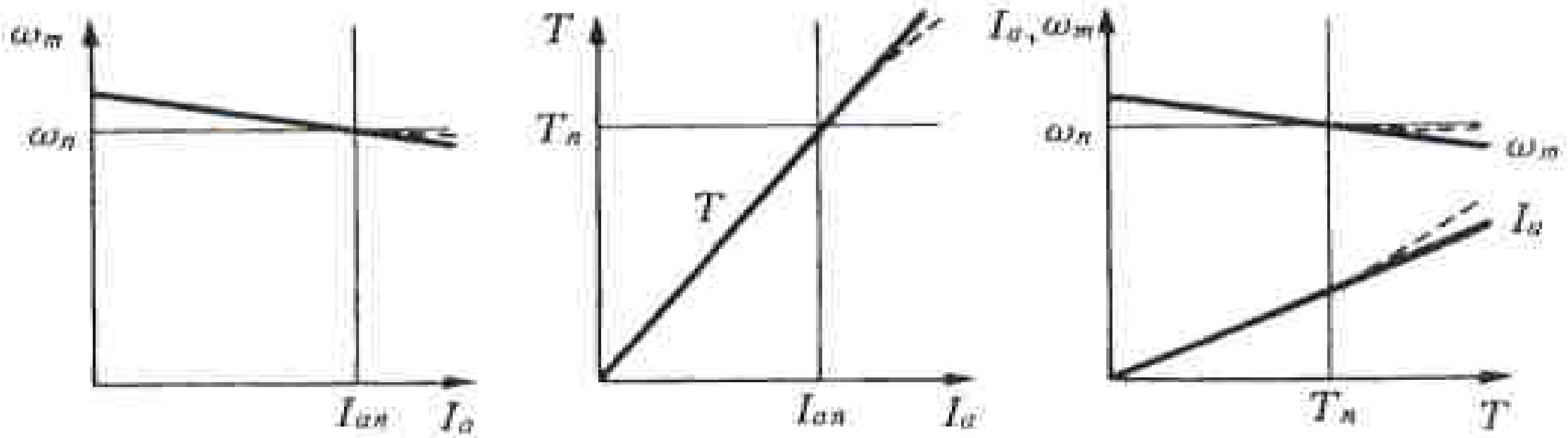
(a) Separately excited

(b) Shunt excited

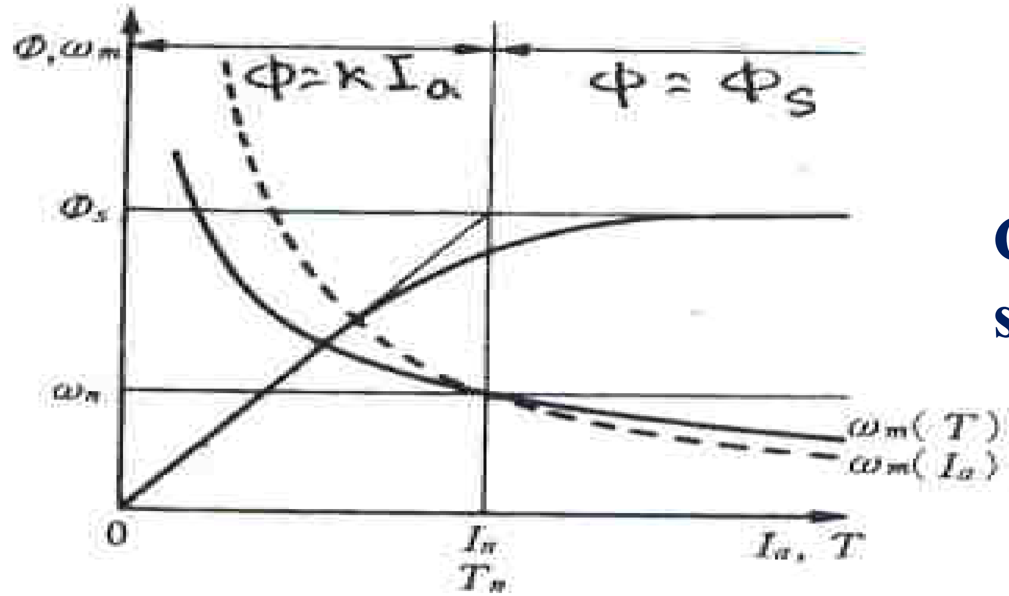
(c) Series excited

(d) Short-shunt compound excitation

(e) long-shunt compound excitation.

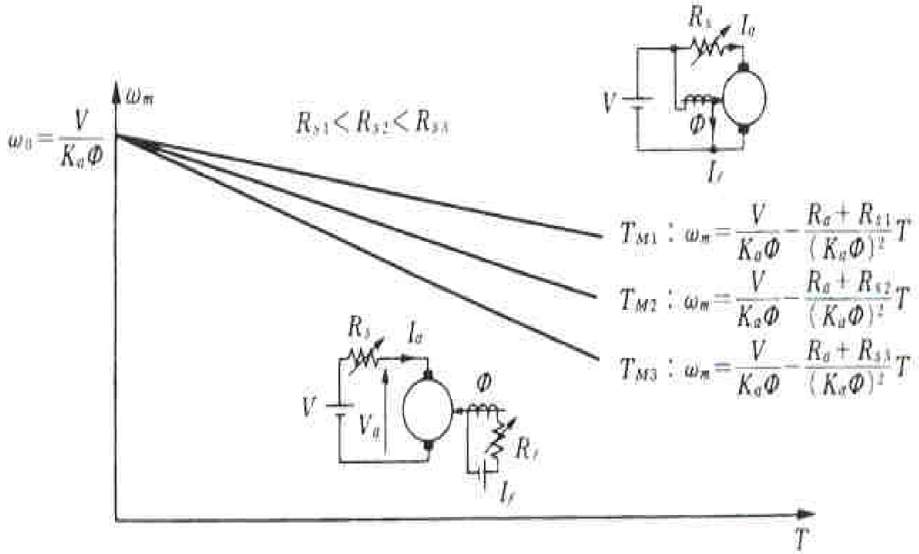


Characteristics of DC shunt motor

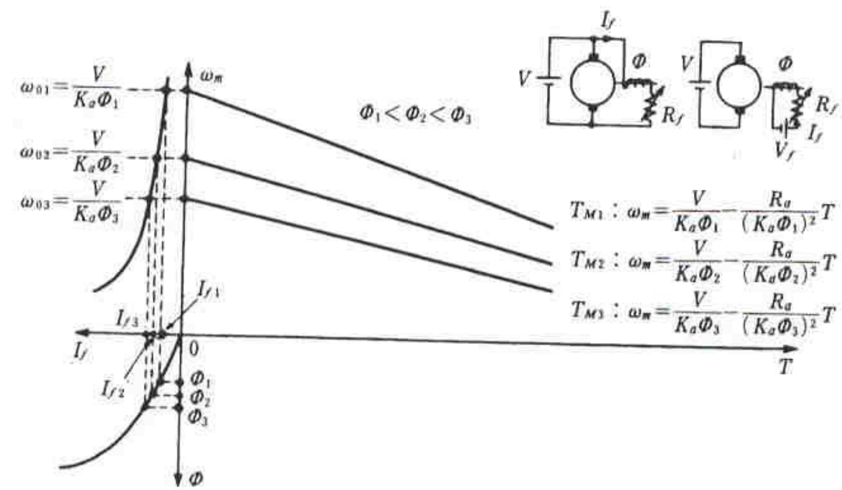


Characteristics of DC series motor

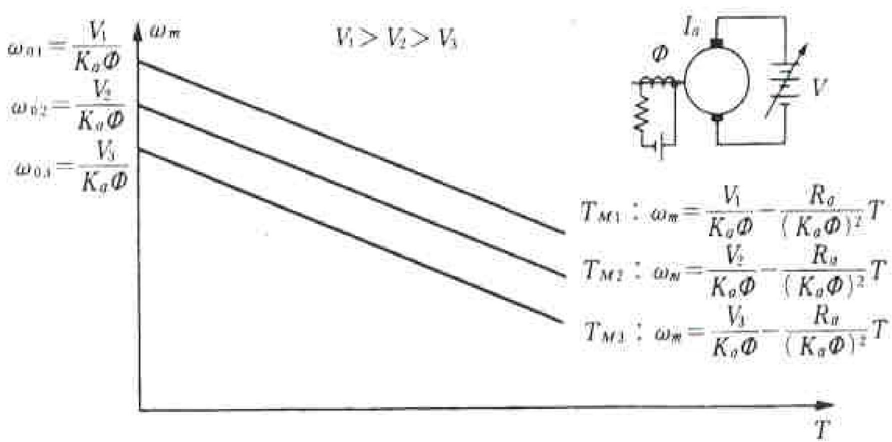
Speed control of DC motor



Speed control through Armature resistance

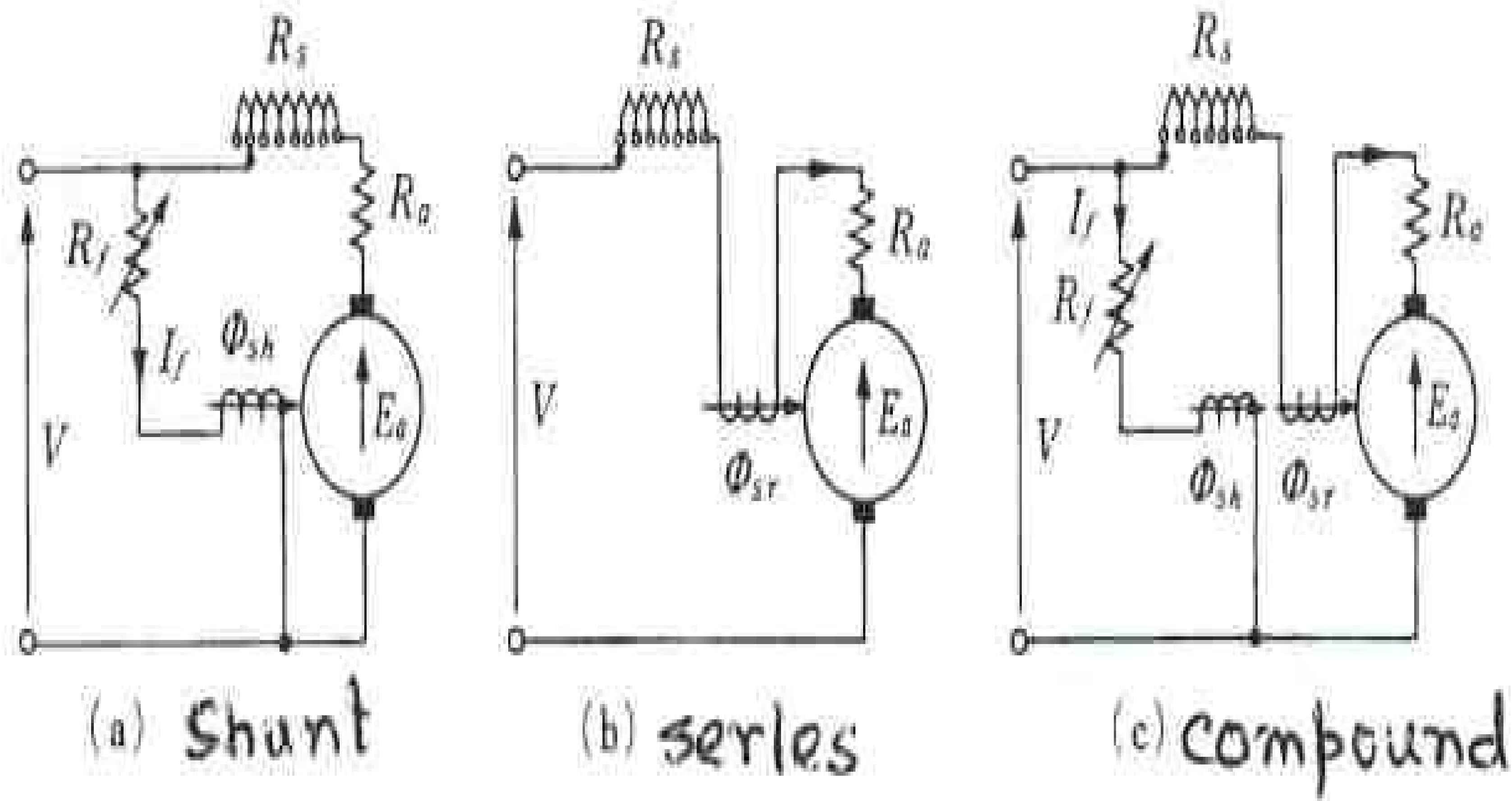


Speed control through Field flux



Speed control through terminal voltage

Starting of DC motors



Losses in rotating motors

I^2R loss (Copper loss): Motor winding (both in stator and rotor)

Magnetic loss: **Combination of eddy current and hysteresis loss**

Friction and windage loss: Also known as rotational loss or mechanical loss.

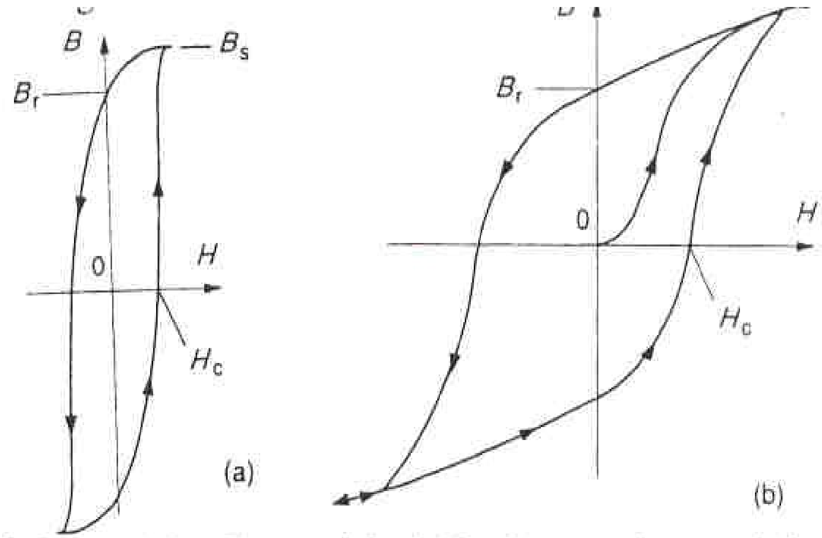
What these losses will do?

They manifested themselves in the form of HEAT and increases the temperature of the winding of the motor. Cooling FAN is required to maintain the TEMPERATURE rise.

Magnetic losses in material due to alternating magnetic field

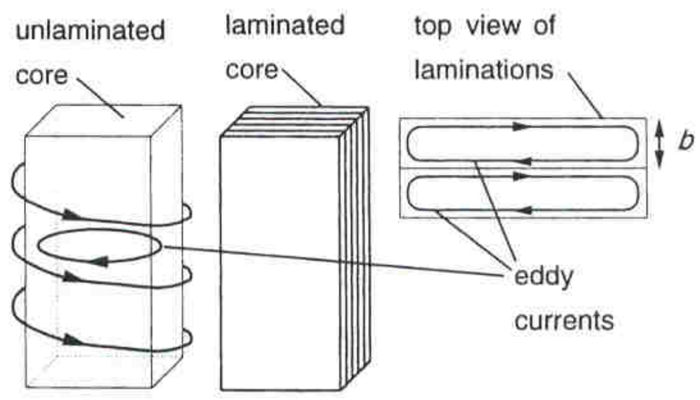
Hysteresis loss

$$P_h = f \oint B\,dH$$ **W/m³**



Eddy current loss

$$P_e = \frac{\pi^2 B_m^2 f^2 t^2}{6\rho}$$ **W/m³**



The following equations are used to analyze the operation of DC motor

$$V = E_a + I_a R_a = K_a \phi \omega + I_a R_a$$

$$K_a = \frac{PZ}{2\pi a}$$

Torque equation $$T = K_a \phi I_a$$

$$I_a = \frac{V - E_a}{R_a} = \frac{V - K_a \phi \omega_m}{R_a}$$

Also $$\omega_m = \frac{V - I_a R_a}{K_a \phi} = \frac{V}{K_a \phi} - \frac{R_a}{K_a \phi} I_a = \frac{V}{K_a \phi} - \frac{R_a}{(K_a \phi)^2} T$$

The mechanical power output is $P_m = T \omega_m$.

So, $E_a I_a = K_a \phi \omega_m I_a = \omega_m K_a \phi I_a = \omega_m T$

So the power developed = output power.

Mathematical model for starting performance

The electric circuit equation is given by

$$V = L\frac{di_a}{dt} + Ri_a + k_e\omega$$

The dynamic equation of the motor under no-load condition is given by

$$T = J\frac{d\omega}{dt} + B\omega \qquad \omega = \frac{d\theta}{dt}$$

The motor torque, T, is given by

$$T = K_a\,\phi\, i_a = k_t i_a\,;$$

ϕ is kept constant for PM DC motor, k_t is a constant and is known as armature constant.

The back emf, *e*, is given by

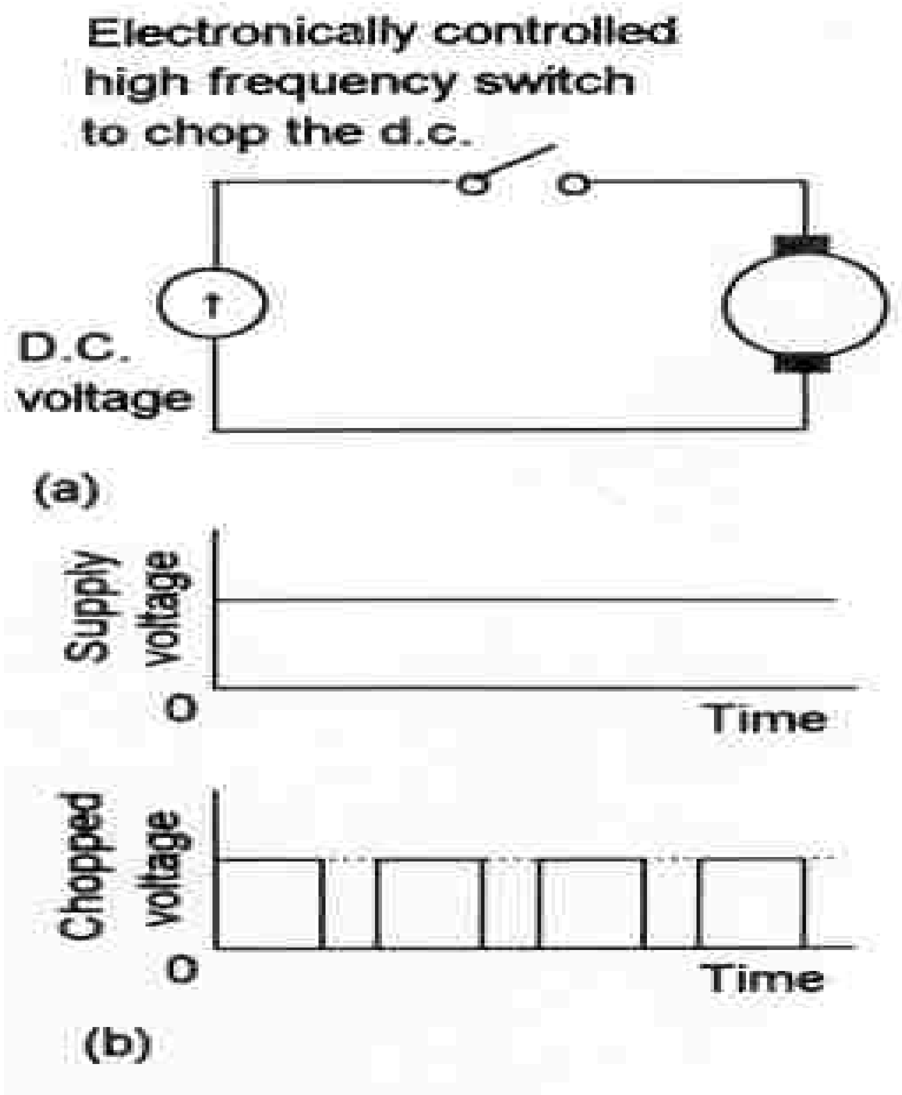
$$e = K_a\,\phi\,\omega = k_e\,\omega\,;$$

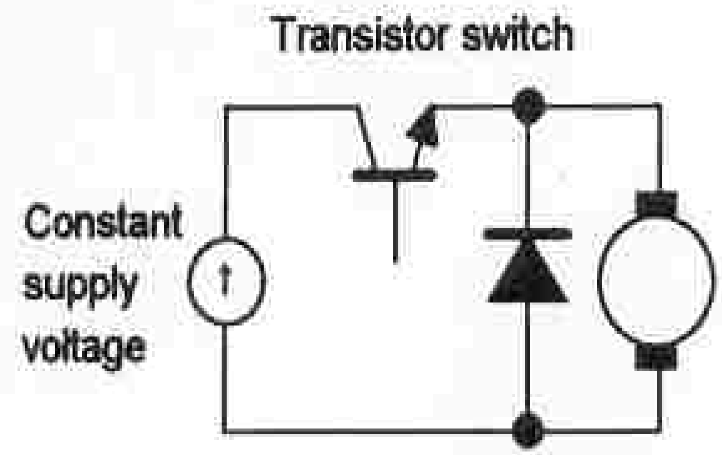
k_e is a constant and is known as motor constant. Usually k_e is equal to k_t

$$J\frac{d\omega}{dt} + B\omega = k_t I_a$$

At t = 0, both i_a and ω are 0

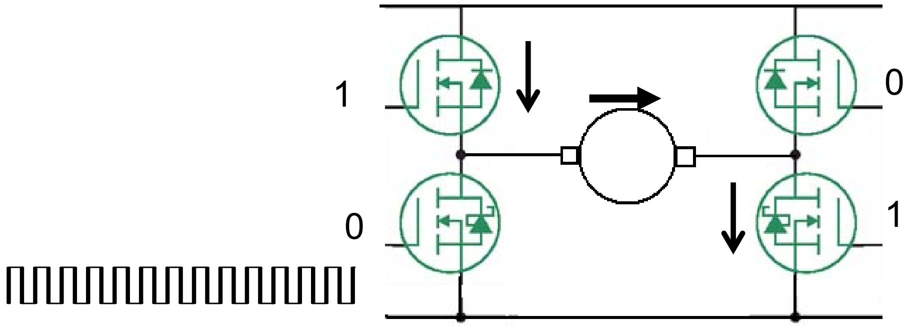
Power electronics based control of DC motor

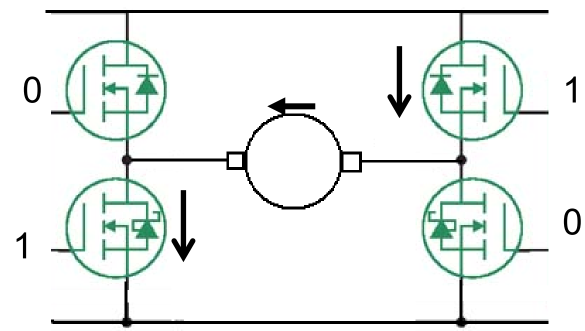


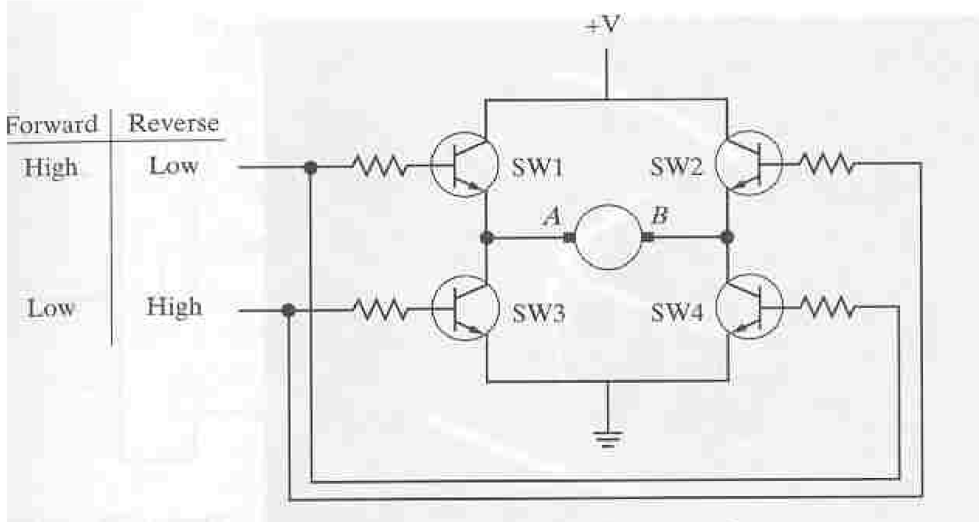


DC Motor H-Bridge

- The DC motor needs four transistors to operate the DC motor
- The combination of transistor is called an H-Bridge, due to the obvious shape
- Transistors are switched diagonally to allow DC current to flow in the motor in either direction
- The transistors can be Pulse Width Modulated to reduce the average voltage at the motor, useful for controlling current and speed






+V
Forward
Reverse
High
Low
Low
High
SW1
SW2
A
B
SW3
SW4

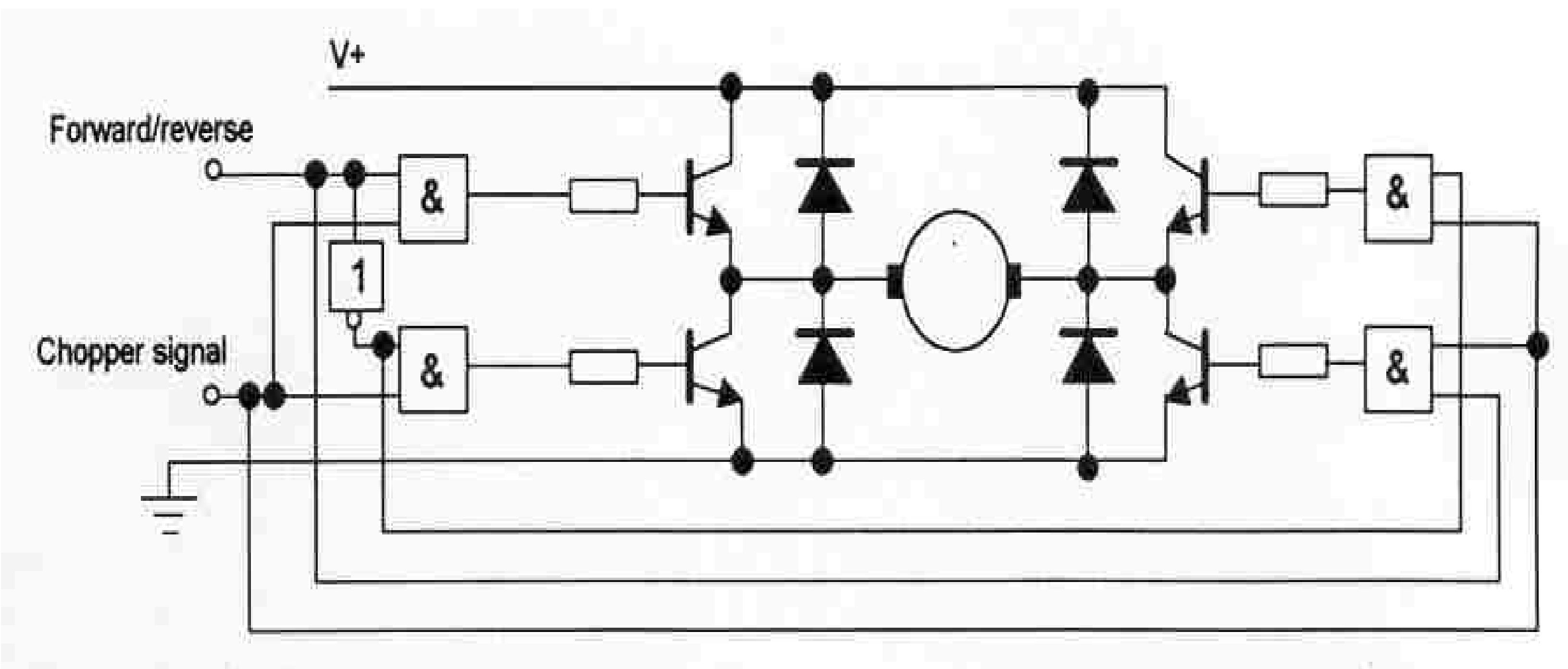

V+
Forward/reverse
&
1
Chopper signal
&
&
&

TABLE 1: COMPARING A BLDC MOTOR TO A BRUSHED DC MOTOR

Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate.
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics.
Speed Range	Higher – No mechanical limitation imposed by brushes/commutator.	Lower – Mechanical limitations by the brushes.
Electric Noise Generation	Low.	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

Selection of Motors

1. Cost
2. Thermal capacity
3. Efficiency
4. Torque-speed profile
5. Acceleration
6. Power density, volume of the motor
7. Ripple, cogging torque
8. Peak torque capability
9. Suitability for hazardous environment
10. Availability of spare parts

Cog: Mechanical transmission; Gear; Toothed wheel

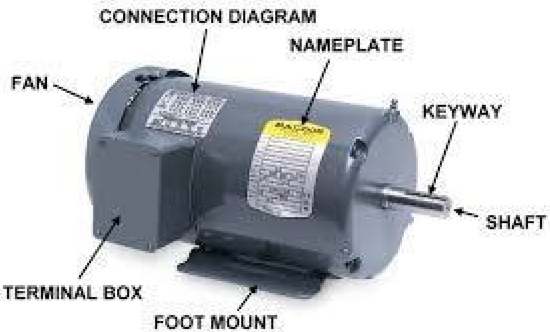
Actuator system for Sydney Trains and Metro

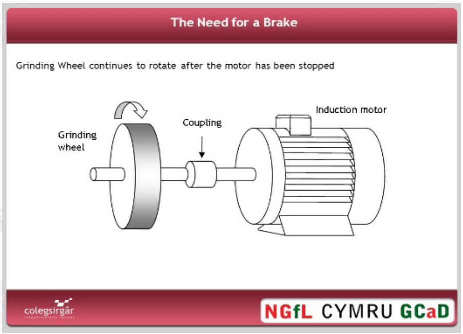
T set	
Traction motors	4 × 170 kW (230 hp) 2-phase DC shunt-wound motor MB-3303-B (Mitsubishi Electric)
Power output	680 kW (910 hp) (4-car) 1,360 kW (1,820 hp) (8-car)
Electric system(s)	1,500 V DC catenary
Current collection method	Pantograph

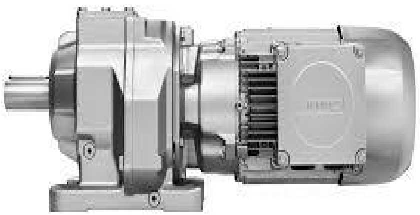
M set	
Traction system	IGBT-VVVF (Alstom ONIX 1500)
Traction motors	4 × 226 kW (303 hp) 3-phase AC induction motor (Alstom ONIX 1500)
Power output	904 kW (1,212 hp) (4-car) 1,808 kW (2,425 hp) (8-car)
Electric system(s)	1,500 V DC catenary

Overhead Rigid Conductor Rail System (ORCS)

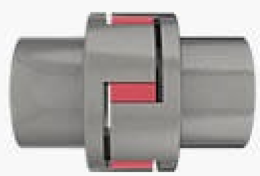
Coupling of loads with motor:

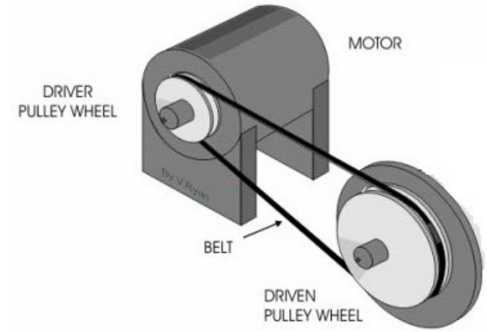






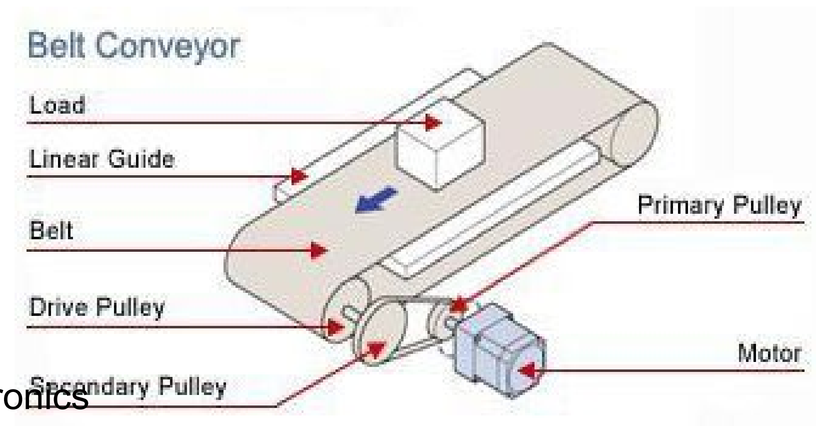
Drive shaft





Belt drives

Jaw coupling



Load

The motor drives a load which has a certain characteristics torque-speed requirement.

In general,

$$T_L \propto \omega_m^k$$

where, k may be an integer or a fraction.

Load

- In a feed drive,

$$T_L \propto \omega_m$$

- In fans and pumps,

$$T_L \propto \omega_m^2$$

- The motor can be connected to the load through a set of gears
- The gears have teeth ratio and can be treated as torque transformers

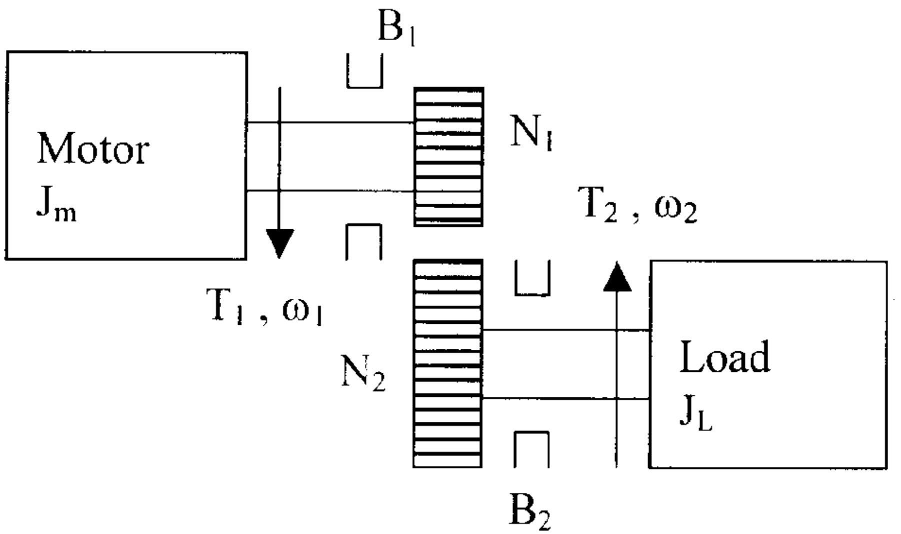
Load

- **The gears are used to amplify the torque on load side at lower speed compared to the motor speed**

- **The motors are designed to run at high speeds because it has been found that the higher the speed, the lower is the volume and size of the motor**

Motor-load connection through a gear

The following laws govern the gear system operation:



1) The power handled by the gear is the same on both sides

$$T_1\omega_1 = T_2\omega_2$$

or,

$$T_2 = T_1\frac{\omega_1}{\omega_2}$$

2) Speed on each side is inversely proportional to its tooth number,

and,

$$\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1}$$

N_1 and N_2 are number of tooth.

Gear connected Load

Substituting for $\frac{\omega_1}{\omega_2}$ in $T_2 = T_1 \frac{\omega_1}{\omega_2}$, we get

$$T_2 = T_1 \frac{N_2}{N_1}$$

Similar to the case of transformer, the constants of the load as reflected to the motor is:

$$J_{1(reflected)} = \left(\frac{N_1}{N_2}\right)^2 J_1$$

$$B_{2(reflected)} = \left(\frac{N_1}{N_2}\right)^2 B_2$$

N_1, N_2 – Teeth number in the gear

B_1, B_2 – Bearings and their friction coefficients

J_m, J_L – Moment of inertia of the motor and load

Motor-load connection through a gear

Hence, the resultant mechanical constants are,

$$J = J_m + \left(\frac{N_1}{N_2}\right)^2 J_1$$

$$B = B_1 + \left(\frac{N_1}{N_2}\right)^2 B_2$$

J_m: **moment of inertia of motor**

B_1: **friction due to motor bearing**

Motor-load connection through a gear

J_1: **moment of inertia of gear system and load**

B_2: **friction due to gear system and load**

The torque equation of the motor-load combination is:

$$J\frac{d\omega_1}{dt} + B\omega_1 = T_1 - T_{2(reflected)} = T_1 - \left(\frac{N_1}{N_2}\right)^2 T_2$$

Control of Electric Motors

Servo Controllers: offer extremely fast response and precise control of acceleration/ deceleration, speed and torque. Servo Control Systems can accelerate from standstill to 100 RPM in several milliseconds.

Servo Control Systems are designed with three feedback loops:

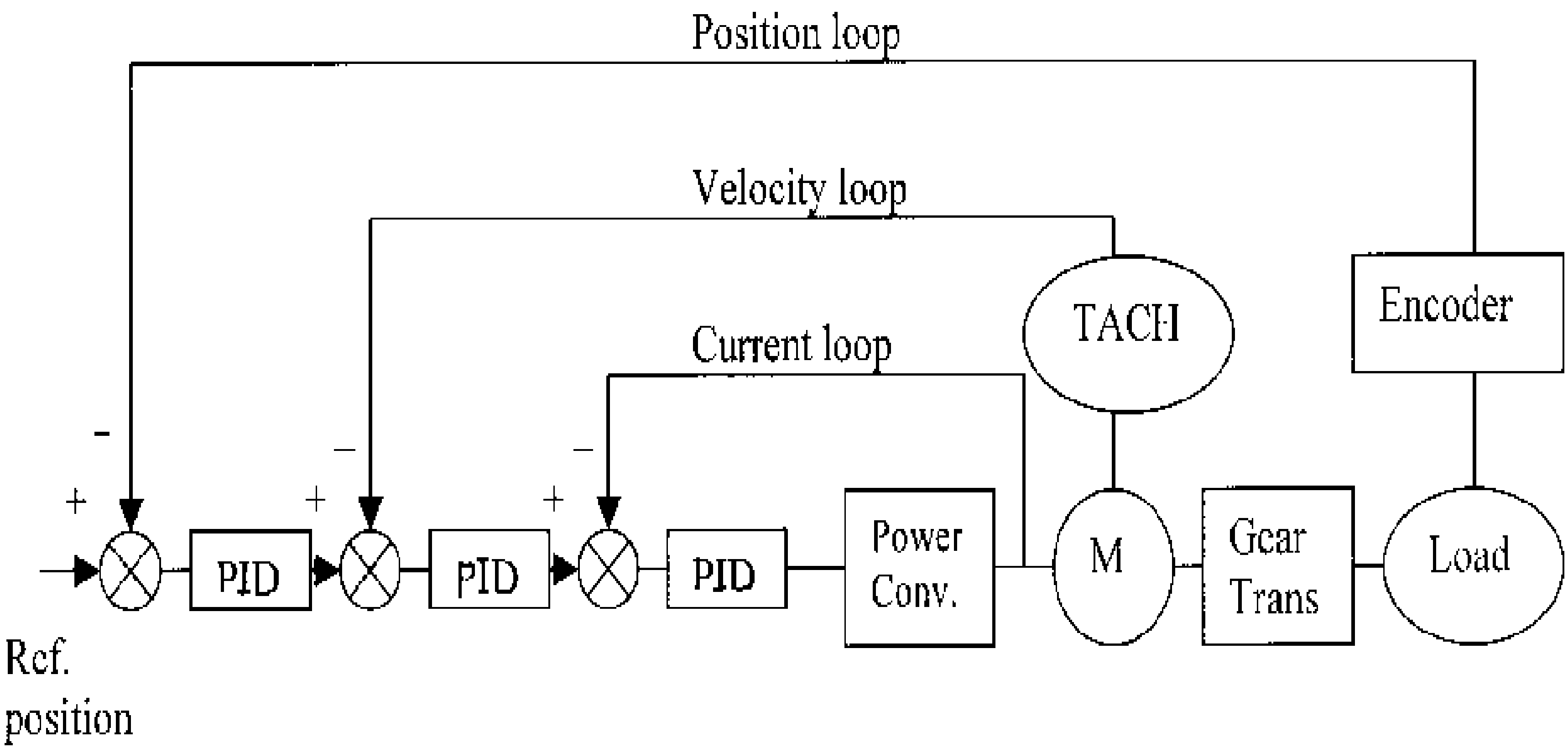
- Position loop
- Velocity loop
- Current loop

Control of Electric Motors

Elements of Servo Control System are:

1) Motor
2) Power Converter
3) Load and Transmission Systems
4) Encoder (position transducer)
5) Tachometer (speed transducer)
6) Current and Voltage Sensors
7) Potentiometers

Control of Electric Motor



Load Characteristics

- ➢ The process of selecting an adjustable AC or DC drive is one where load is primary consideration.

- ➢ When considering load characteristics, the following should be evaluated:

- ✓ What type of load is associated with the application ?

- ✓ What is the size of the load?

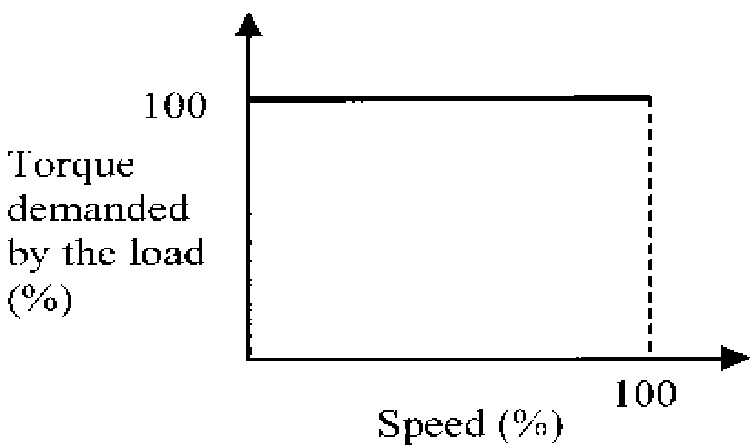
Load Characteristics

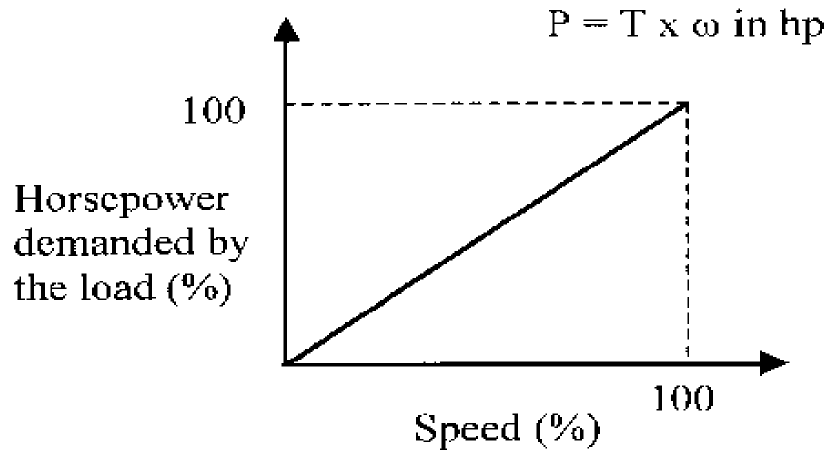
- ✓ **Does the load involve heavy inertia ?**
- ✓ **What are the motor considerations ?**
- ✓ **Over what speed range are heavy loads encountered ?**

Load Types

Constant Torque Load

In this group, the torque demanded by the load is constant throughout the speed range





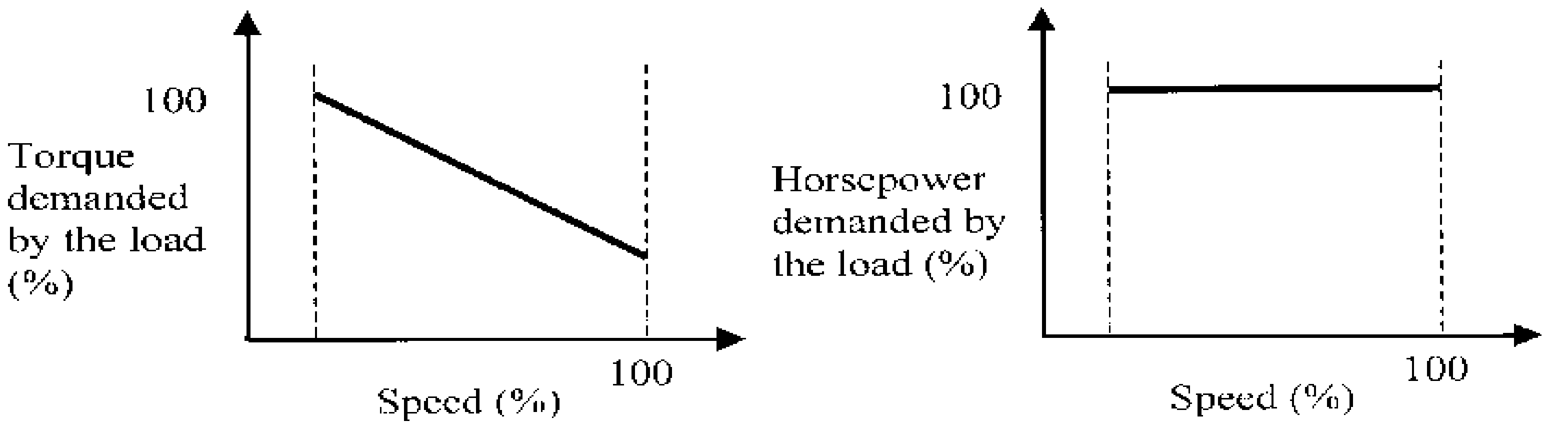
Loads of this type are essentially friction loads

Examples: Conveyors, Extruders, and Surface Winders

Load Types

Constant horsepower Load

The horsepower demanded by the load is constant within the speed range. The load requires high torque at low speeds.

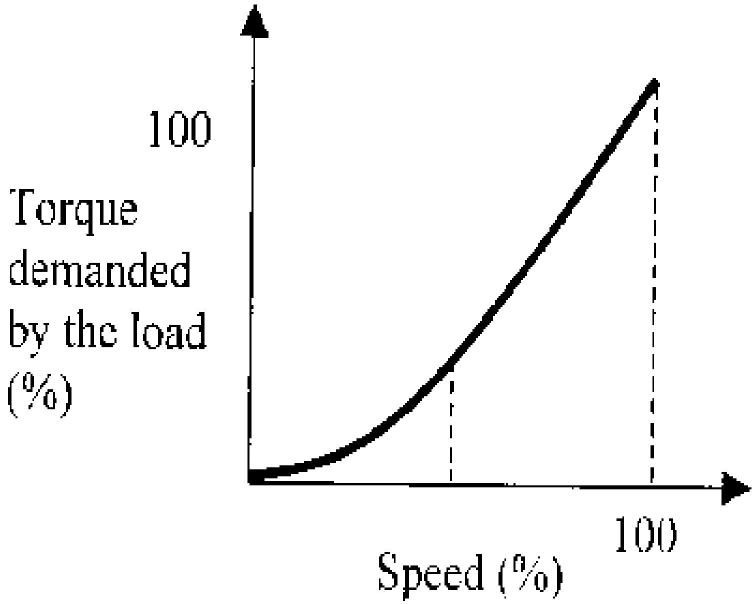


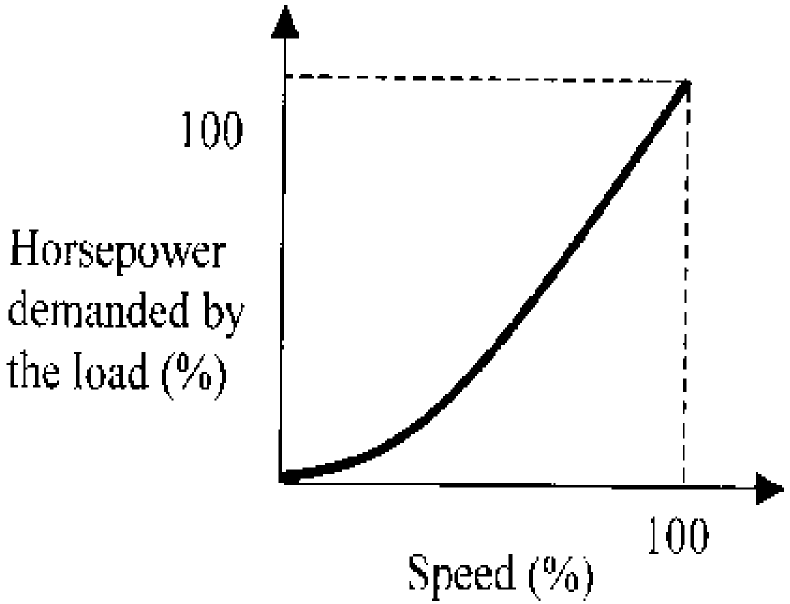
Examples: Center-driven winders and Machine tool spindles

Load Types

Variable torque load

Load torque = (Torque constant) x $(\text{speed})^2$





Power and torque characteristics of Load

- Constant horsepower, torque varies inversely with speed
- Applications: Metal cutting tools operating over wide speed range, mixer, extruder and special machines where operation at low speed may be continuous

Power and torque characteristics of Load

- **Constant torque, horsepower varies as the speed**
- **Applications: General machinery hoists, conveyors, printing press**

Power and torque characteristics of Load

- **Horsepower varies as square of the speed, torque varies with speed**

- **Applications: Positive displacement pumps, some mixers, some extruders**

Power and torque characteristics of Load

- **Horsepower varies as cube of the speed, torque varies as square of speed**

- **Applications: All centrifugal pumps and some fans (Note that fan power may vary as the power of speed)**

Power and torque characteristics of Load

- High inertial loads
- Applications: Are typically associated with machines using flywheel to supply most of the operating energy, punch press

Power and torque characteristics of Load

- Shock loads

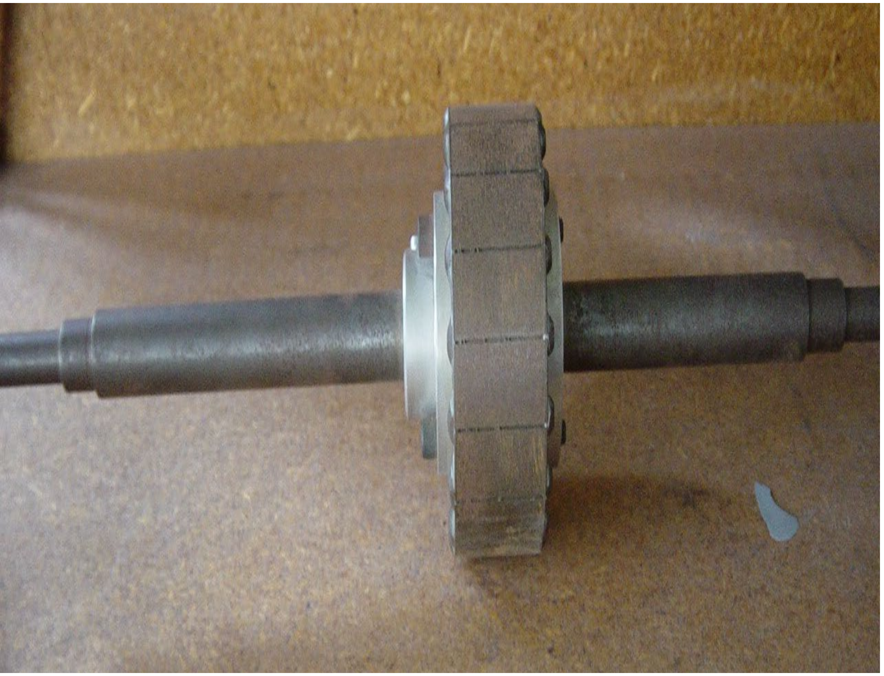
- Applications: Drives of crushers, separators, grinders, conveyors, and vehicular systems

➢ Power converters and motors can be damaged if they are not protected from the overload conditions

Stator and Rotor

Typical stator construction

Typical rotor construction



Induction motor