Actuation Systems

Introduction

Pneumatic and Hydraulic Systems

Mechanical Actuation Systems

Electrical Actuation Systems

Introduction

- Actuation systems are the elements of control systems which are responsible for transforming the output of a microprocessor or control system into a controlling action on a machine or device.

- For example, we may have an electrical output from the controller which has to be transformed into a linear motion to move a load.

- Or, we might have an electrical output from the controller which has to be transformed into an action to control the flow of liquid into a vessel.

Pneumatic and Hydraulic Systems

- Pneumatic signals are often used to control elements even if the control system is electrical, since these signals can actuate large valves and other high power control devices and accordingly move large loads.

- The main drawback of pneumatic devices is the compressibility of air.

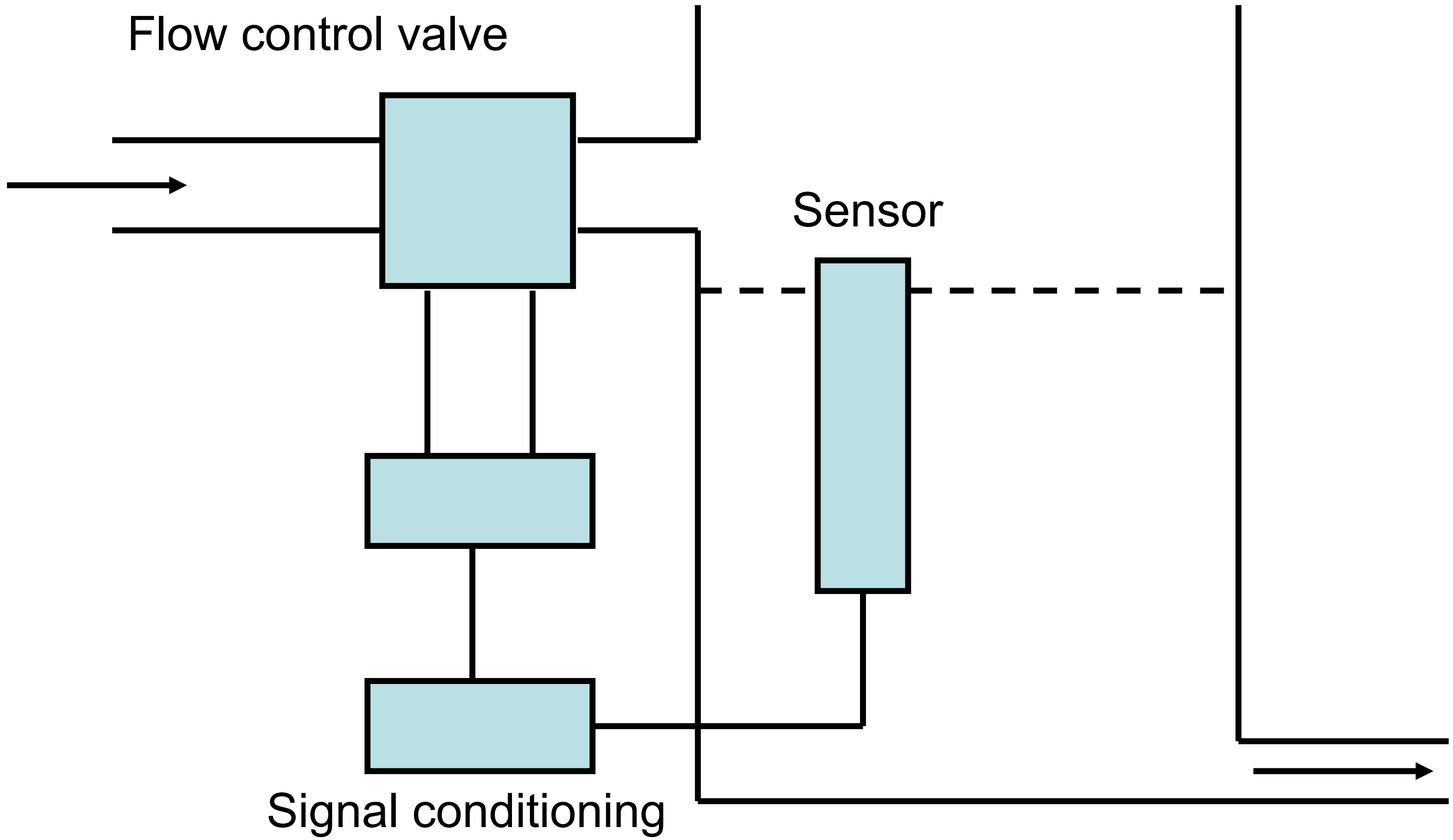
- Hydraulic signals can be used for even higher power control devices but are more expensive.

- Pneumatic and hydraulic systems use directional control systems to direct the flow of fluid through a system. They are not intended to vary the flow of fluid but are either completely open or completely closed (on / off). Examples include spool valves and proppet valves.

- Pneumatic and hydraulic systems use process control valves that control the rate of fluid flow and are used where the rate of flow of a liquid into a tank has to be controlled. This is accomplished by moving a plug into the flow pipe and so alter the cross section of the pipe through which the fluid can flow. Examples include diaphragm actuator and gauge pressure.

Example of Fluid System

System for the control of a variable such as the level of a liquid in a container by controlling the rate at which liquid enters.



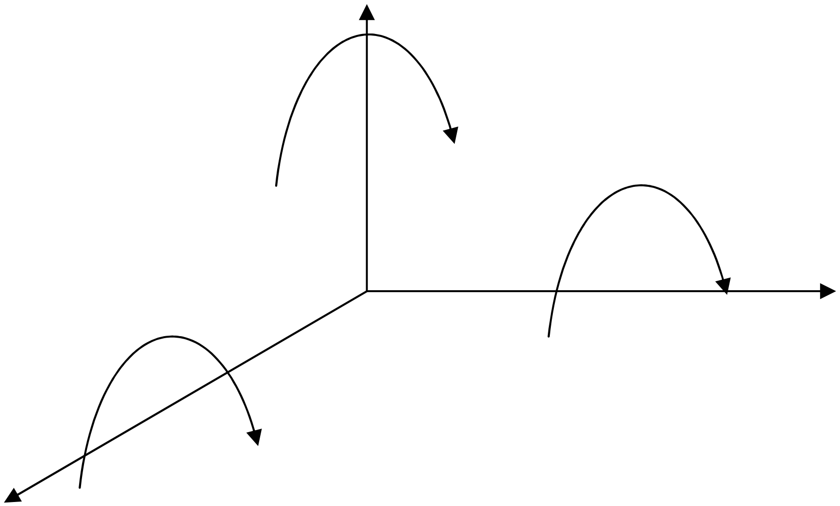
Mechanical Actuation Systems

Mechanical Aspects of Motor Selection: Moment of Inertia and Torque

- Mechanical devices are motion converters: they transform motion from one form into another form. For example they transform linear motion into rotational motion.
- Mechanical elements may include the usage of linkages, cams, gears, rack and pinion, chains, belt drives.
- Examples: Force amplification given by levers; change of speed given by gears; transfer of rotation about one axis to rotation about another using timing belts.

Types of Motion

- Translational
- Rotational
- Complex motion: Combinational of translational and rotational including the components of the motion in three dimensions



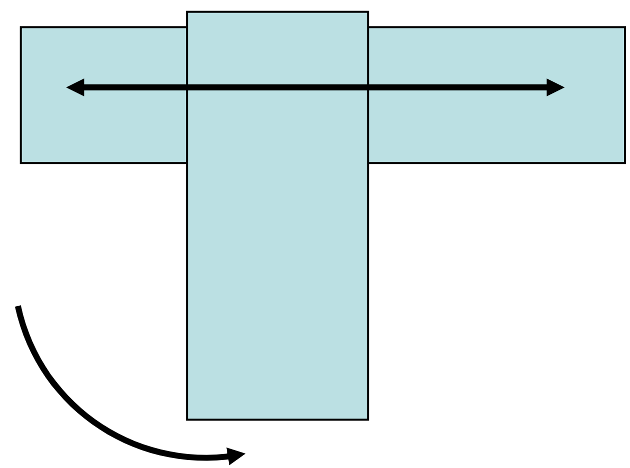
Freedom and Constraints

An important aspect in the design of mechanical elements is the orientation and arrangement of the elements and parts. A body that is free in space can move in three, independent, perpendicular directions and rotate in three ways about those directions. It is said to have six degrees of freedom (number of components of motion that are required to generate motion).

$$6 - \text{number of constraints} = \text{number of degrees of freedom} - \text{number of redundancies}$$

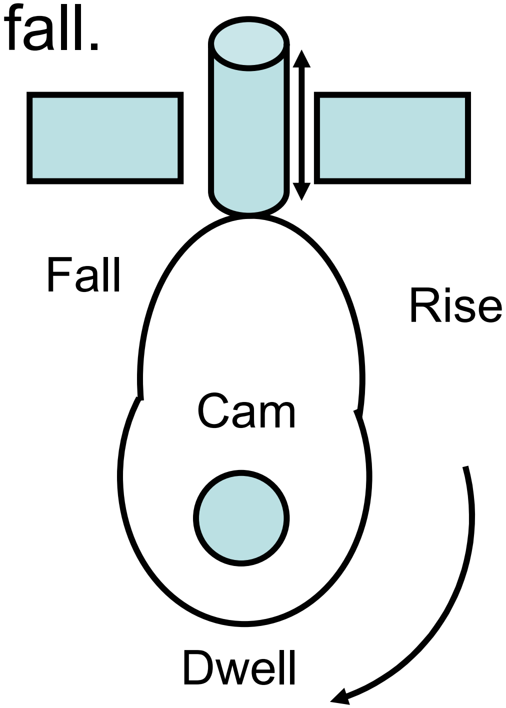
One degree of motion

Two degrees of motion



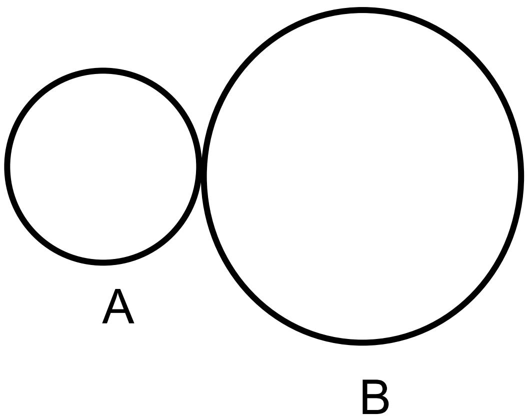
Cams

- A cam is a body which rotates or oscillates and in doing so imparts a reciprocating or oscillatory motion to a second body called the follower, with which it is in contact. As the cam rotates so the follower is made to rise, dwell, and fall.



Gear Trains

Gear trains are mechanisms which are widely used to transfer and transform rotational motion. They are used when a change in speed or torque of a rotating device is needed. For example, the care gearbox enables the driver to match the speed and torque requirements of the terrain with the engine power available.



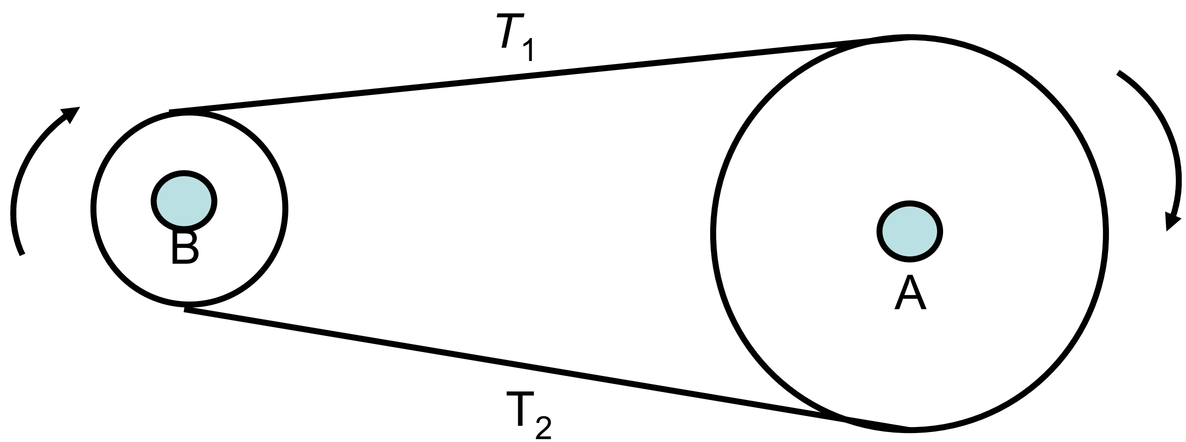
$$\frac{\omega_A}{\omega_B} = \frac{\text{number of teeth on B}}{\text{number of teeth on A}} = \frac{d_B}{d_A}$$

ω angular velocity

d diameter

Belt and Chain Drives

Belt drives are just a pair of rolling cylinders with the motion of one cylinder being transferred to the other by a belt. Belt drives use the friction that develops between the pulleys attached to the shafts and the belt around the arc of contact in order to transmit a torque.

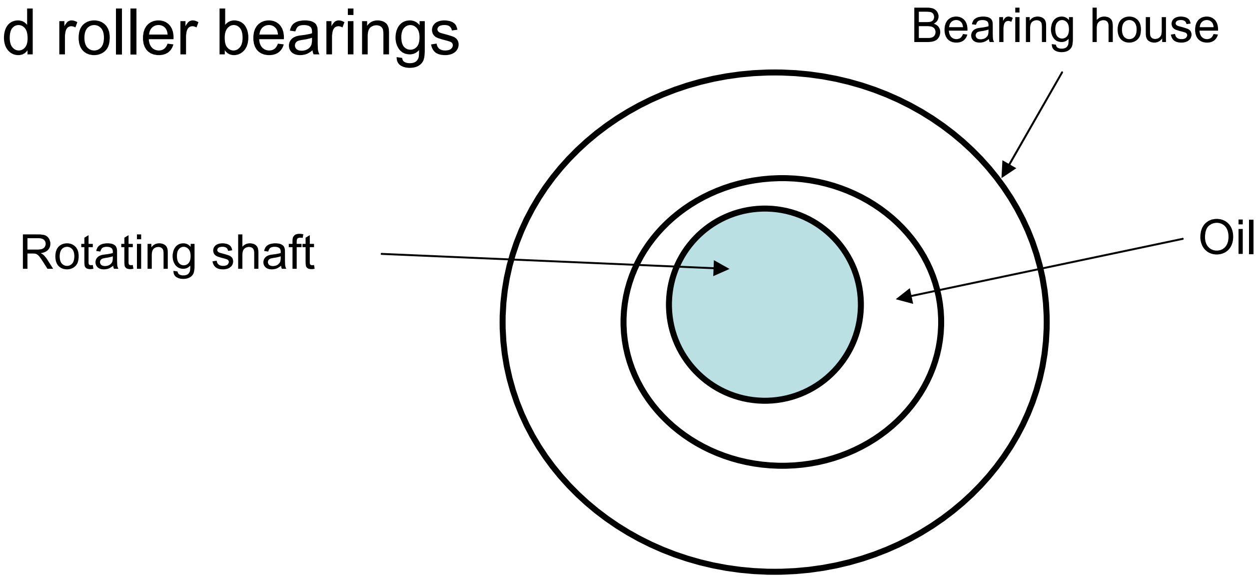


$$T_A = \left(T_1 - T_2\right) r_A$$
$$T_B = \left(T_1 - T_2\right) r_B$$

Bearings

Whenever there is relative motion of one surface in contact with another, either by rotating or sliding, the resulting frictional forces generate heat which wastes energy and results in wear. The function of a bearing is to guide with minimum friction and maximum accuracy the movement of one part relative to another.

- Plain journal bearings
- Ball and roller bearings



Electrical Actuation Systems

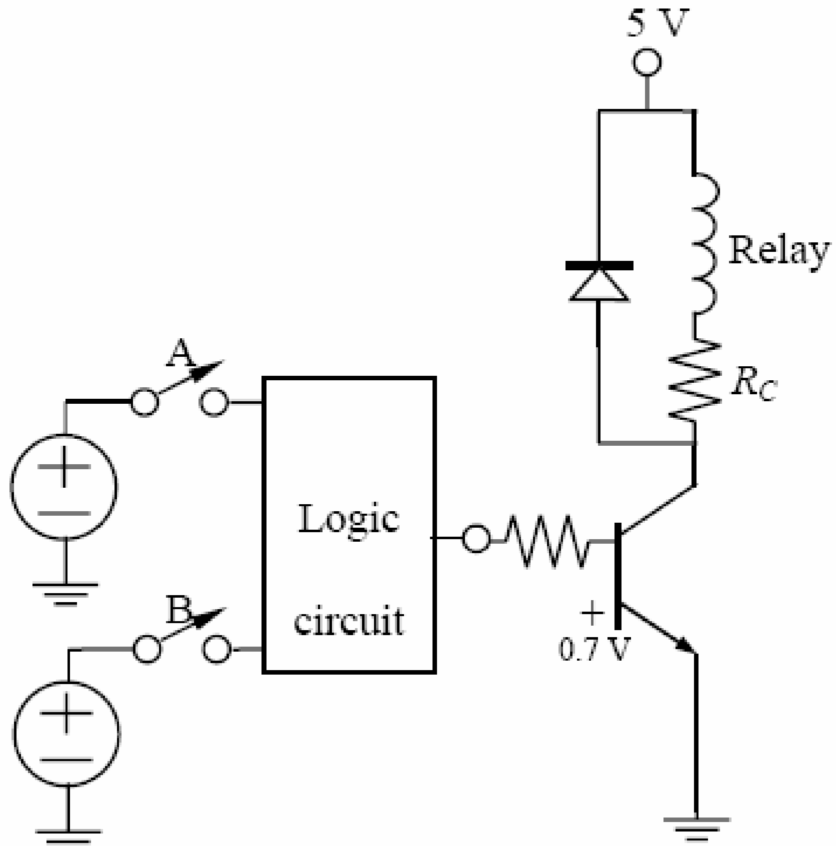
- **Switching devices** such as mechanical switches, e.g., relays, or solid-state switches, e.g., diodes, thyristors, and transistors.

- **Solenoid type devices** where a current through a solenoid is used to actuate a soft iron core. For example a solenoid operating hydraulic/pneumatic valve.

- **Drive systems** such as DC and AC motors where a current through a motor is used to produce rotation.

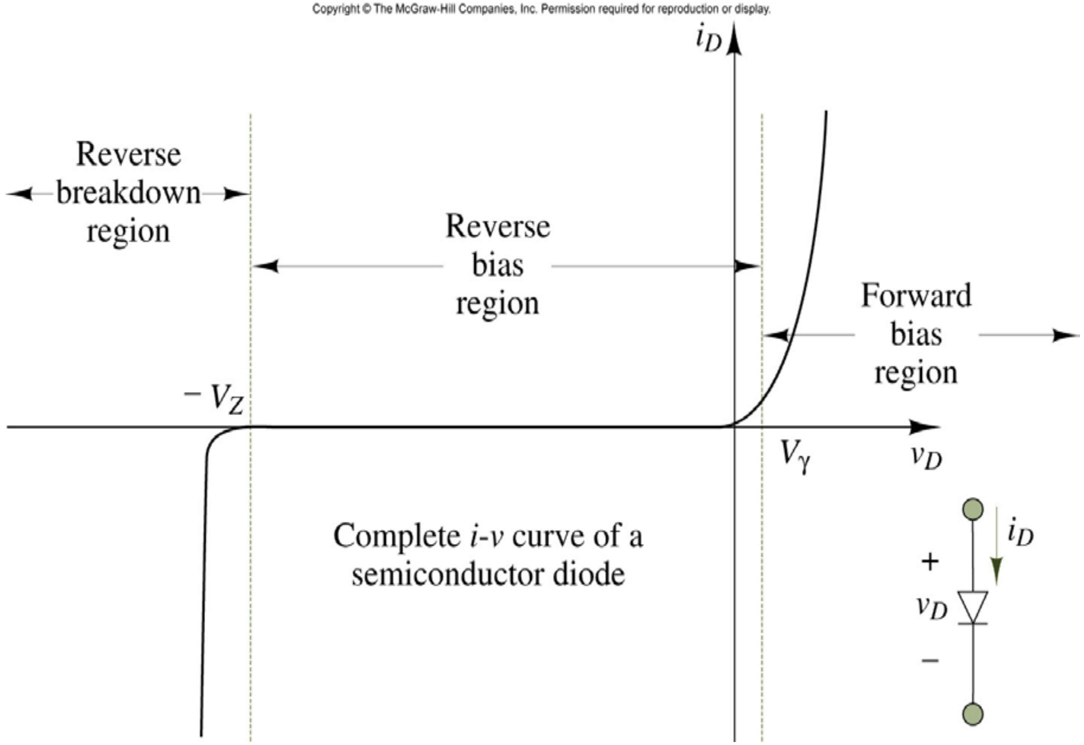
Relays

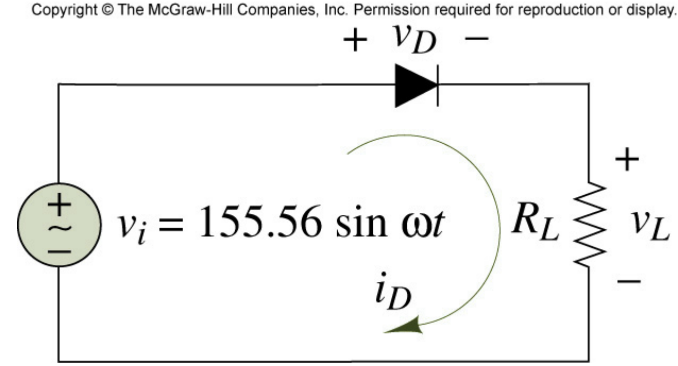
are electronically operated switches in which changing a current in one electrical circuit switches a current on or off in another circuit.



Solid-State Switches

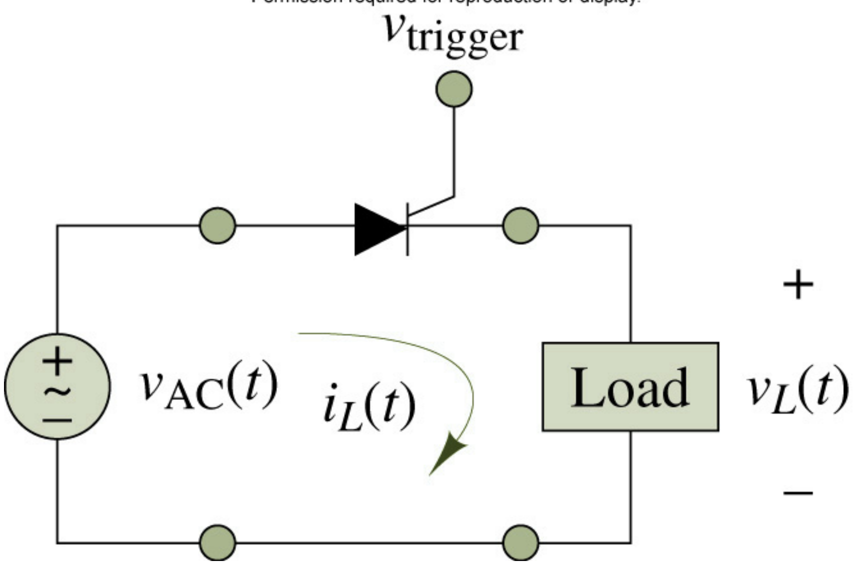
Diodes; Thyristors and triacs; transistors; and power MOSFETS
The diode is one directional element, only passing a current when forward biased. Accordingly the current through the diode is half rectified to become just the current due to the positive halves of the input voltage.

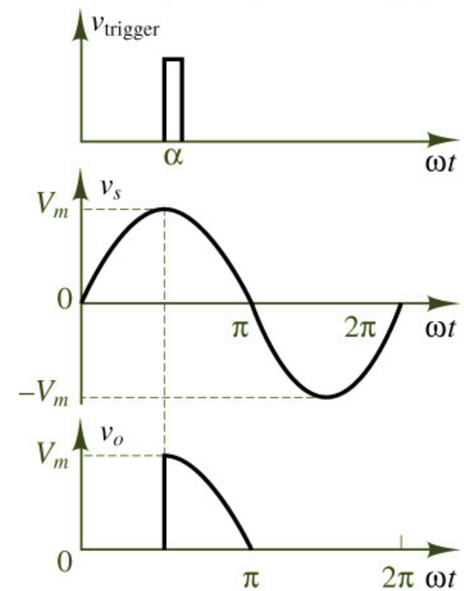




Thyristors

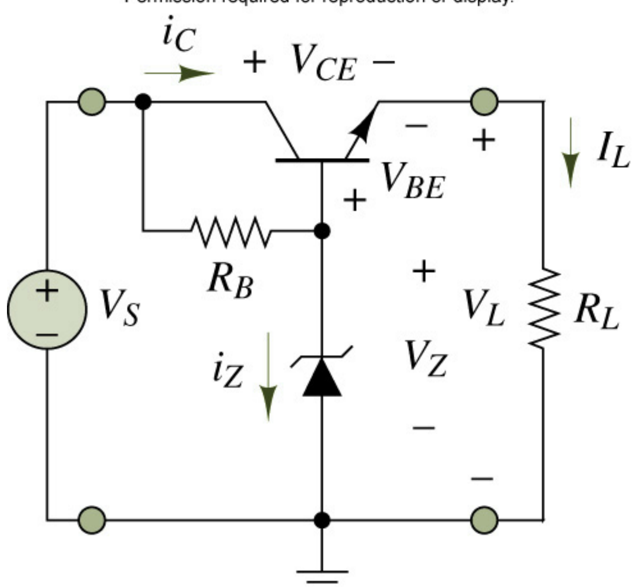
The thyristor or silicon-controlled rectifier (SCR) may be regarded as a diode which has a gate controlling the conditions under which the diode can be switched on. Examples of control is that of AC for electric heaters, electric motors, or lamp dimmers.

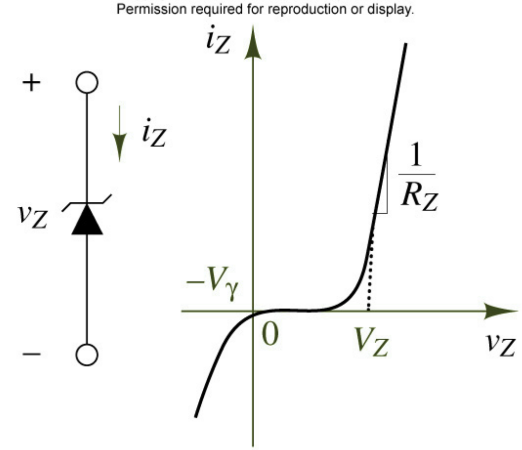


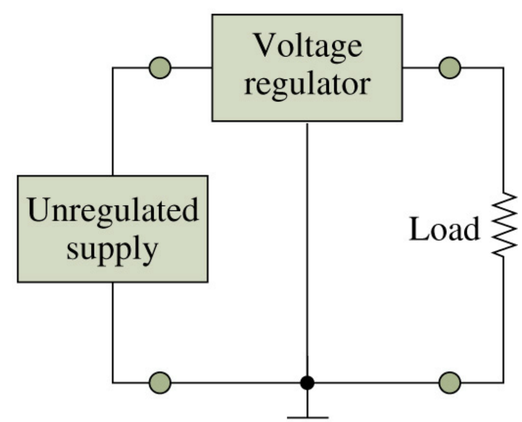


Transistors

Transistors may be used as switches or part of regulating systems but their power handling capability is less than that of thyristors.







DC Motors

They are used as the final control element in positional or speed-control systems. DC motors are used in most control systems

- Permanent magnet DC motors: It has constant value of flux density.
- **DC motors with field coils**
  - **Separately excited motors** have separate control of the armature and field currents.
  - **Series wound motors:** armature and fields coil are in series. Such motors exerts the highest starting torque and has the greatest no-load speed. Reversing the polarity of the supply to the coils has no effect on the direction of rotation.
  - **Shunt wound motors:** armature and fields coils are in parallel. It provides the lowest starting torque. It has good speed regulation. They are widely used because of their constant speed regardless of load.
  - **Compound motors:** Get same features as series wound and shunt wound motors.

The Induced (Generated) Voltage E_a

$$E_{aav=}\frac{1}{2\pi}\int_0^{2\pi}\frac{d\psi_p(\theta_r)}{dt}d\theta_r$$

$$E_a=\frac{2PN_a\psi_p\omega_r}{a}=L_{af}i_f\omega_r\ (\psi_p \text{ is the magnetic flux per pole}=\frac{N_f i_f}{\Re_m};$$

N_a is the number of turns;

and a is the number of parallel currnt paths in the armature windings.

From Kirchhoff's law, one obtains the following steady - state

equation for the armature voltage for electric motors

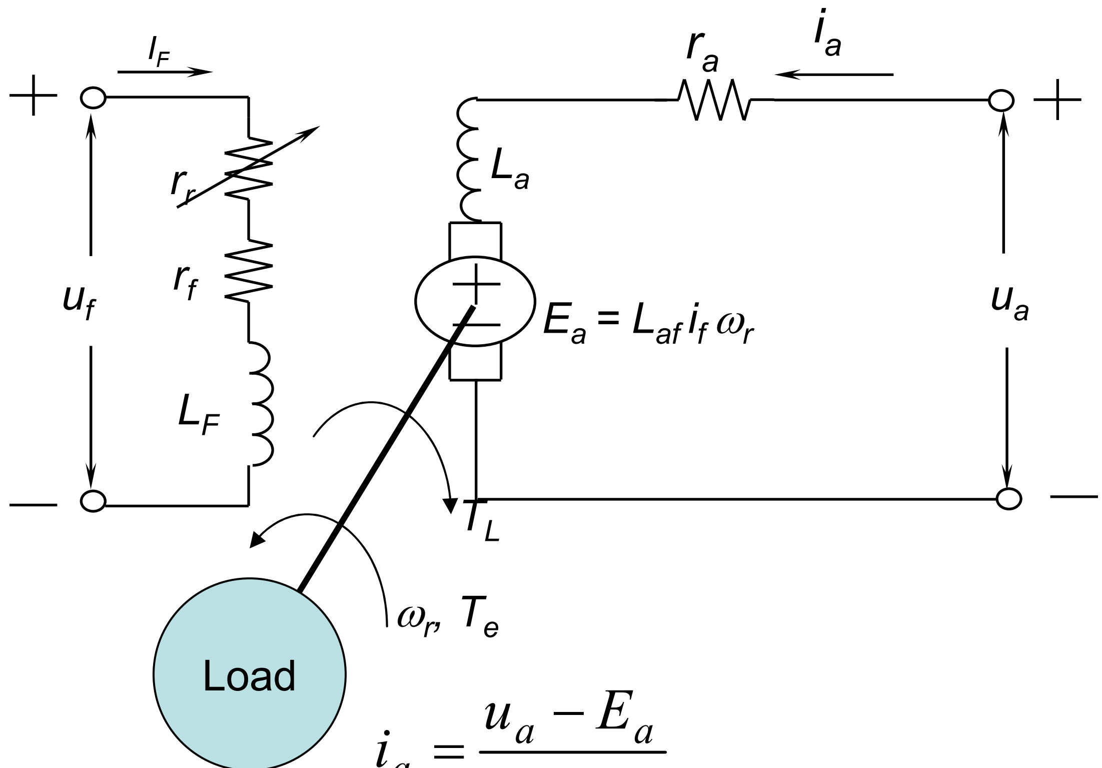
$u_a - E_a = i_a r_a$ (u_a is the applied voltage to the armature;

i_a is the current in the armature;

r_a is the resistance of the armature.

For generators : $u_a - E_a = -i_a r_a$

Separately-Excited DC Motor: Differential Equations of Motion

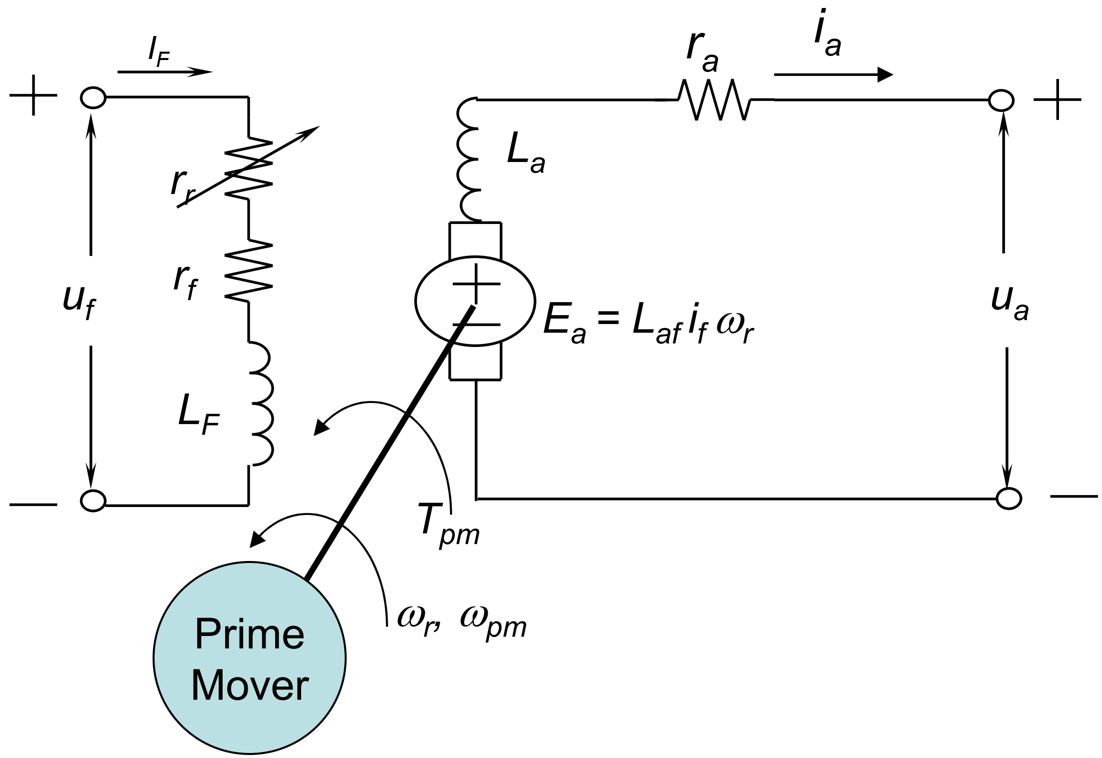


$$i_a = \frac{u_a - E_a}{r_a}$$

$$u_a - L_{af} i_f \omega_r = r_a i_a + \frac{d\psi_a}{dt} = r_a i_a + L_a \frac{di_a}{dt}$$

$$u_f = r_f i_f + \frac{d\psi_f}{dt} = r_f i_f + L_f \frac{di_f}{dt}$$

Separately-Excited DC Generator: Differential Equations of Motion



$$u_a - L_{af} i_f \omega_r = -r_a i_a - L_a \frac{di_a}{dt}$$

$$u_f = r_f i_f + L_f \frac{di_f}{dt}$$

The steady-state operating conditions for a generator are

$$u_a - L_{af} i_f \omega_r = -r_a i_a; \quad u_f = r_f i_f$$

The Steady-State Quantities

$$W_C(i_a, i_f, \theta_r) = \frac{1}{2} L_a i_a^2 + L_{sr}(\theta_r) i_a i_f + \frac{1}{2} L_f i_f^2$$

$$T_e = \frac{\partial W_C(i_a, i_f, \theta_r)}{\partial \theta_r} = -L_{af} i_a i_f \sin\theta_r$$

$$L_{af} = L_M = L_{sr\max} = \frac{N_a N_f}{\Re_m(90^0)}$$

$$T_e = L_{af} i_a i_f;\ P_{em} = E_a i_a;\ P_{mec} = T_e \omega_r;\ T_e = \frac{E_a i_a}{\omega_r}$$

$$\omega_r = \frac{u_a - r_a i_a}{L_{af} i_f} = \frac{u_a}{L_{af} i_f} - \frac{r_a}{\left(L_{af} i_f\right)^2} T_e \text{ (Steady state relation)}$$

Modeling Separately Excited DC Motor

$$u_a - L_{af} i_f \omega_r = \left(r_a + r_{ar}\right) i_a + L_a \frac{di_a}{dt}$$

$$u_f = \left(r_f + r_{fr}\right) i_f + L_f \frac{di_f}{dt}$$

$$\omega_r = \frac{u_a}{L_{af} i_f} - \frac{r_a + r_{ar}}{\left(L_{af} i_f\right)^2} T_e$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - B_m \omega_r - T_L)$$

$$\frac{di_a}{dt} = -\frac{r_a}{L_a} i_a - \frac{L_{af}}{L_a} i_f \omega_r + \frac{1}{La} u_a$$

$$\frac{di_f}{dt} = -\frac{r_f}{L_f} i_f + \frac{1}{L_f} u_f$$

$$\frac{d\omega_r}{dt} = \frac{L_{af}}{J} i_a i_f - \frac{B_m}{J} \omega_r - \frac{1}{J} T_L$$

Modeling Separately Excited DC Generator

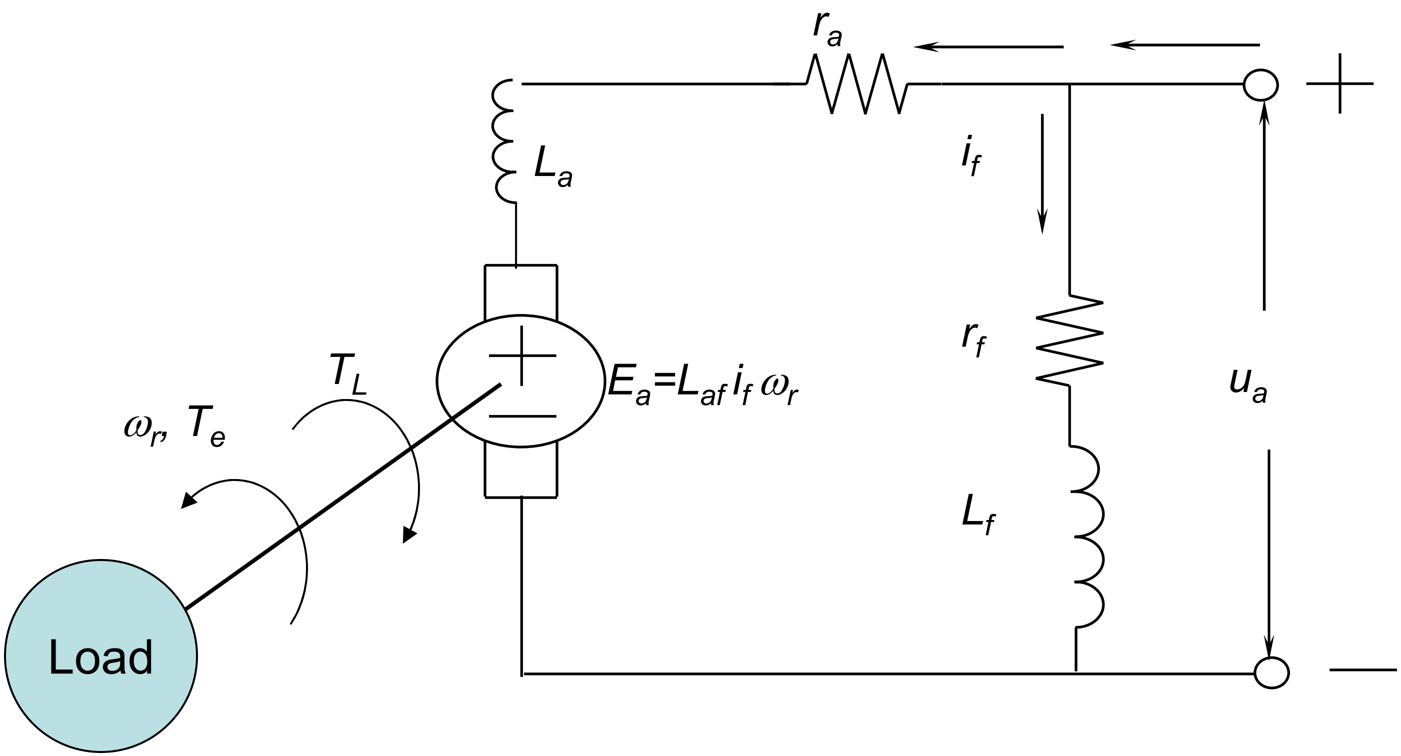
$$-T_e - B_m\omega_r + T_{pm} = J\frac{d\omega_r}{dt}$$

$$\frac{di_a}{dt} = -\frac{r_a}{L_a}i_a - \frac{L_{af}}{L_a}i_f\omega_r + \frac{1}{La}\ u_a$$

$$\frac{di_f}{dt} = -\frac{r_f}{L_f}i_f + \frac{1}{L_f}u_f$$

$$\frac{d\omega_r}{dt} = \frac{L_{af}}{J}i_a i_f - \frac{B_m}{J}\omega_r - \frac{1}{J}T_{pm}$$

Shunt-Connected Direct-Current Machines



$$u_a - L_{af} i_f \omega_r = r_a i_a + L_a \frac{di_a}{dt}$$

$$u_f = r_f i_f + L_f \frac{di_f}{dt}$$

Use Kirchhoff's equations for circuits and apply Newton's second law to generate the following differential equations

$$\frac{di_a}{dt} = -\frac{r_a}{L_a} ia - \frac{L_{af}}{L_a} i_f \omega_r + \frac{1}{L_a} u_a$$

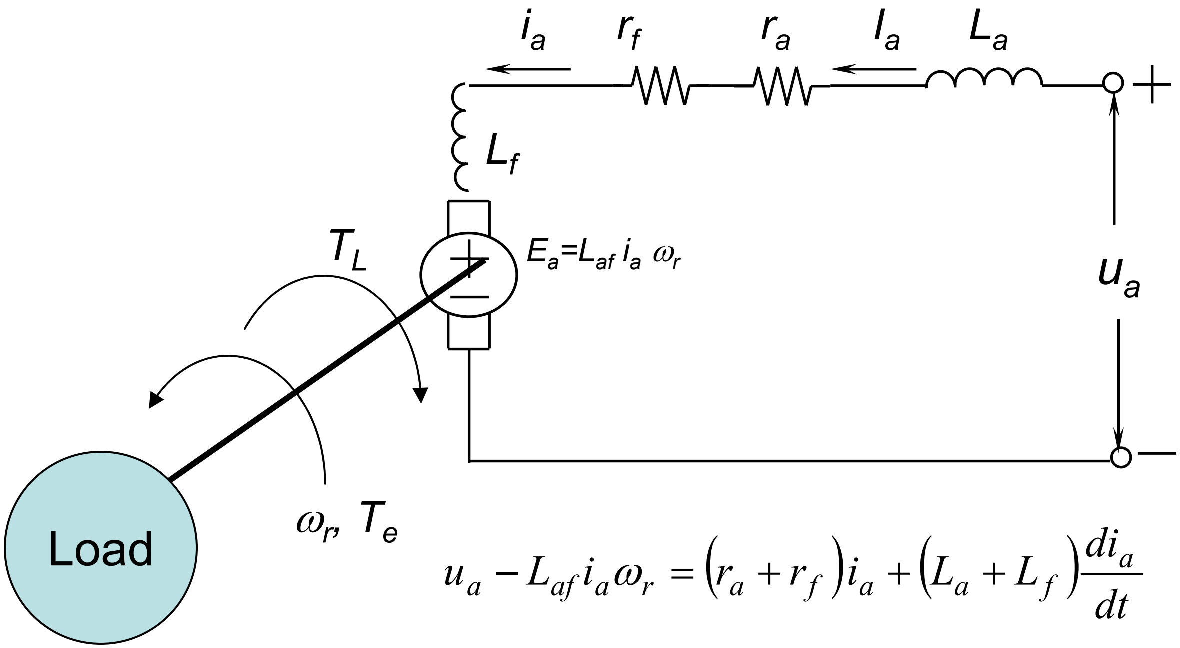
$$\frac{di_f}{dt} = -\frac{r_f}{L_f} i_f + \frac{1}{L_f} u_a ; u_a = u_f$$

$$\frac{d\omega_r}{dt} = \frac{L_{af}}{J} i_a i_f - \frac{B_m}{J} \omega_r - \frac{1}{J} T_L$$

$$i_a = \frac{u_a - L_{af} i_f \omega_r}{r_a} ; i_f = \frac{u_a}{r_f}$$

$$T_e = L_{af} i_a i_f = \frac{L_{af}}{r_a r_f} \left(1 - \frac{L_{af} \omega_r}{r_f} \right) u_a^2$$

Series-Connected DC Machines



$$u_a - L_{af} i_a \omega_r = \left(r_a + r_f\right) i_a + \left(L_a + L_f\right)\frac{di_a}{dt}$$

$$i_a = \frac{u_a}{L_{af}\omega_r + r_a + r_f}$$

$$T_e = L_{af} i_a^2 = \frac{L_{af}}{\left(L_{af}\omega_r + r_a + r_f\right)^2} u_a^2$$

$$\frac{di_a}{dt} = -\frac{r_a + r_f}{L_a + L_f} i_a - \frac{L_{af}}{L_a + L_f} i_a \omega_r + \frac{1}{L_a + L_f} u_a$$

$$\frac{d\omega_r}{dt} = \frac{L_{af}}{J} i_a^2 - \frac{B_m}{j}\omega_r - \frac{1}{j} T_L$$

Electronic Control of Direct Current Motors

Based on Electrical Machines, Drives, and Power Systems, Fifth Edition
by Theodore Wildi: Prentice Hall

High-speed, reliable, and inexpensive semiconductor devices have produced a dramatic change in the control of DC motors.

Here in this lecture, we will examine some of the basic principles of such electronic drives. The circuits involve rectifiers and inverters already studies in ELG3311.

In this lecture, we will only study the behavior of power circuits.

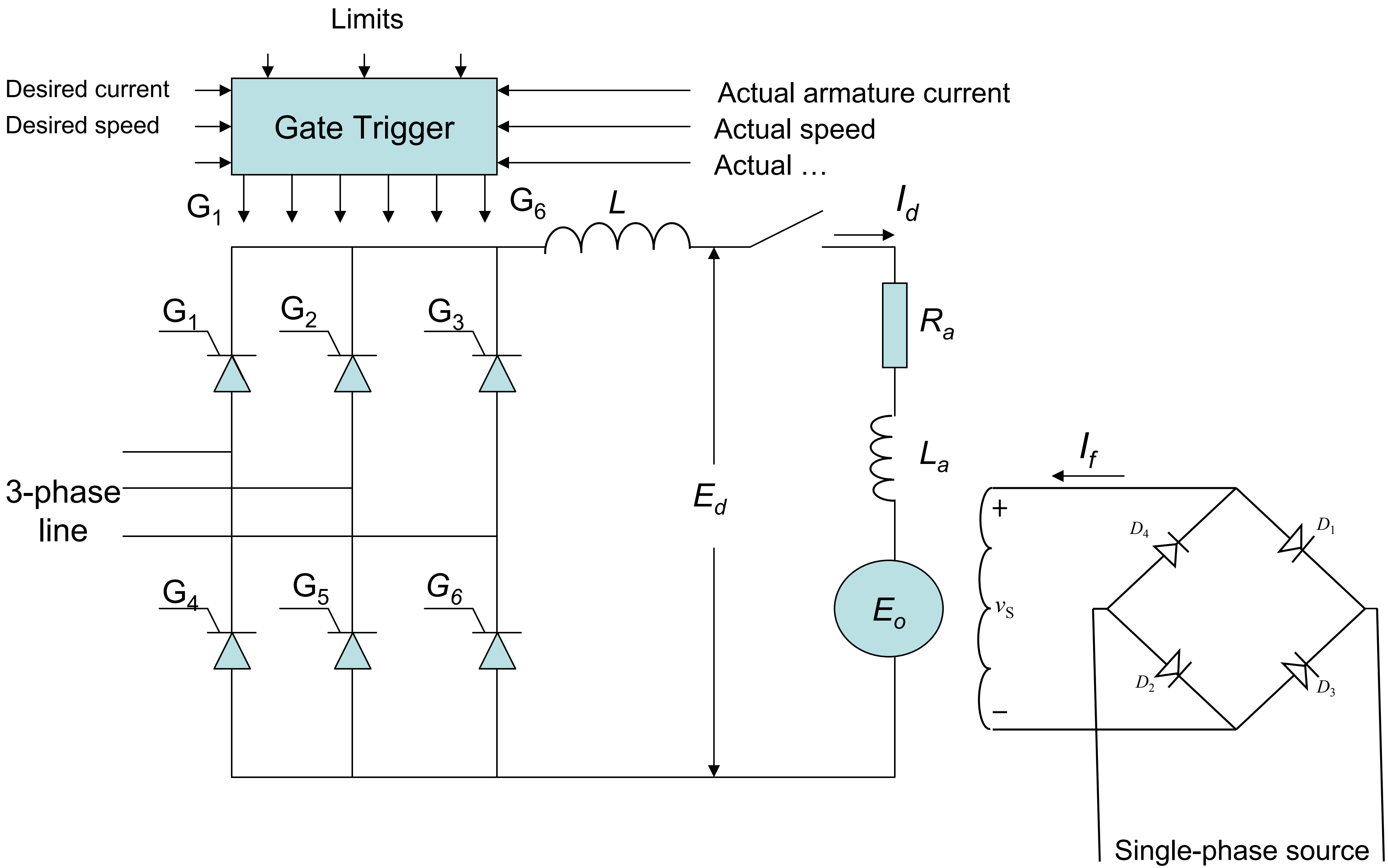
First Quadrant Speed Control

- Let us consider a variable speed drive for a DC shunt motor.
- We assume that its operation is restricted to quadrant 1.
- The field excitation is fixed, and the speed is varied by changing the armature voltage.
- A 3-phase, 6-pulse converter is connected between the armature and the 3-phase source as shown in the Figure shown in the next page.
- The field current I_f is provided by a single-phase bridge rectifier.
- A gate triggering processor receives external inputs such as external speed, actual torque, etc. These inputs are picked off the power circuit by means of suitable transducers.
- The processor can be set for any desired motor speed and torque. The actual values are compared with the desired values, and the processor automatically generates gate pulses to bring the two as close together as possible.
- Limit settings are also incorporated so that the motor never operates beyond acceptable values of current, voltage, and speed.

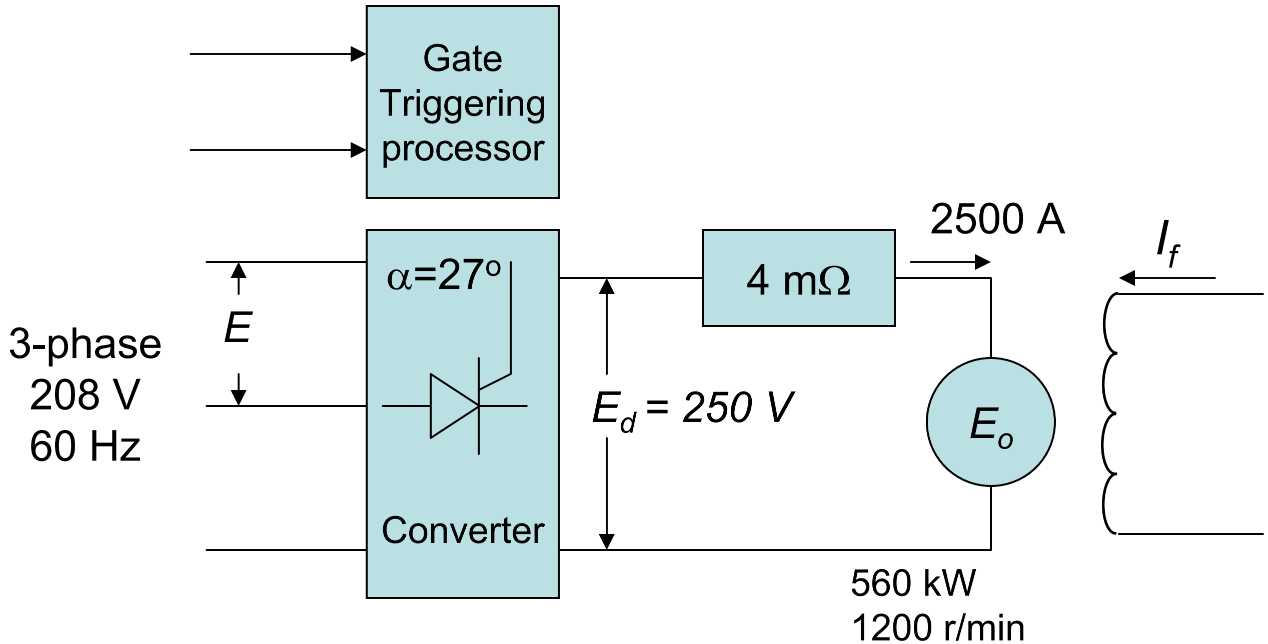
- Gate pulses are initially delayed by an angle α = 90 ^{o} so that converter output voltage Ed is zero.
- Switch S is then closed and α is gradually reduced so that E_d begins to build up.
- Armature current I_d starts flowing and the motor gradually accelerates.
- During the starting period, the current is monitored automatically.
- Moreover, the gate-triggering processor is preset so that pulses can never produce a current in excess.
- When the motor reaches full speed, the firing angle is usually between 15^{o} and 20^{o}. Converter voltage E_d is slightly greater than induced voltage E_0 by the amount equal to the armature circuit I_dR_a drop. The converter voltage is given by the basic equation:

$$E_d = 1.35E\cos\alpha$$

Armature Torque and Speed Control of a DC Motor using a Thyristor Converter



Example: A 750 hp, 250 V, 1200 r/min DC motor is connected to a 208 V, 3-phase, 60 Hz line using a 3-phase bridge converter as shown. The full-load armature current is 2500 A and the armature resistance is 2500 A and the armature resistance is 4 mΩ.



Find the required firing angle α under rated full-load conditions.

Find the firing angle required so that the motor develops its rated torque at 400 r/min

(a) At full load the converter must develop a DC output of 250 V

$E_d = 1.35 E \cos\alpha$

$250 = 1.35 \times 208 \cos\alpha$

$\alpha = 27^o$

Armature IR drop at rated current = $2500\text{ A} \times 0.004\,\Omega = 10\text{V}$

Counter - emf at 1200 r/min (E_o) = 250 - 10 = 240 V

(b) To develop rated torque at 400 r/min, the armature current must still be

be 2500 A. The emf at 400 r/min is : $E_o = \left(\dfrac{400}{1200}\right) \times 240 = 80\text{ V}$

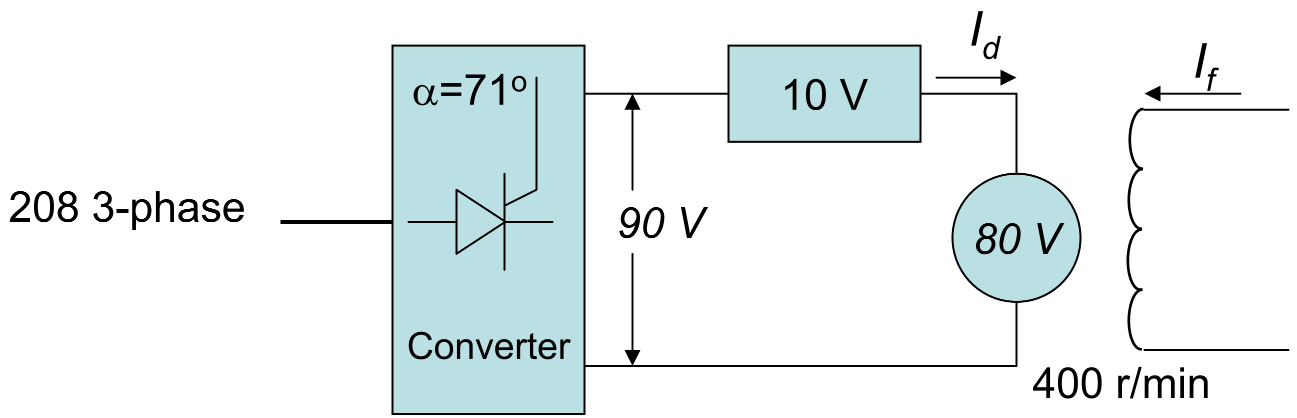
Armature terminal voltage is $E_d = 80 + 10 = 90\text{ V}$

The converter must generator 90 V. To determine the firing angle, we have

$E_d = 1.35\, E \cos\alpha = 1.35 \times 208 \cos\alpha$

$\alpha = 71^{\circ}$ (see the Figure in the next page)

For the same example, calculate the reactive power absorbed by the converter when the motor develops full torque at 400 r/min.



The DC power absorbed by the motor $P = E_d I_d = 90 \times 2500 = 225\ \text{kW}$

The active power supplied by the AC source is 225 kW

The reactive power drawn from the source is $Q = P \tan\alpha = 225 \tan 71^o = 653\ \text{kVAR}$

AC Motors

They are used as the final control element in positional or speed-control systems. AC motors have the great advantage over DC motors of being cheaper, more rugged, reliable, and maintenance free.

- Single phase
- Polyphase
- Induction
- Synchronous

Electronic Control of Alternating Current Motors

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Why AC Machines?

AC machines have no commutators and brushes; consequently, they require less maintenance.

AC machines cost less and weigh less than DC machines

AC machines are more rugged and work better in hostile environments

AC machines can operate at much higher voltages: up to 25 kV. DC machines are limited to about 1000 V.

AC machines can be build in much larger sizes: up to 50000 kW machines. DC machines are limited to about 2000 kW.

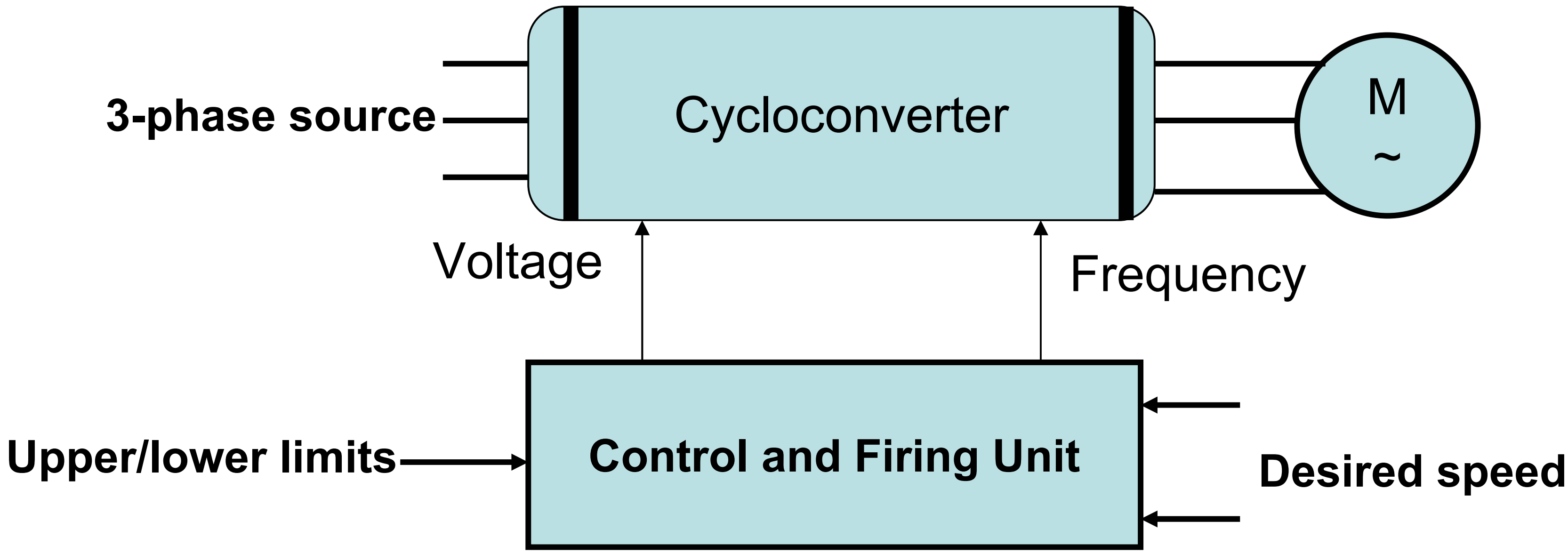
AC machines can run at speeds up to 100000 r/min, whereas large DC machines are limited to about 2000 kW.

Types of Electronic AC Drives

- Static frequency changers.
- Static voltage controllers.
- Rectifier-inverter systems with line commutation.
- Rectifier-inverter system with self commutation.
- Pulse-width modulation systems.

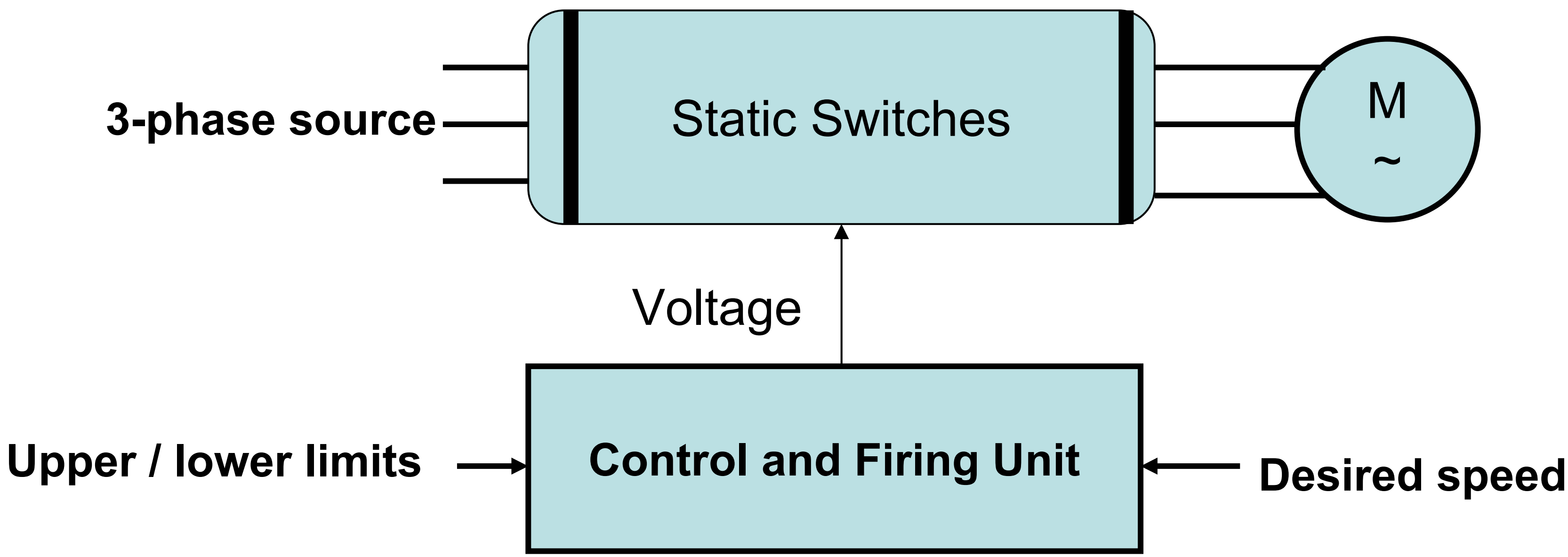
Static frequency changers

They convert the incoming line frequency directly into the desired load frequency. Cycloconverters fall into this category, and they are used to drive both synchronous and squirrel-cage induction motors.



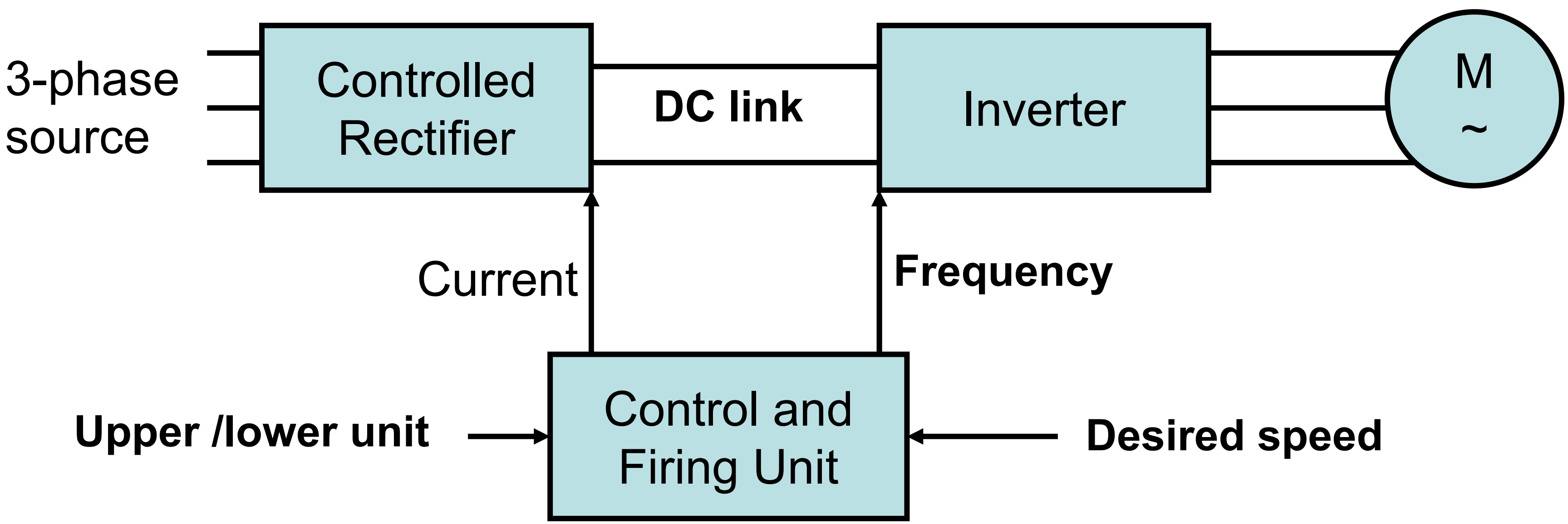
Static Voltage Controllers

They enable speed and torque control by varying the AC voltage. They are used with squirrel-cage induction motors. Static voltage controllers are also used to soft-start induction motors.



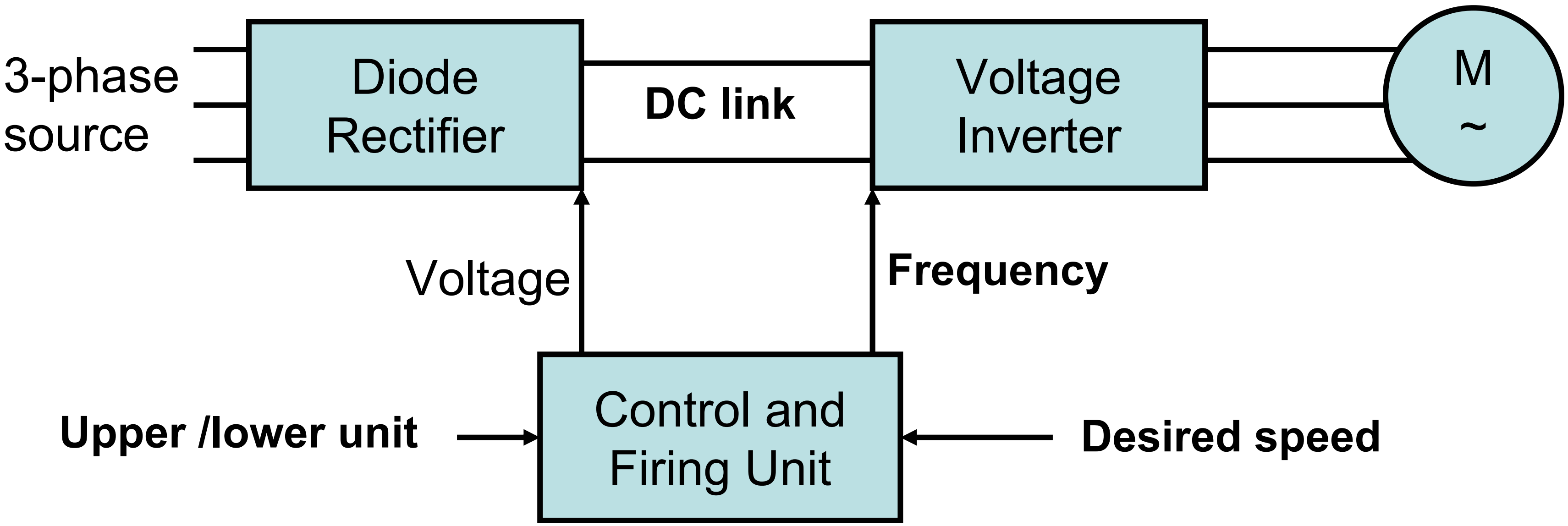
Rectifier-Inverter System with Line Commutation

It rectifies the incoming line frequency to DC, and the DC is reconverted to AC by an inverter. The inverter is line commutated by the very motor it drives. Such systems are used to control synchronous motors and the speed of wound-rotor induction motors.

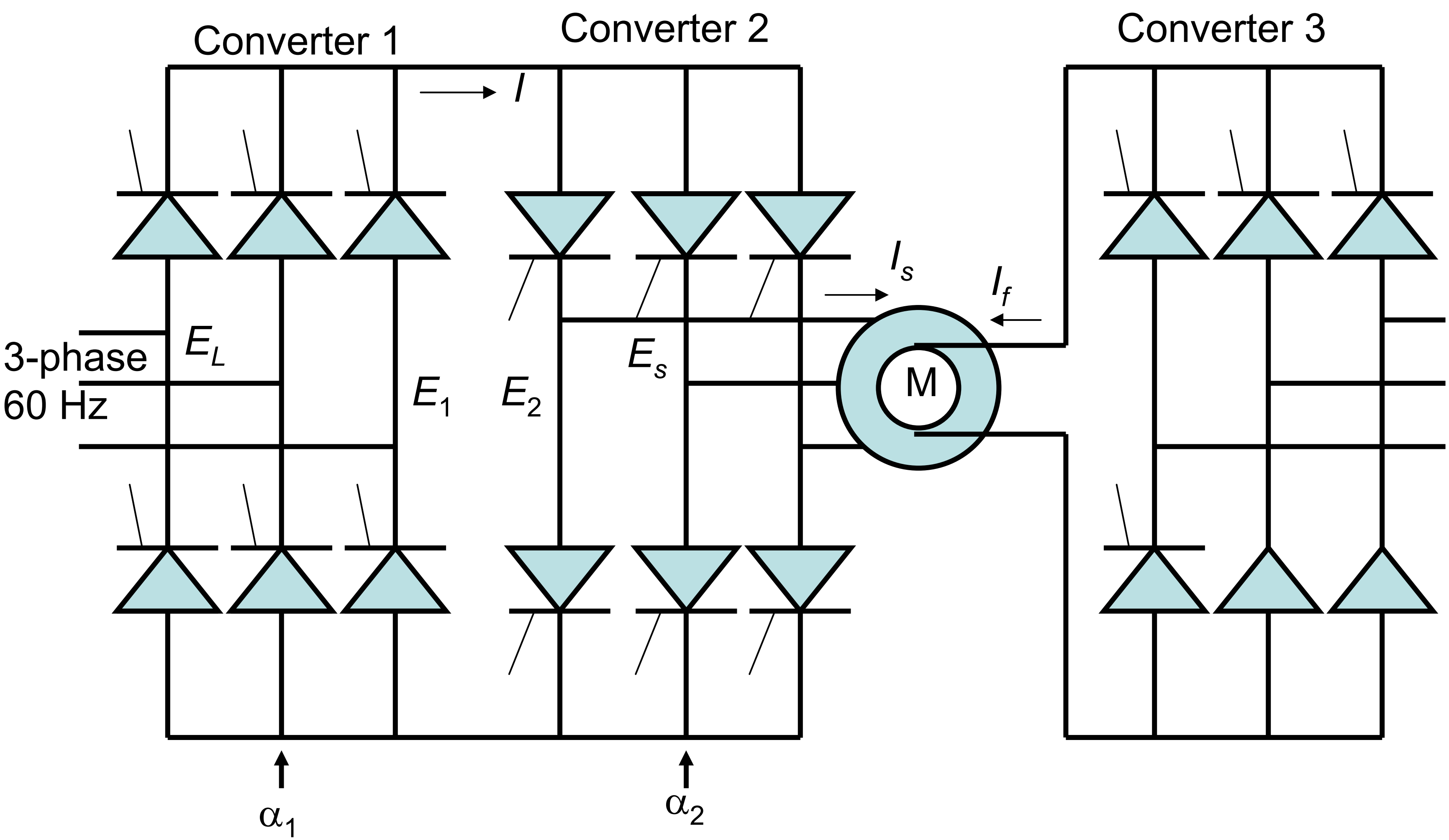


Pulse-Width Modulation Systems

They are relatively new! They enable variable speed induction motor drives ranging from zero speed and up.



Synchronous Motor Drive Using Current-Source DC Link



Example: A 3-phase synchronous motor rated at 200 kW, 480 V, 60 Hz, 450 r/min, is connected to a drive similar to the Figure shown in the previous page. The three-phase electric utility voltage is 600 V, 60 Hz. The motor runs at a speed of 535 r/min. The effective terminal voltage is 511 V and the motor draws an effective line current Is of 239 A at a power factor of 95%. The motor has an efficiency of 93%. Calculate (1) the frequency applied to the rotor, (2) the fundamental component of the stator current Is, (3) the current I flowing in the DC link, (4) α_2, (5) E_2, (6) α_2, (7) α_1, (8) The reactive power supplied to converter 1, (9) the mechanical power developed by the motor.

$$(1)\ f = \frac{535}{450} \times 60 = 71.3\ \text{Hz}$$

$$(2)\ I_F = 0.955\, I_s = 0.955 \times 239 = 228\ \text{A}$$

$$(3)\ I = \frac{I_F}{0.78} = \frac{228}{0.78} = 293\text{A}$$

$$(4)\ \alpha = \text{-across}\, 0.95 = 180^{\circ}\ \text{-}18.2^{\circ} = 161.80^{\circ}$$

$$(5)\ E_2 = 1.35 E_s \cos\alpha_2 = 1.35 \times 511 \times \cos 161.8^{\circ} = \text{-}655\ \text{V}$$

$$(6)\ E_1 = 1.35\, E_L \cos\alpha_1; \alpha_1 = 36^{\circ}$$

$$(7)\ P = E_1 I = 655 \times 293 = 192\ \text{kW};\ PF = \cos\alpha_1 = \cos 36^{\circ} = 0.809 = 80.9\%$$

$$S = 192\ \text{kW}/0.809 = 237\ \text{kVA}$$

$$Q = \sqrt{S^2\ \text{-}\ P^2} = \sqrt{237^2 - 192^2} = 139\ \text{KVAR}$$

$$(8)\ P_m = 192\ \text{kW} \times 0.93 = 179\ \text{kW} \approx 240\ \text{hp}$$

Stepper Motors

The stepper motor is a device that produces rotation through equal angles called steps for each digital pulse supplied to its input. The following are some of the terms commonly used in specifying stepper motors:

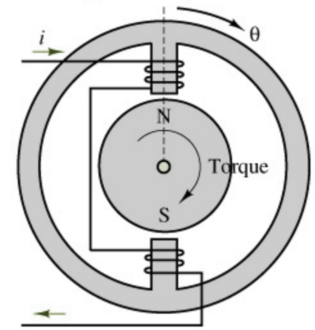
- **Phase:** Related to the number of windings on the stator.
- **Step angle:** Refers to the angle through which the rotor rotates for one switching change for the stator coil.
- **Holding torque:** Refers to the maximum torque that can be applied to a powered motor without moving it from its rest position and causing spindle rotation.
- **Pull-in-torque:** Refers to the maximum torque that can be applied to a motor running at a given stepping rate without losing synchronism.
- **Pull-in-rate:** Refers to the maximum switching rate at which a loaded motor can start without losing a step.
- **Pull-out-rate:** Refers to the switching rate at which a loaded motor will remain in synchronism as the switching rate is reduced.

Stepping Motors

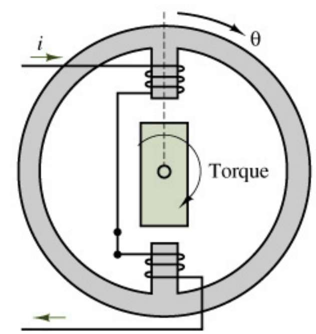
A special type of synchronous motor which is designed to rotate a specific number of degrees for every electric pulse received by its control unit. Typical steps are 7.5 or 15^{o} per pulse. It is a motor that can rotate in both directions, move in precise angular increments, sustain a holding torque at zero speed, and be controlled with digital circuits. It moves in accurate angular increments known as steps, in response to the application of digital pulses to the electric drive circuit. Generally, such motors are manufactured with steps per revolution. Step motors are either bipolar, requiring two power sources or unipolar requiring only one power source.

$$\theta_m = \frac{2}{p}\theta_e$$

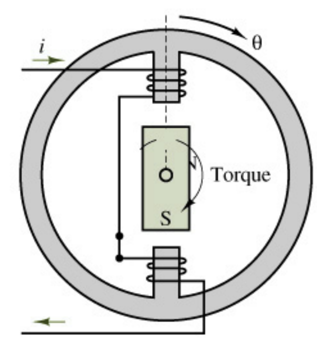
$$\omega_m = \frac{2}{p}\omega_e$$



(a) Permanent-magnet stepping motor

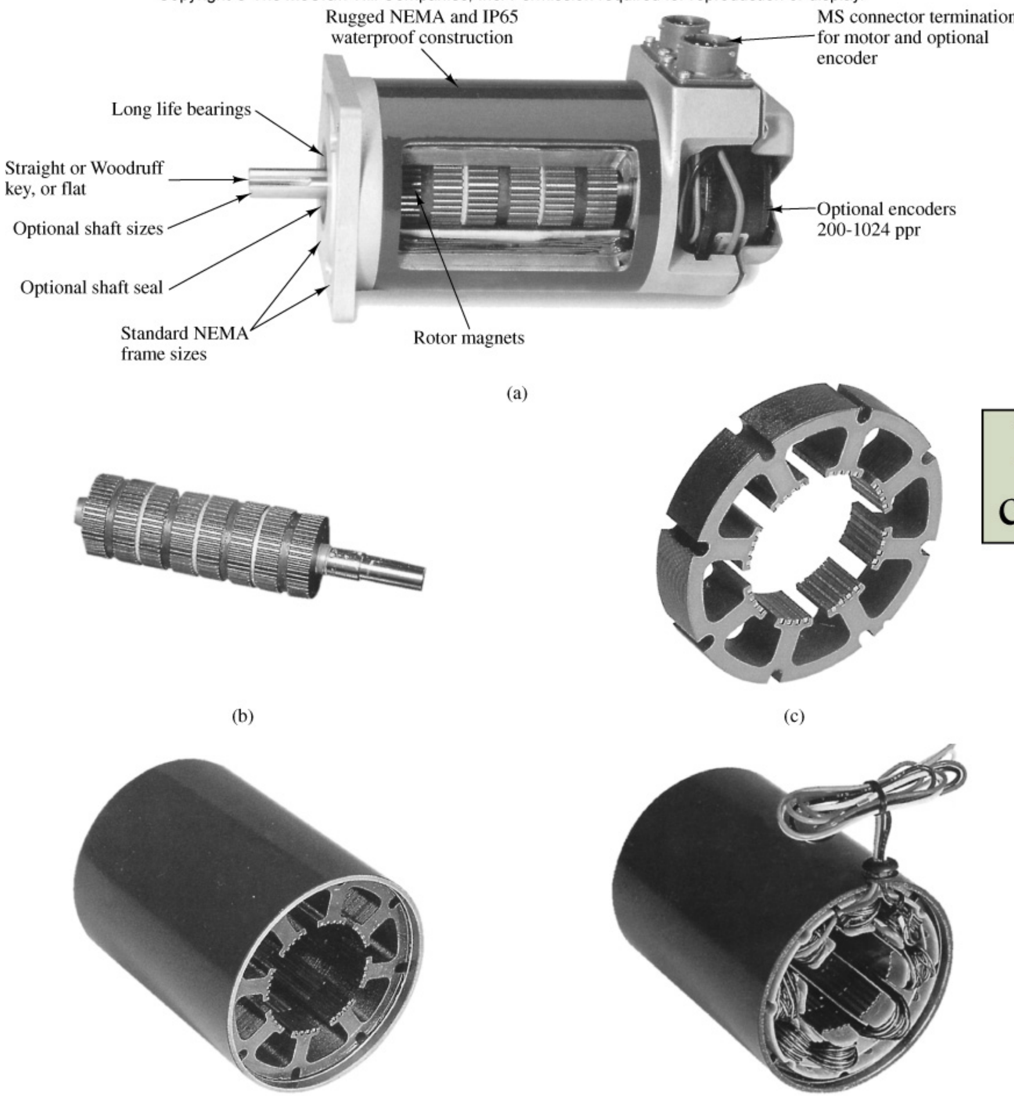


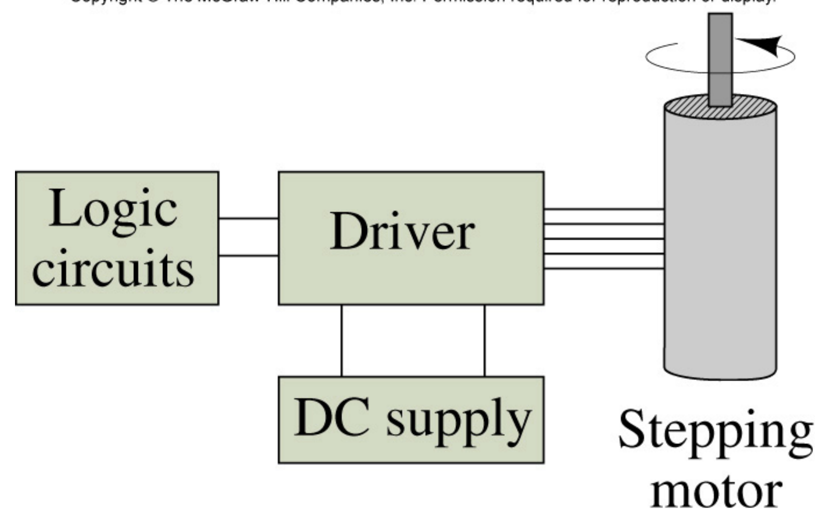
(b) Variable-reluctance stepping motor



(c) Hybrid stepping motor

Variable Reactance (VR) Stepper Motor (a) Complete Motor Assembly; (b) PM Rotor; (c) Stator Cross Section; (d) Fully Assembled Stator; (e) Stator with Windings.





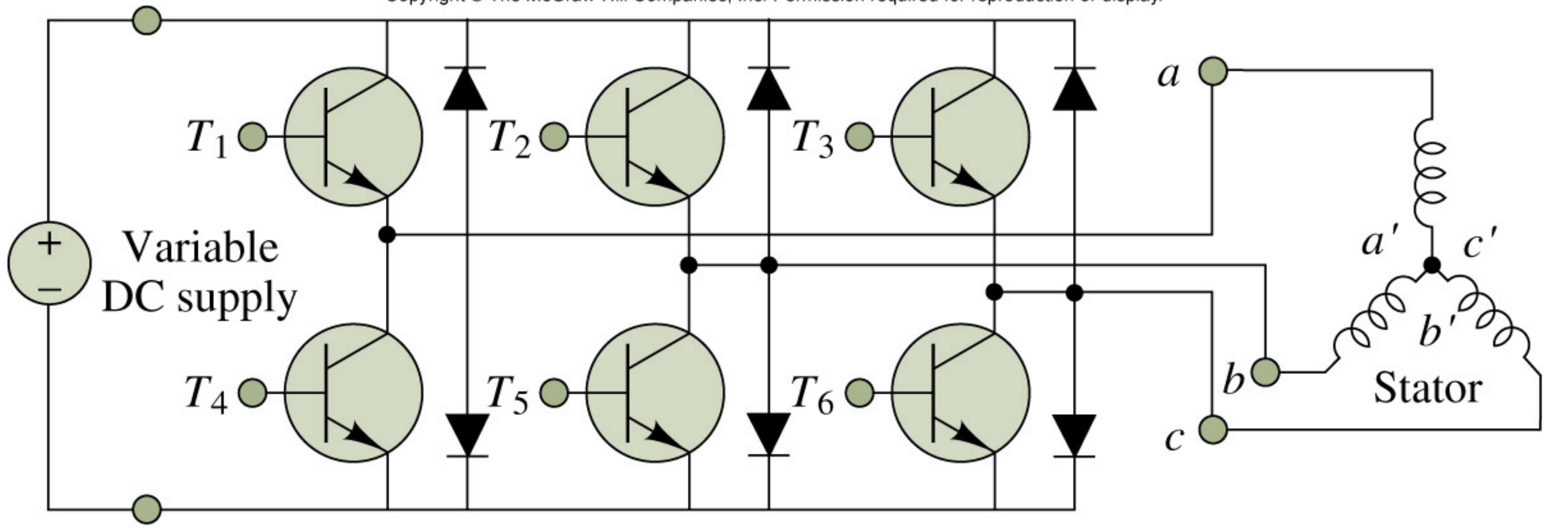
Basic Components of a Brushless DC Motor

- A permanent magnet rotor.
- A stator with a three-, four-, or more phase winding.
- A rotor position sensor.
- An electronic circuit to control the phases of the rotor winding.

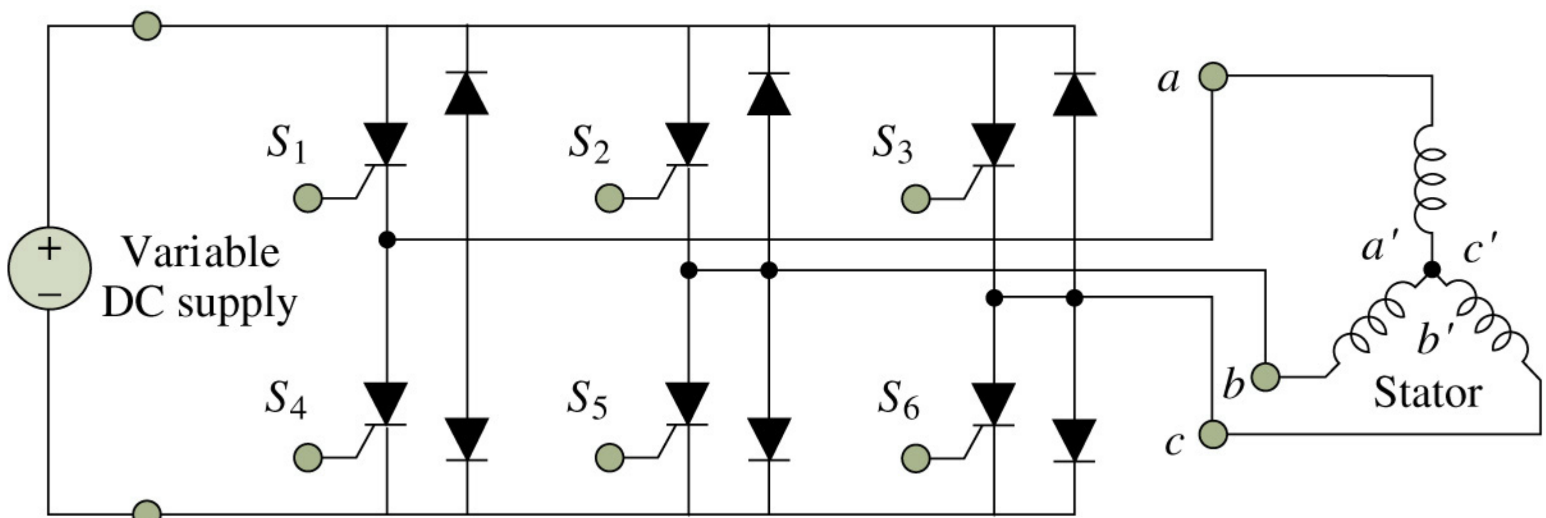
Characteristics

- Brushless DC motors are available only on small sizes, up to 20 W.
- They have relatively high efficiency.
- They have long life and high reliability.
- Little or no maintenance.
- Very low RF noise compared to DC motors with brushes.
- Very high speed (up to 50,000 r/min).

Transistor and SCR Drives for a Brushless DC Motor



Transistor supply for brushless DC motor



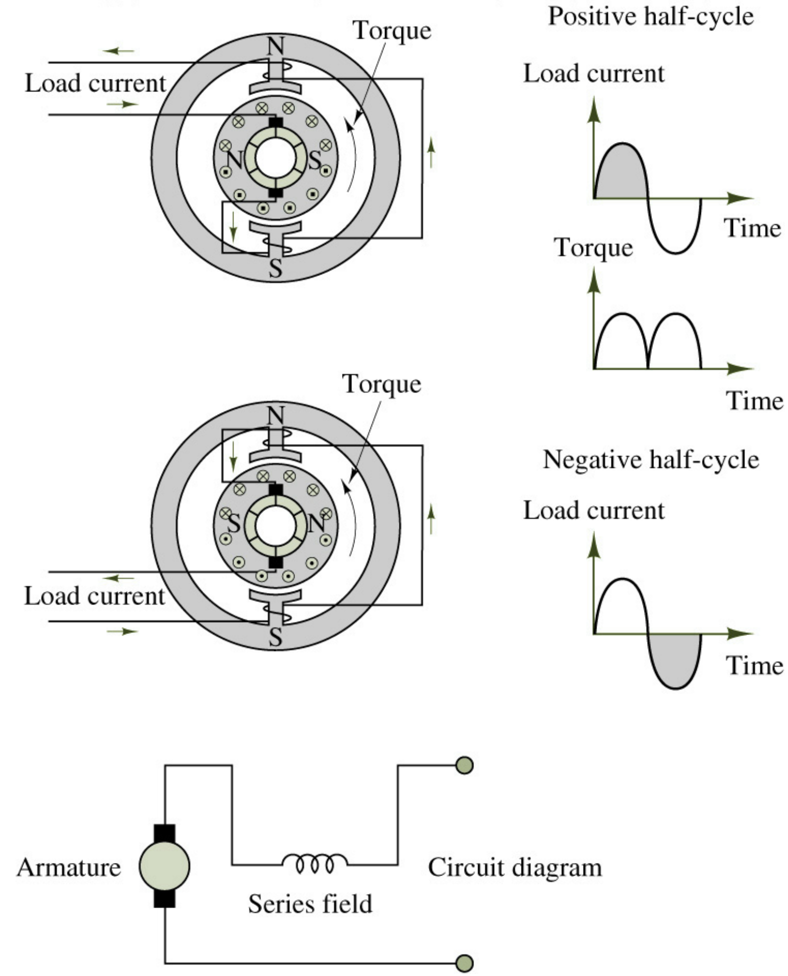
SCR supply for brushless DC motor

Universal Motor

The universal motor is a rotating machine similar to a DC motor but designed to operate either from DC or single-phase AC. The stator and rotor windings of the motor are connected in series through the rotor commutator. Therefore the universal motor is also known as an AC series motor or an AC commutator motor. The universal motor can be controlled either as a phase-angle drive or as a chopper drive.

The universal motor has a sharply drooping torque-speed characteristics of a DC series motor.

Typical applications in vacuum cleaners, drills, and kitchen appliances.



Motor Selection Criteria

- Available power (DC or AC)
- Operating condition.
- Starting characteristics (torque and current)
- Operating speed.
- Forward/reverse operation.
- Acceleration characteristics (depending on load)
- Efficiency at rated load.
- Overload capability.
- Electrical and thermal safety.
- Life span and maintenance.
- Mechanical aspects (size, weight, noise level, environment).
- EMC and EMI
- Control complexity and Cost.