Mechatronics

Prepared by

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وزارة الصحة والسكان

Acknowledgments

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توصيف مقرر دراسى

1- بيانات المقرر		
الرمز الكودى :	اسم المقرر : ميكاترونيكس **Mechatronics**	الفرقة /المستوى : 2
التخصص :	عدد الوحدات الدراسية : 2 نظرى - عملى 2	

2- هدف المقرر:	The main objective of the course is to provide the students with the basic knowledge, and practices related to the mechatronic systems in pharmaceutical manufacturing.
3- المستهدف من تدريس المقرر :	
ا. المعلومات والمفاهيم :	**By the end of this course, the students should be able to:** a1- Describe the main motion control concepts. a2- Describe the switching sequence of three phase rectification circuits. a3- Describe the switching sequence of three phase inversion circuits. a4- Identify the theory of operation of DC motors, their advantage and disadvantages. a5- Identify the theory of operation of induction motors, their advantage and disadvantages. a6- State different applications of PLC's.
ب- المهارات الذهنية :	b1- Compare between DC motors and induction motors. b2- Allocate specific switching circuit to a desired control function, and application. b3- Recognize the interrelations between various switches, relays, and contactors in industrial control systems. b4- Use 'fail and safe' analysis for PLC codes.
ج- المهارات المهنية الخاصة بالمقرر:	c1- Select an appropriate motor control algorithm for motion control. c2- Analyze the performances of various switching circuits for motor control systems. c3- Size the main components comprising various switching circuits. c4- Calculate the performance indicators of various motors as affected by supply switching circuits. c5- Design a ladder diagram for performing required functions.
د- المهارات العامة :	d1- Work, and communicate effectively within a team, d2- Writing neat technical reports. d3- Apply presentation of a technical report. d4- Manage effectively time and resources.

4- محتوى المقرر:

Week	Topic
1	Review of electric, and power electronic circuits.
2	Introduction of the basic motion control systems for industrial applications.
3-4	Three phase uncontrolled rectification circuits
5	Three phase controlled rectification circuits
6	- (Midterm exam)
7-8	Three phase inversion circuits
9	Control of DC motors
10	Control of three-phase induction motors
11	Switches, relays, and sensors
12-13	Programmable logic controllers, and their programming
14	Project, or site visit
15	- (Final exam)

1 – Lectures 2-Assignments 3– Site visits	5- أساايب التعليم والتعلم
Special care will be given for applicable, and acceptable cases.	6- أساليب التعليم والتعلم للطلاب ذوى القدرات المحدودة
	7- تقويم الطلاب :
1. Quiz 2. Midterm exam 3. Clinical skills 4. Final written exam	أ- الأساليب المستخدمة
1. Quiz (5th,week) 2. Midterm exam (7th week) 3. Clinical skills through the semester 4. Final exam (15th week)	ب- التوقيت
Quiz : 3 mark Midterm: 5 marks Attendance 2 marks Clinical: 10 marks Final written exam 80 marks. **Total percentage 100 mark**	ج- توزيع الدرجات
	8- قائمة الكتب الدراسية والمراجع :
To be delivered to the students as notes, and presentations.	أ- مذكرات

The course textbook.	ب- كتب ملزمة
Muhammad H Rashid,Power Electronics Circuits Devices and Applications, 3rd edition, Prentice Hall, 2008	ج- كتب مقترحة
IEEE transactions on power electronics IEEE transaction on industrial applications http://shimymb.tripod.com	د- دوريات علمية أو نشرات الخ ......

Contents

Course Description

This book provides the content sufficient for the first course in mechatronics. The main objective of the books is the habilitation of non-engineers for working in motion control, and mechatronics systems of industrial scale, and of high power applications. The first two chapters of the book present the core materials necessary for understanding the fundamentals of mechatronics, control elements, and practical applications. The rest of the book presents chapters dealing with specific elements required for the operation, and control of mechatronics systems in motion control applications, and power supply processing.

Core Knowledge

By the end of this course, students should be able to:

- List the types of various mechanical drives and compare between them.
- Explain the main components of an industrial motion control system.
- List various types of electric motors used in mechatronics systems.
- Explain the move profile and the required motion control.
- List various types of switches, relays, and contactors.
- Define the functions of various types of switches, relays, and contactors.
- Explain the control logic of various mechatronic systems.
- Explain the fail-safe design requirements.
- Explain the requirements of interlocks in various control logics.
- Explain the switching sequence of three phase rectifier switches
- Explain the switching sequence of three phase inverter switches
- Compare DC motors to Induction Motors
- Elaborate the theory of operation of DC motors, their advantage and disadvantages
- Elaborate the theory of operation of Induction motors, their advantage and disadvantages
- Enumerate different applications of PLC’s

Core Skills

By the end of this course, students should be able to:

- Calculate the inertia of various systems of drive mechanics.
- Selection of a suitable electric motor drive for a required move profile.
- Specify the control and power requirements for a given move profile.
- Devise control logic alternatives.
- Analyze control logic systems.

- Design a Ladder diagram for a simple industrial process.
- Calculate the voltage output and current ratings of a three phase rectifier
- Calculate the output speed and torque of a DC motor
- Calculate the voltage output and current ratings of a three phase inverter
- Calculate the output speed and torque of an Induction Motor
- Enumerate different commercial relays and sensors related to medicine manufacturing processes
- Show the ability of connecting and operating a simple automation system

Course Overview

		Methods of Teaching/Training with Number of Total Hours per Topic				
ID	**Topics**	**Interactive Lecture**	**Field Work**	**Class Assignments**	**Research**	**Lab**
1	Basics of Motion Control for Industrial Applications	6	2			4
2	Switches, Relays, Contactors, and Ladder Diagrams	6				4
3	Fundamentals of electric and electronic circuits	2				4
4	Electronic Converters	4				4
5	DC motor control	4				4
6	Control of induction motors	2				4
TOTAL HOURS (48)		**24**	**2**			**22**

Chapter 1

Basics of Motion Control for Industrial Applications

Objectives

- Drive mechanics, and modeling of generalized electromechanical motion and positioning applications.
- General structure of motion control system
- Selection of a suitable drive.

Drive mechanics

The first step in determining the requirements of a motion control system is to analyze the drive mechanics, including friction and inertia of the load to be controlled and/or positioned. Load friction can easily be determined either by estimating using mathematical models, or by simply measuring with a torque wrench. The inertia may be defined as the resistance of an object to accelerate, or decelerate. It defines the torque required to accelerate a load from one speed to another, but it excludes frictional forces. The inertia is calculated by analyzing the moving mechanical linkage system; for example, a solid cylinder (Fig. 1), or a hollow cylinder (Fig. 2).

Such systems are categorized as one of four basic drive designs: *direct (Fig. 3)*, *gear (Fig. 4)*, *tangential (Fig. 5)*, or *leadscrew (Fig. 6)*. A direct drive mechanism is one that takes the power coming from a motor without any additional power transmission, such as a gearbox. In a gear drive, the mechanism consisting of toothed wheels or gears that engage and transmit rotary motion of the motor to the load, usually transforming angular velocity and torques. A tangential drive consists of a timing belt and pulley, chain and sprocket, or rack and pinion; it also requires reflecting load parameters back to the motor shaft. A leadscrew (or lead screw), also known as a power screw or translation screw, is a screw used as a linkage in a machine, to translate turning motion into linear motion.

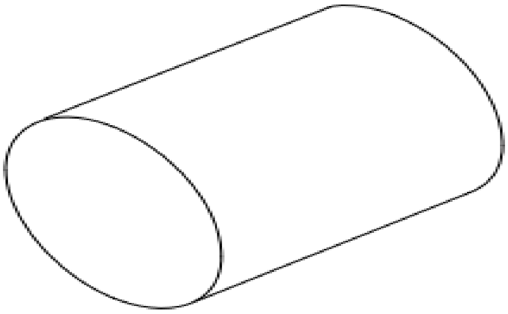


Fig. 1: Solid cylinder

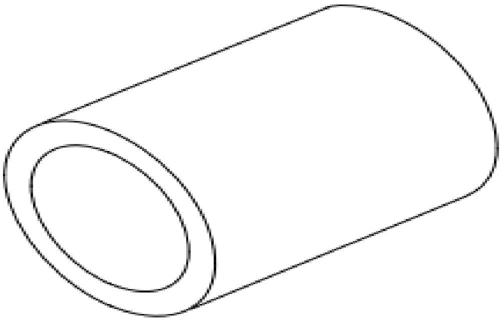


Fig. 2: Hollow cylinder

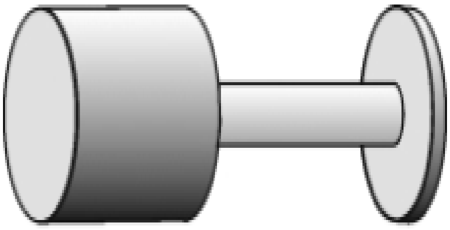


Fig. 3: Direct drive

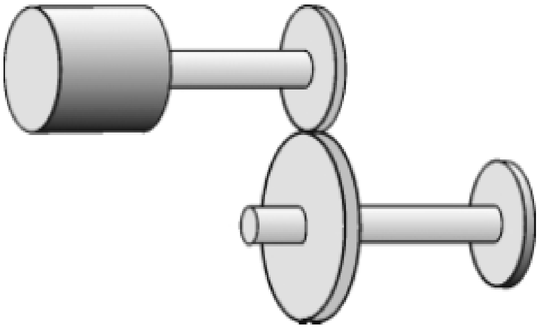


Fig. 4: Gear drive

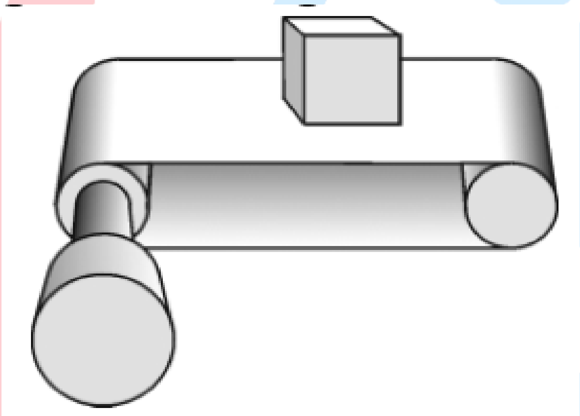


Fig. 5: Tangential drive

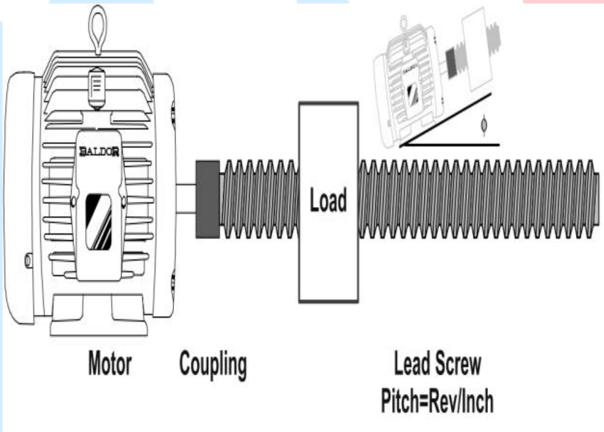


Fig. 6: Leadscrew drive

In the following analyses of mechanical linkage systems, the equations reflect the load parameters back to the motor shaft are presented along with numerical examples. The accurate estimation of the reflected load at the motor shaft is essential for the correct selections of the motor, and the associated controls.

Nomenclature

e = Efficiency
F_l = Load force, lb
F_f = Friction force, lb
F_{pf} = Preload force, lb
g = Gravitational constant, 386 in./sec^2
J = Inertia, lb–in–sec^2
J_l = Load Inertia, lb–in–sec^2
J_{ls} = Leadscrew Inertia, lb–in–sec^2
J_m = Motor Inertia, lb–in–sec^2
J_p = Pulley Inertia, lb–in–sec^2
J_t = Total Inertia, lb–in–sec^2
L = Length, in.
μ = Coefficient of friction
N = Gear ratio
N_l = Number of load gear teeth
N_m = Number of motor gear teeth
ρ = Density, lb/in^3
P = Pitch, rev/in.
R = Radius, in.
R_i = Inner radius, in.
R_0 = Outer radius, in.
S_l = Load speed, RPM
S_m = Motor speed, RPM
T_f = Friction torque, lb–in
T_l = Load torque, lb–in
T_m = Motor torque, lb–in
T_r = Torque reflected to motor, lb–in
V_l = Load velocity, imp
W = Weight, lb
W_{lb} = Weight of load plus belt, lb

α_{acc} = Rotary acceleration, radians/sec^2
I_{acc} = Current during acceleration, A
I_{RMS} = Root–mean–squared current, A
J_{ls} = Leadscrew inertia, lb–in–sec^2
J_m = Motor inertia, lb–in–sec^2
J_t = Total inertia (load plus motor), lb–in–sec^2
K_t = Torque constant, lb–in/A
P = Total power, W
P_{del} = Power delivered to the load, W
P_{diss} = Power (heat) dissipated by the motor, W
R_m = Motor resistance, ohms
S_m = Motor speed, RPM
t_{acc} = Acceleration time, sec
t_{dec} = Deceleration time, sec
t_{idle} = Idle time, sec
t_{run} = Run time, sec
T = Torque, lb–in
T_{acc} = Acceleration torque, lb–in
T_{dec} = Deceleration torque, lb–in
T_f = Friction torque, lb–in
T_{RMS} = Root–mean–squared torque, lb–in
T_{run} = Running torque, lb–in
T_s = Stall torque, lb–in

Cylinder inertia

The inertia of a cylinder can be calculated based on its weight and radius, or its density, radius, and length.

Inertia for solid cylinder based on weight and radius. ⇨ $$J = \frac{WR^2}{2g} \quad (1)$$

Inertia for solid cylinder based on density, radius, and length. ⇨ $$J = \frac{\pi L \rho R^4}{2g} \quad (2)$$

Inertia for hollow cylinder based on weight and radius. ⇨ $$J = \frac{W}{2g}(R_0^2 + R_i^2) \quad (3)$$

Inertia for hollow cylinder based on density, radius, and length. ⇨ $$J = \frac{\pi L \rho}{2g}(R_0^4 - R_i^4) \quad (4)$$

Example: If a cylinder is a leadscrew with a radius of 0.312 in. and a length of 22 in., the inertia can be calculated by using Table 1 and substituting in Equation (2).

Table 1: Densities of materials

Material	**Density** lb per in^3
Aluminum	0.096
Copper	0.322
Plastic	0.040
Steel	0.280
Wood	0.029

$$J = \frac{\pi L \rho R^4}{2g} = \frac{\pi(22)(0.28)(0.312)^4}{2(386)}$$
$$= 0.000237 \text{ lb-in.-sec}^2$$

Direct Drive

The simplest drive system is a direct drive, Figure 3. Because there are no mechanical linkages involved the load parameters are directly transmitted to the motor. The speed of the motor is the same as that of the load, so the load friction is the friction the motor must overcome, and load inertia is what the motor "sees." Therefore, the total inertia is the load inertia plus the motor inertia.

$$J_t = J_l + J_m \qquad (5)$$

Gear drive

The mechanical linkage between the load and motor with a gear drive, Figure 4, requires reflecting the load parameters back to the motor shaft. As with any speed changing system, the load inertia reflected back to the motor is a squared function of the speed ratio.

- Motor speed:

$$S_m = S_l \times N \qquad (6)$$

or

$$S_m = \frac{S_l \times N_l}{N_m} \qquad (7)$$

- Motor torque:

$$T_m = \frac{T_l}{Ne} \qquad (8)$$

- Reflected load inertia:

$$J_r = \frac{J_l}{N^2} \qquad (9)$$

- Total inertia at the motor:

$$J_t = \frac{J_l}{N^2} + J_m \qquad (10)$$

Example: To calculate the reflected inertia for a 6 lb, solid cylinder with a 4 in. diameter, connected through a 3:1 gear set, first use Equation (1) to determine the load inertia.

$$J = \frac{WR^2}{2g} = \frac{6 \times (2)^2}{2 \times 386} = 0.031 \text{ lb–in–sec}^2$$

To reflect this inertia through the gear set to the motor, substitute in Equation (9).

$$J_r = \frac{J_l}{N^2} = \frac{0.031}{3^2} = 0.0034 \text{ lb–in–sec}^2$$

For accuracy, the inertia of the gears should be included when determining total inertia. This value can be obtained from literature or calculated using the equations for the inertia of a cylinder. Gearing efficiencies should also be considered when calculating required torque values.

Tangential drive

Consisting of a timing belt and pulley, chain and sprocket, or rack and pinion, a tangential drive, Figure 5, also requires reflecting load parameters back to the motor shaft.

- Motor speed:

$$S_m = \frac{V_l}{2\pi R} \qquad (11)$$

- Load torque:

$$T_l = F_l R \qquad (12)$$

- Friction torque:

$$T_f = F_f R \qquad (13)$$

- Load inertia:

$$J_l = \frac{W_{lb} R^2}{g} \qquad (14)$$

- Total inertia:

$$J_t = \frac{W_{lb} R^2}{g} + J_{p1} + J_{p2} + J_m \qquad (15)$$

Example: A belt and pulley arrangement will be moving a weight of 10 lb. The pulleys are hollow cylinders, 5 lb each, with an outer radius of 2.5 in. and an inner radius of 2.3 in.
To calculate the inertial for a hollow, cylindrical pulley, substitute in Equation (3):

$$J_p = \frac{W}{2g}\left(R_o^2 + R_i^2\right) = \frac{5}{2(386)}\left(2.5^2 + 2.3^2\right) = 0.0747 \text{ lb-in.-sec}^2$$

Substitute in Equation (14) to determine load inertia:

$$J_l = \frac{WR^2}{g} = \frac{10(2.5)^2}{386} = 0.1619 \text{ lb-in.-sec}^2$$

Total inertia reflected to the motor shaft is the sum of the two pulley inertias plus the load inertia:

$$J = J_l + J_{p1} + J_{p2} = 0.1619 + 0.0747 + 0.0747 = 0.3113 \text{ lb-in.-sec.}^2$$

Also, the inertia of pulleys, sprockets or pinion gears must be included to determine the total inertia.

Leadscrew drive

Illustrated in Figure 6, a leadscrew drive also requires reflecting the load parameters back to the motor. Both the leadscrew and the load inertia have to be considered. If a leadscrew inertia is not readily available, the equation for a cylinder may be used. For precision positioning, the leadscrew may be preloaded to eliminate or reduce backlash. Such preload torque can be significant and must be included, as must leadscrew efficiency. For typical values of leadscrew efficiency (e) and coefficient of friction (μ), see Tables 2 and 3.

Table 2 - Typical leadscrew efficiencies

Type	Efficiency
Ball nut	0.90
ACME (plastic nut)	0.65
ACME (metal nut)	0.40

Table 3 - Leadscrew coefficients of friction

Material	Coefficient
Steel on steel (dry)	0.58
Steel on steel (lubricated)	0.15
Teflon on steel	0.04
Ball bushing	0.003

- Motor speed:

$$S_m = V_l \times P \qquad (16)$$

- Load torque reflected to motor:

$$T_r = \frac{1}{2\pi}\frac{F_l}{Pe} + \frac{1}{2\pi}\frac{F_{pf}}{P} \times \mu \qquad (17)$$

- Friction force:

$$F_f = \mu \times W \qquad (18)$$

- Friction torque:

$$T_f = \frac{1}{2\pi}\frac{F_f}{Pe} \qquad (19)$$

- Total inertia:

$$J_t = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 + J_{ls} + J_m \qquad (20)$$

Example: A 200 lb load is positioned by a 44 in. long leadscrew with a 0.5 in. radius and a 5 rev/in. pitch.
The reflected load inertia is:

$$J_l = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 = \frac{200}{386}\left(\frac{1}{2\pi 5}\right)^2 = 0.00052 \text{ lb–in–sec}^2$$

Leadscrew inertia is based on the equation for inertia of a cylinder:

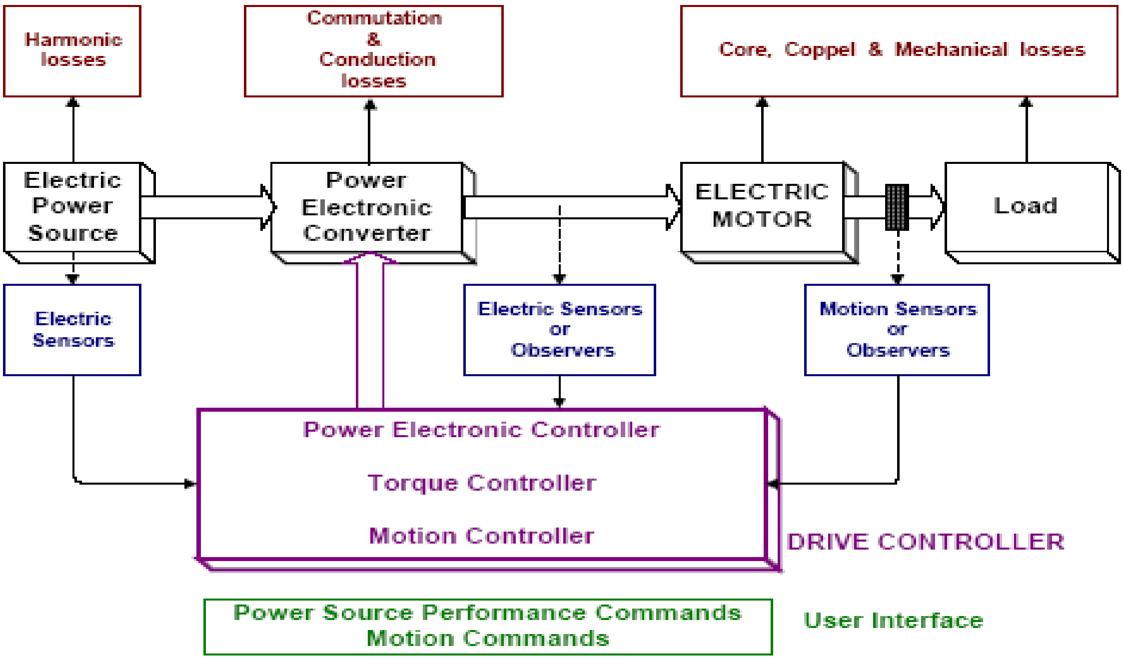
$$J_{ls} = \frac{\pi L \rho R^4}{2g} = \frac{\pi \times 44 \times 0.28 \times 0.5^4}{2 \times 386} = 0.00313 \text{ lb–in–sec}^2$$

Total inertia to be connected to the motor shaft is:

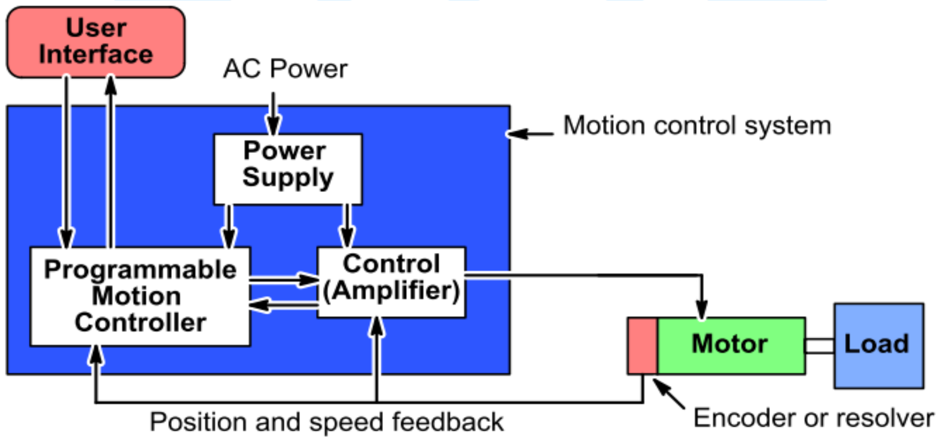
$$J = J_l + J_{ls} = 0.00052 + 0.00313 = 0.00365 \text{ lb–in–sec}^2$$

General structure of a motion control system

Fig. 7(a) shows the general structure of a motion control system. As shown, there are several blocks. The motor is the most important block as its choice significantly affects the correctness of the motion control processes. In addition, the choice of the correct motor is highly dependent on the application type. After selecting the motor, a particular power electronic converter is specified, and then particular algorithms of the power converter, torque control and motion control end up as selected. Other important elements are the sensor and interfaces.



(a)



(b)

Fig. 7: General structure of a motor control system

Power converter. All AC and DC drives use power semiconductor devices to convert and control electrical power. The devices operate in the switching mode (either ON -OFF states), which cause the losses to be reduced, and energy conversion efficiency to be improved. The Power Converter built up with the power semiconductor devices modifies the electric power from the mains to another voltage-frequency relationship able to supply the electric motor as control loop decides.

Motion controllers. Motion controllers include all the closed loops and related controllers that drive the motor to the desired reference (Fig. 1), being the most important the torque controller. Many adjustable-speed drive (ASD) applications require medium- or high-bandwidth torque control in order to achieve adequate control performance. What this means is that if a drive system can function as a controllable source of torque, with fast dynamic response, it should be able to implement the desired motion control operation.

The right motor and control for any electromechanical positioning application can be determined based on the drive mechanics presented in the previous section. Once the mechanics of the application have been analyzed, and the friction and inertia of the load are known, the next step is to determine the torque levels required. Then, a motor can be sized to deliver the required torque and the control sized to power the motor. If friction and inertia are not properly determined, the motion system will either take too long to position the load, it will burn out, or it will be unnecessarily expensive.

In a basic motion control system, Fig. 7(b), the load represents the mechanics being positioned. The load is coupled or connected through one of the mechanical linkages described previously. The motor may be a traditional Permanent Magnet Direct Current (PMDC) servo motor, a vector motor, or a brushless servo motor. Motor starting, stopping and speed are dictated by the control (or amplifier), which takes a low level incoming command signal and amplifies it to a higher power level for driving the motor.

The programmable motion controller is the brain of the motion system. The motion controller is programmed to accomplish a specific task for a given application. This controller reads a feedback signal to monitor the position of the load. By comparing a preprogrammed, "desired" position with the feedback "actual" position, the controller can take action to minimize an error between the actual and desired load positions.

Overview of popular types of motors

An overview of the most popular electric motors used in industrial applications, and positioning systems is presented in this section. These motors are the brushed permanent magnet DC motors, brushless DC motors, stepper motors, synchronous motors (SMs), and AC induction (or asynchronous) motors.

Brushed DC motor systems

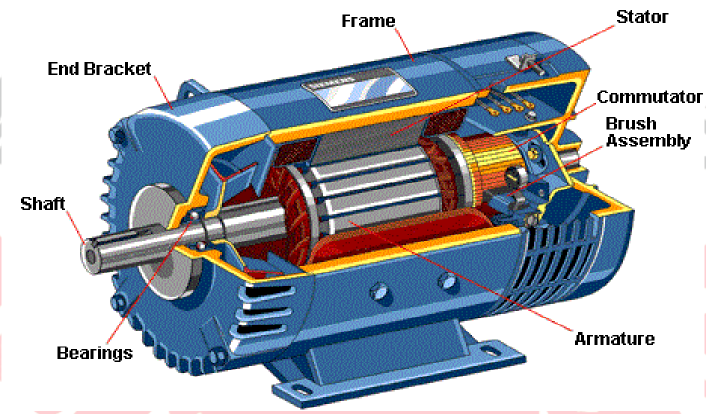
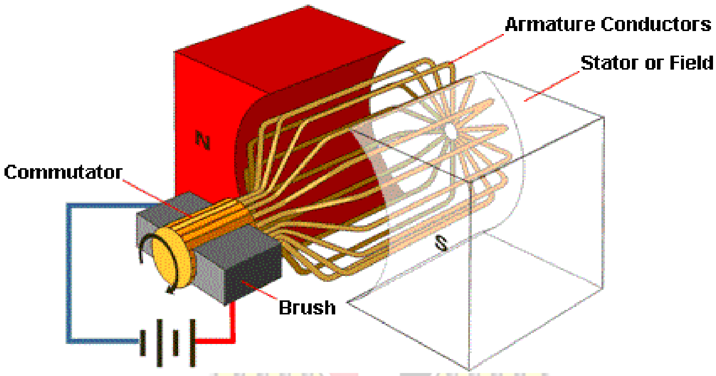
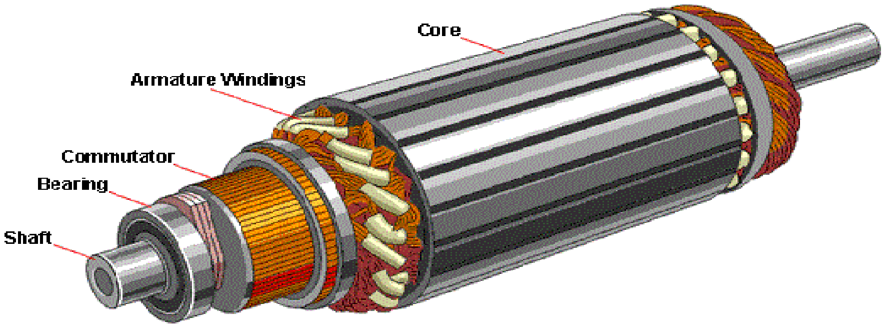


Fig. 8: CAD Drawing of DC motor with cut-away

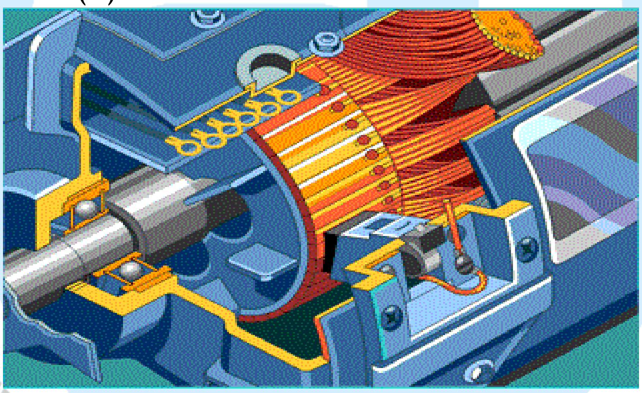
Fig. 8 illustrates a cut-away of the brushed DC motor, while Fig. 9 illustrates its main components. These main components are the armature winding (on the rotor and attached to the output shaft), the field winding (on the rotor and attached to the motor's frame), and commutator and brushes which are used to connect the armature to the input electric power source.



(a) Schematic diagram of brushed DC motor with permanent magnet field

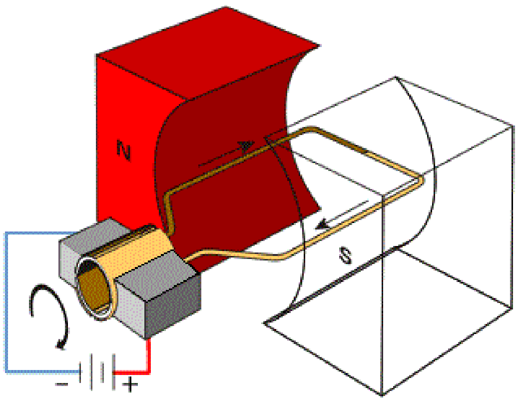


(b) Detailed view of the Armature

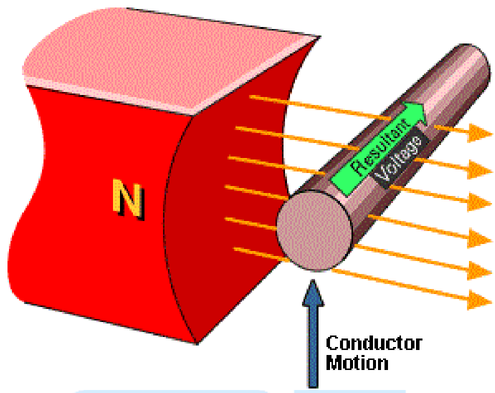


(c) Close-up view of the Commutator and brushes
Fig. 9: Main components of brushed DC motors

The operation of DC motors involves two basic actions; the torque production, and the counter-electromotive force (CEMF), or back emf. The torque is defined as that force which tends to produce and maintain rotation. The function of torque in a DC motor is to provide the mechanical output or drive the piece of equipment that the DC motor is attached to. When a voltage is applied to a motor, current will flow through the field winding, establishing a magnetic field. Alternatively, the magnetic field can be produced by permanent magnets as shown in Fig. 10. The current will also flow through the armature winding, from the negative brush to the positive brush as shown in Fig. 10(a).



(a) Torque production



(b) Back emf

Fig. 10: Concepts of operation of DC motors

Since the armature is a current carrying conductor in a magnetic field, the conductor has a force exerted on it, tending to move it at right angles to that field. Using the left hand rule for current carrying conductors, you will see that the magnetic field on one side is strengthened at the bottom, while it is weakened on the other side. Using the right-hand rule for motors, we can see that there is a force exerted on the armature which tends to turn the armature in the counter-clockwise direction. The sum of the forces, in pounds, multiplied by the radius of the armature, in feet, is equal to the torque developed by the motor in pound-feet (1b - ft).

It is evident from Fig. 10 that if the armature current is reversed, but the field is the same, torque will be developed in the opposite direction. Likewise, if the field polarity is reversed and the armature remained the same, torque will also be developed in the opposite direction.

The force that is developed on a conductor of a motor armature is due to the combined action of the magnetic fields. The force developed is directly proportional to the strength of the main field flux and the strength of the field around the armature conductor. As we know, the field strength around each armature conductor depends on the amount of current flowing through the armature conductor. Therefore, the torque which is developed by the motor can be determined using the following equation:

$$T = K\Phi I_a$$

where

T = torque, lb-ft
K = a constant depending on physical size of motor
Φ = field flux, number of lines of force per pole
I_a = armature current

A generator action is developed in every motor. When a conductor cuts lines of force, an emf is induced in that conductor. The current to start the armature turning will flow in the direction determined by the applied DC power source. After rotation starts, the conductor cuts lines of force. By applying the left-hand rule for generators, the emf that is induced in the armature will produce a current in the opposite direction. The induced emf, as a result of motor operation, is called counter-electromotive force (CEMF), or back emf. Since the CEMF is generated by the action of the armature cutting lines of force, the value of CEMF will depend on field strength and armature speed, as shown in the following equation:

$$E_{CEMF} = K\Phi N$$

where

E_{CEMF} = counter EMF
K = constant
Φ = field flux strength
N = speed of the armature

The CEMF opposes the applied voltage and functions to lower armature current. The effective voltage acting in the armature of a motor is the applied voltage, minus the CEMF. Armature current can be found by using Ohm's law,

$$I_a = \frac{E_t - E_{CEMF}}{R_a}$$

where

I_a = armature current
E_t = terminal voltage
E_{CEMF} = counter EMF
R_a = armature resistance

The field of a DC motor is varied using external devices, usually field resistors. For a constant applied voltage to the field (E), as the resistance of the field (R_f) is lowered, the amount of current flow through the field (I_f) increases as shown by Ohm's law in the following equation:

$$\uparrow I_f = \frac{\overset{\leftrightarrow}{E}}{\downarrow R_f}$$

An increase in field current will cause field flux (Φ_f) to increase. Conversely, if the resistance of the field is increased, field flux will decrease. If the field flux of a DC motor is decreased, the motor speed will increase. The reduction of field strength reduces the CEMF of the motor, since fewer lines of flux are being cut by the armature conductors, as shown in the following equation:

$$\downarrow E_{CEMF} = \vec{K}\,\overset{\downarrow}{\Phi_F}\,\vec{N}$$

A reduction of CEMF allows an increase in armature current as shown in the following equation:

$$\uparrow I_a = \frac{\overset{\rightarrow}{E_t} - \overset{\downarrow}{E_{CEMF}}}{\overset{\rightarrow}{R_a}}$$

This increase in armature current causes a larger torque to be developed; the increase in armature current more than offsets the decrease in field flux as shown in the following equation:

$$\uparrow T = \vec{K}\,\overset{\downarrow}{\Phi_F}\,\overset{\uparrow}{I_a}$$

This increased torque causes the motor to increase in speed.

$$\uparrow T \propto N\uparrow$$

This increase in speed will then proportionately increase the CEMF. The speed and CEMF will continue to increase until the armature current and torque are reduced to values just large enough to supply the load at a new constant speed.

There are many types of DC motors found in the industry today. Each type contains various characteristics that make it desirable for certain applications. Fig. 11 shows a widely used classification of DC motor types.

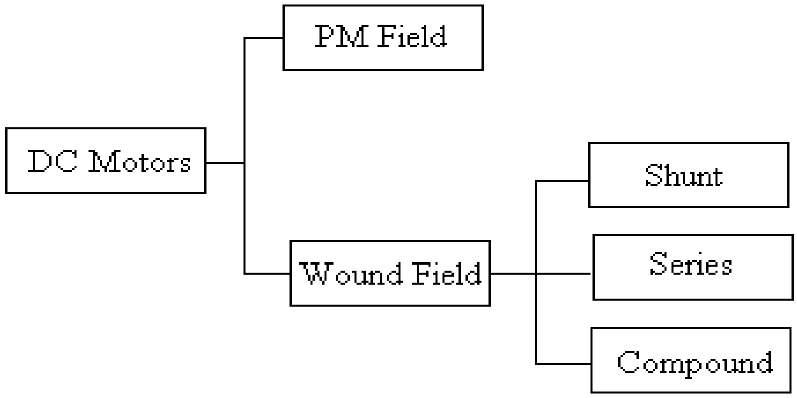


Fig. 11: Types of brushed DC motors

This classification is based on the method of connecting the field and armature circuits in a DC motor as shown in Fig. 12. The circular symbol represents the armature circuit, and the squares on the side of the circle represent the brush commutator system. The direction of the arrows indicates the direction of the magnetic fields.

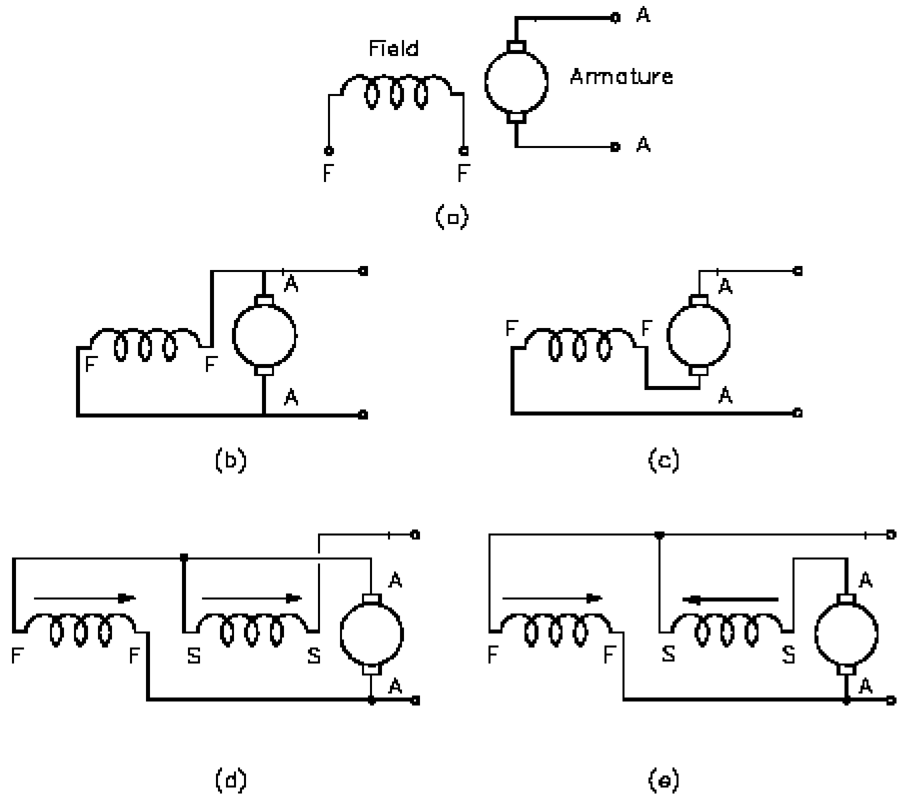


Fig. 12: Connections of wound field brushed DC motors

The circular symbol represents the armature circuit, and the squares on the side of the circle represent the brush commutator system. The direction of the arrows indicates the direction of the magnetic fields. Fig. 12(a) shows an externally-excited (or Separately-excited) DC motor. This type of DC motor is constructed such that the field is not connected to the armature. This type of DC motor is not normally used. Fig. 12(b) shows a shunt DC motor. The motor is called a "shunt" motor because the field is in parallel, or "shunts" the armature. Fig. 12(c) shows a series DC motor. The motor field windings of a series motor are in series with the armature. Fig. 12(d) and Fig. 12(e) show a compounded DC motor. A compounded DC motor is constructed so that it contains both a shunt and a series field. Fig. 12(d) is called a "cumulatively-compounded" DC motor because the shunt and series fields are aiding one another. Fig. 12(e) is called a "differentially-compounded" DC motor because the shunt and series field oppose one another. Table 4 shows the torque-speed characteristics of DC motors considering various connections.

The speed-torque relationship for a typical shunt-wound motor is shown in Fig. 13. A shunt-wound DC motor has a decreasing torque when speed increases. The decreasing torque vs. Speed is caused by the armature resistance, voltage drop and armature reaction. At a value of speed near 2.5 times the rated speed, armature reaction becomes excessive, causing a rapid decrease in field flux, and a rapid decline in torque until a stall condition is reached. The characteristics of a shunt-wound motor gives it very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as the load is increased. Shunt-wound motors are used in industrial and automotive applications where precise control of speed and torque are required.

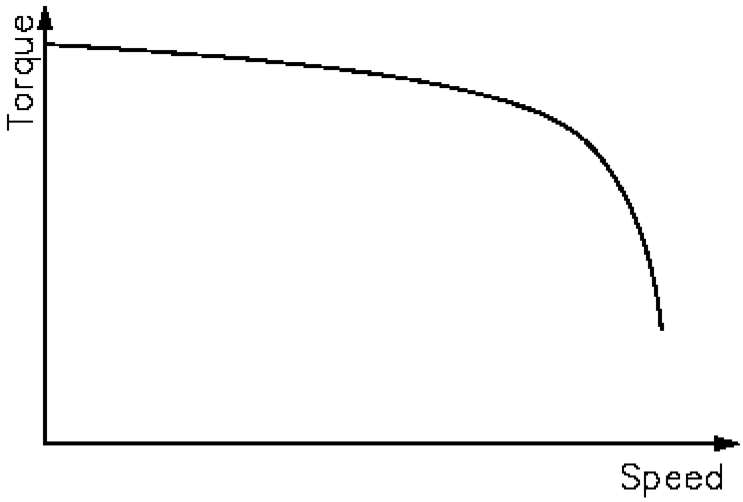


Fig. 13: Torque-speed characteristics of shunt wound DC motor

Now, consider the series connected DC motor. Since the armature and field in a series-wound motor are connected in series, the armature and field currents become identical, and the torque can be expressed as shown in the equation:

$$T = KI_a^2$$

The torque vs. speed characteristics of a series-wound motor with a constant voltage source are shown in Fig. 14. As the speed decreases, the torque for a series-wound motor increases sharply. As the load is removed from a series motor, the speed will increase sharply. For these reasons, series-wound motors must have a load connected to prevent damage from high speed (or run away) conditions.

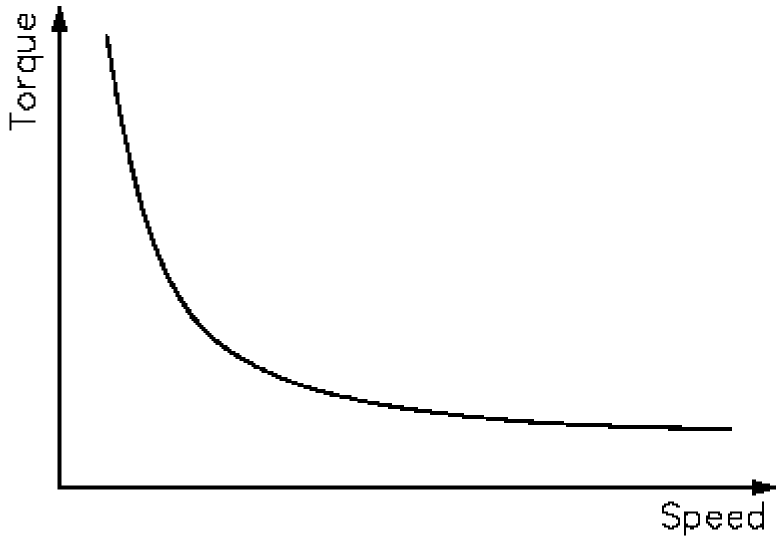


Fig. 14: Torque-speed characteristics of series-wound DC motor

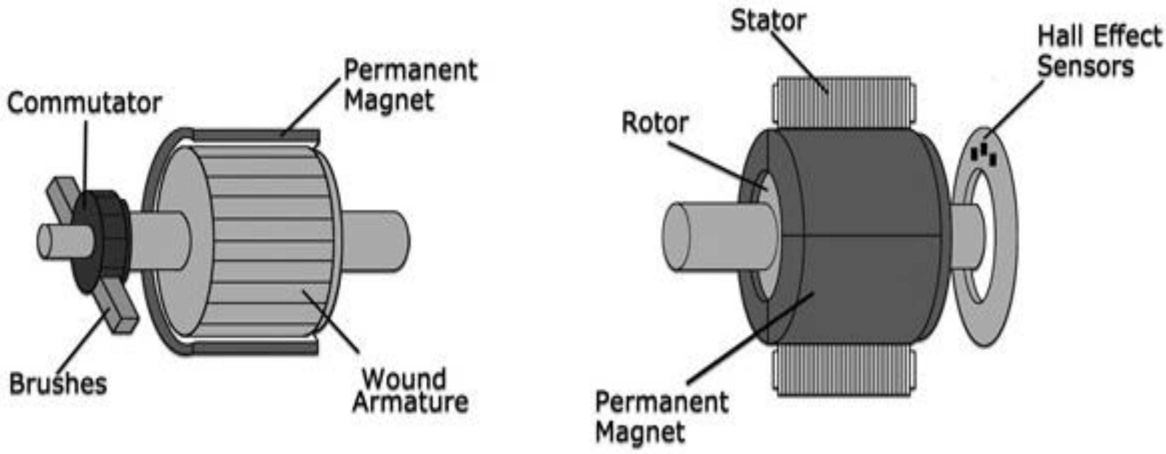
In comparison with a shunt connected motor, the advantage of a series-wound motor is that it develops a large torque, and can be operated at low speed. It is a motor that is well-suited for starting heavy loads; it is often used for industrial cranes and winches where very heavy loads must be moved slowly and lighter loads moved more rapidly.

The compounded motor is desirable for a variety of applications because it combines the characteristics of a series-wound motor and a shunt-wound motor. The compounded motor has a greater torque than a shunt motor due to the series field; however, it has a fairly constant speed due to the shunt field winding. Loads such as presses, shears, and reciprocating machines are often driven by compounded motors.

Brushless DC Motors

Although the name implies a DC motor, it is actually an AC motor. Concentrated coil windings on the stator work in conjunction with surface mounted magnets on the rotor to generate a nearly uniform flux density in the air gap. This permits the stator coils to be driven by a constant DC voltage (hence the name brushless DC), which is simply switched from one stator coil to the next. This process (referred to as *commutation*) must be electronically synchronized to the rotor angular position, and results in an AC voltage waveform which resembles a trapezoidal shape. Since there is no brushes or commutator, the BLDC motor does not exhibit the arcing problems associated with a brushed DC motor. Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors), or synchronous DC motors.

The advantages of a brushless motor over brushed motors (see Fig. 15) are high power to weight ratio, high speed, and electronic control. Brushless motors find applications in such places as computer peripherals (disk drives, printers), handheld power tools, and vehicles ranging from model aircraft to automobiles.



Brushed DC Motor Brushless DC Motor

Fig. 15: Constructions brushed and brushless DC motors

In brushed motors, invented in the 19th century, this is done with a rotary switch on the motor's shaft called a commutator; see Fig. 9. It consists of a rotating cylinder divided into multiple metal contact segments on the rotor. The segments are connected to wire the electromagnet windings on the rotor. Two or more stationary contacts called "brushes", made of a soft conductor like the graphite press against the commutator, making sliding electrical contact with successive segments as the rotor turns, providing electric current to the windings. Each time the rotor rotates by 180° the commutator reverses the direction of the electric current applied to a given winding, so the magnetic field creates a torque in one direction. The commutator has many engineering disadvantages that have led to the decline in use of brushed motors. These disadvantages include,

- The friction of the brushes sliding along the rotating commutator segments causes power losses that can be significant in a low power motor.
- The soft brush material wears down due to friction, creating dust, and eventually the brushes must be replaced. This makes commutated motors unsuitable for low particulate or sealed applications like hard disk motors.
- The resistance of the sliding brush contact causes a voltage drop in the motor circuit called brush drop which consumes energy.
- The repeated abrupt switching of the current through the inductance of the windings causes sparks at the commutator contacts. These are a fire hazard in explosive atmospheres, and create electronic noise, which can cause electromagnetic interference in nearby microelectronic circuits.

During the last hundred years high power DC brushed motors, once the mainstay of the industry, were replaced by alternating current (AC) synchronous motors. Today brushed motors are only used in low power applications or where only DC is available, but the above drawbacks limit their use even in these applications. Brushless motors were invented to solve these problems.

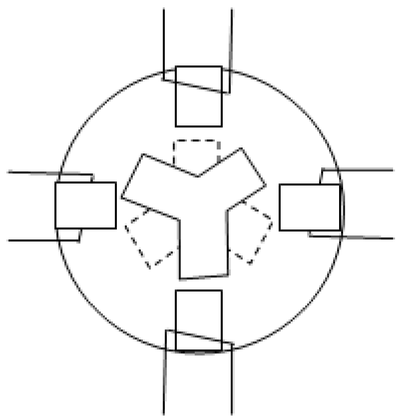
The development of semiconductor electronics in the 1970s allowed the commutator and brushes to be eliminated in DC motors. In brushless DC motors, an electronic servo system replaces the mechanical commutator contacts. An electronic sensor detects the angle of the rotor, and controls semiconductor switches such as transistors which switch current through the windings, either reversing the direction of the current, or in some motors turning it off, at the correct time each 180° shaft rotation so the electromagnets create a torque in one direction. The elimination of the sliding contact allows brushless motors to have less friction and longer life; their working life is only limited by the lifetime of their bearings.

Stepper motors

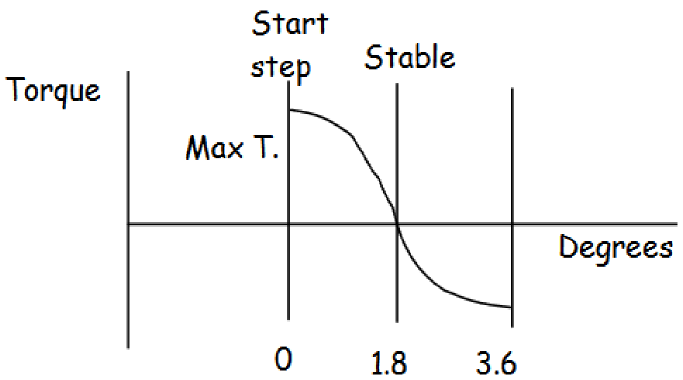
Most stepper motors or step motors or stepping motors are basically brushless DC electric motors that divide a full rotation into a number of equal steps (Fig. 16). The motor's position can then be commanded to move and hold on one of these steps without any position sensor for feedback (an open-loop controller), as long as the motor is carefully sized to the application in respect to torque and speed.

Computer controlled stepper motors are a type of motion-control positioning system. They are typically digitally controlled as part of an open loop system for use in holding or positioning applications.

A typical step motor has 200 full step positions. Thus, the typical stepper will move 1.8 degrees in one step. When the stator portion of the stepper makes a step (but prior to the rotor actually moving), the stepper sees its maximum torque. As the rotor moves under the influence of this torque, the torque drops to a zero value when the rotor reaches the end of its step (1.8 degrees). This results in a static torque curve that may look something like that shown in Fig. 16(b). The rotor on a step motor could lag commanded motion by as much as 1.8 degrees during an acceleration phase, or lead by as much as 1.8 degrees during deceleration. Driving the motor at a step speed near its natural frequency can greatly increase the oscillations during response. The natural frequency of the motor depends on the stiffness (electro-magnetic field) and rotational inertia. Higher inertia will decrease the natural frequency of the system and provide more separation between typical driving frequencies and ωn. Typical ωn for an unloaded stepper may be 100-200 Hz. An additional consideration in driving steppers is the acceleration profile. Remember that the maximum torque of the system cannot be exceeded. Therefore, to operate at a desired rotation or slew rate, the motor must be started (and stopped) in a profiled manner, approaching the desired speed such that the motor is not driven past maximum acceleration.



(a) Structure



(b) Static torque curve

Fig. 16: Stepper motor

In the field of lasers and optics stepper motors are frequently used in precision positioning equipment such as linear actuators, linear stages, rotation stages, goniometers (a device used to rotate an object precisely, within a small angular range, about a fixed axis in space.), and mirror mounts. Other uses are in packaging machinery, and positioning of valve pilot stages for fluid control systems. Commercially, stepper motors were and are used in floppy disk drives, flatbed scanners, computer printers, plotters, slot machines, image scanners, compact disc drives, intelligent lighting, camera lenses, CNC machines and, more recently, in 3D printers.

AC Motors (Induction, and Synchronous)

AC motors are the most commonly used prime mover in industry. The classification of the types of ac motors commonly used in industrial applications is shown in Fig. 17.

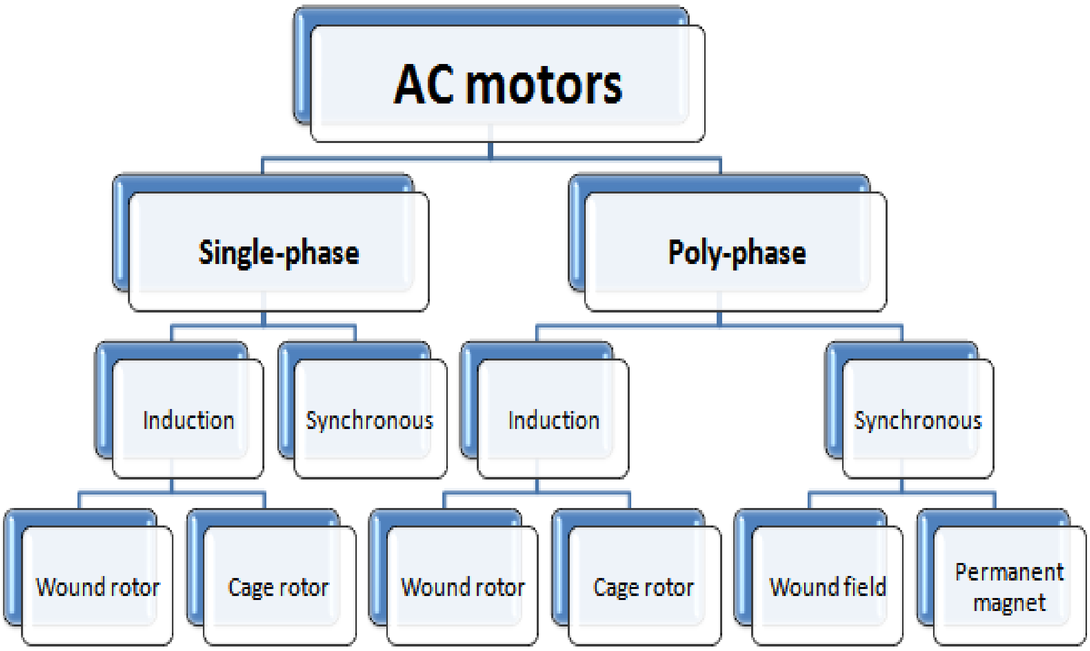
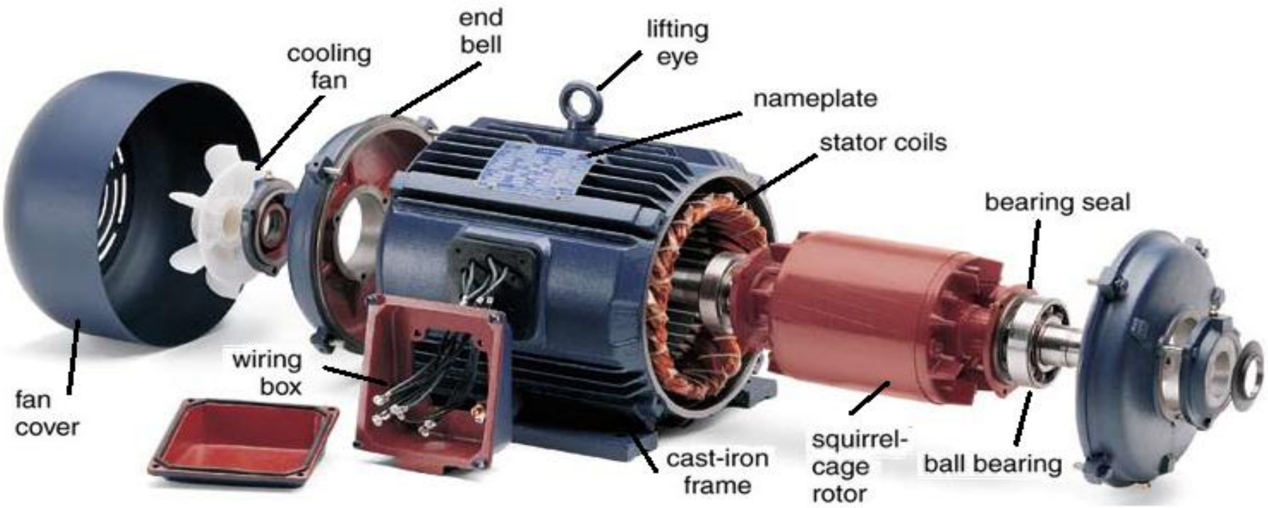


Fig. 17: Classification of AC motors

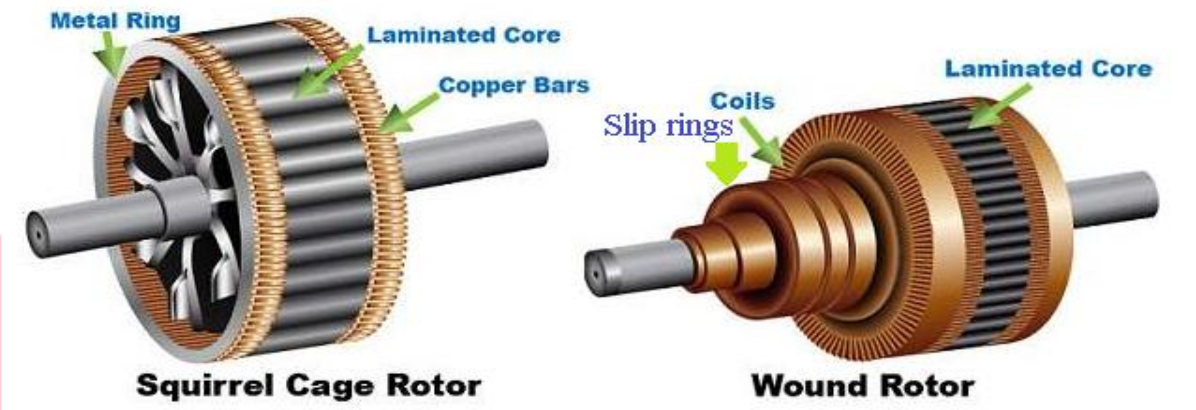
Single-phase AC motors occupy the low end of the horsepower spectrum and are offered commercially up to about 5 hp. Single-phase synchronous motors are only used below about 1/10 of a horsepower. Typical applications are timing and motion control, where low torque is required at fixed speeds. Single-phase induction motors are used for operating household appliances and machinery from about 1/3 to 5 hp.

Poly-phase AC motors are primarily three-phase and are by far the largest electric prime mover in all of industry. They are offered in ranges from 5 up to 50,000 hp and account for a large percentage of the total motor industry in the world. In number of units, the three-phase squirrel cage induction motor is the most common (see Fig. 18). It is commercially available from 1 hp up to several thousand horsepower and can be used on conventional ac power or in conjunction with adjustable speed ac drives. Fans, pumps, and material handling are the most common applications.

When the torque-speed characteristics of a conventional AC induction motor need to be modified, the wound rotor induction motor is used (see Fig. 18). These motors replace the squirrel cage rotor with a wound rotor and slip rings. External resistors are used to adjust the torque-speed characteristics for speed control in such applications as ac cranes, hoists, and elevators.



(a) Assembly with squirrel-cage rotor



(b) Rotor types

Fig. 18: Three-phase induction motor

Three-phase synchronous motors can be purchased with Permanent Magnet (PM) fields up to about 5 hp and are used for applications such as processing lines and transporting film and sheet materials at precise speeds. In the horsepower range above about 10,000 hp, three-phase synchronous motors with wound fields (see Fig. 19) are used rather than large squirrel cage induction motors. Starting current and other characteristics can be controlled by the external field exciter. Three-phase synchronous motors with wound fields are available up to about 50,000 hp.

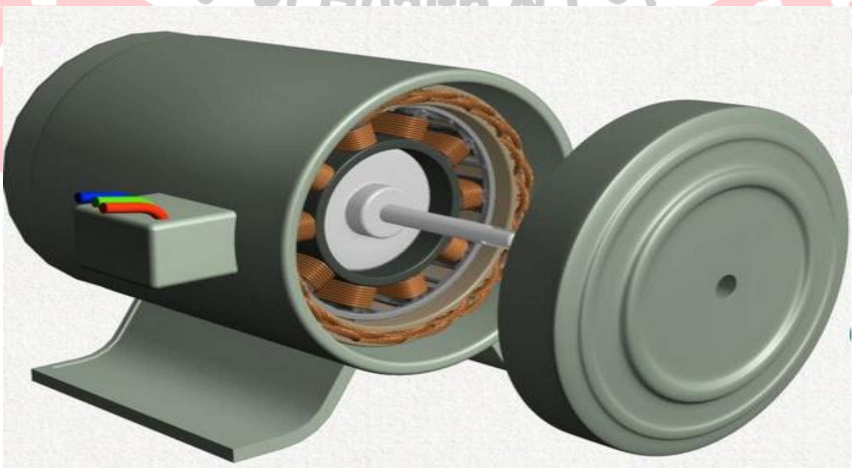


Fig. 19: Wound field three-phase synchronous motor

The speed of an AC motor is determined for the most part by two factors: The applied frequency and the number of poles.

$$N = \frac{120f}{P}$$

Where:
N = RPM
f = frequency
P = number of poles

Some motors such as in a typical paddle fan have the capability to switch poles in and out to control speed. In most cases however, the number of poles is constant and the only way to vary the speed is to change the applied frequency. Changing the frequency is the primary function of an AC drive. However, one must consider that the impedance of a motor in determined by the inductive reactance of the windings.

$$X_L = 2\pi fL$$

Where:
X_L = Inductive reactance in Ohms
f = Line frequency
L = inductance

This means that if the frequency applied to the motor is reduced, the reactance and therefore impedance of the motor is reduced. In order to keep current under control we must lower the applied voltage to the motor as the frequency is reduced. This is where we get the phrase “volts per hertz”. The most common method of controlling the applied voltage and frequency is with a pulse width modulated “PWM” technique. With this method, a DC voltage is applied to the motor windings in time controlled pulses in order to achieve current that approximates a sine wave of the desired frequency. IGBTs or Isolated Gate Bipolar Transistors are the latest technology and offer the ability to switch the PWM pulses very fast. This allows several thousand pulses to be applied in one cycle of the applied motor frequency. More pulses in a given cycle result in a smoother current waveform and better motor performance.

Motor Drive – Introduction

Defining a drive can be a bit tricky. Some drives are wholly incorporated into the controller, so that the profile generation takes place in the controller as well as the torque command for the motor. On the other hand, a drive can also refer to the specific power electronic circuitry needed to drive the motor (see Fig. 7). Electric motors that drive industrial machines need some way to control motor speed, and at its most basic level, a motor drive controls the speed of the motor.

Some manufacturers refer to a controller and motor together as a drive system. However, from the electrical side of things, the drive is often specifically the electrical components that make up the variable frequency inverter itself. So drives are the interface between the control signals and the motor and include power electronic devices such as SCRs (silicon controlled rectifiers), transistors, and thyristors.

Matching the correct drive to the type of motor in an application is critical for getting the best fit for torque, speed, and efficiency. There are a wide range of drives available depending on the needs of the specific application and motor type. In general though, drive types typically fall into two categories; dc and ac drives.

DC drives control dc motors. A basic dc drive is similar in operation to an ac drive in that the drive controls the speed of the motor. For dc motor control, a common method is a thyristor-based control circuit. These circuits consist of a thyristor bridge circuit that rectifies ac into dc for the motor armature. And varying the voltage to the armature controls the motor's speed. Detailed presentation of the drives of various motor types is presented in the next chapter; however, this section provides a conceptual overview of various motor drives, their selection, and their applications.

Selection of motor drives

Digital microprocessor-controlled power converter technology, both for DC and AC drives, has now reached a level of technical sophistication which (in purely technological terms) enables almost any drive job to be handled both with DC and AC drives. Nevertheless, the conventional DC drive will continue to play an important role, for technical and physical reasons alike, when dynamic drives with a constant load torque and limited requirements for overload withstand capability throughout a large speed setting range are involved.

The first thing a user should do is to objectively check out the options currently available in DC and AC drive technology for his/her specific requirements/processes. The main criteria applying for this check are:

1. Total purchase costs for the Variable Speed Drive (VSD) system(s).
2. Running operating costs: maintenance process costs/efficiency levels, space requirements, etc.
3. Technological/Innovative aspects: dynamic response, ramp-up time; 4-quadrant operation; emergency stop, etc.
4. Operational dependability, availability of the drives: international regulations like IEC, EN, CE-EMC; CSA, UL, etc. environmental conditions; degrees of protection service; "on-the-spot" repairs
5. Any effects on the surroundings: supply network Electromagnetic Compatibility (EMC).
6. Required space for converter and motor.
7. Heat dissipation from the control room.

For general motor evaluation, many users adopt the following rather simplistic view:

1. The brushed DC motor is complicated and requires a lot of maintenance, which makes it expensive to run; it also has a lower degree of protection.
2. The AC motor, on the other hand, is simple and sturdy, does not need much maintenance, is therefore less expensive, and possesses a higher degree of protection.

From maintenance point of view, currently, depending on the application involved, the useful lifetime of brushes in DC motors is at approx. 7000 ... 12000 hours (h), carbon brushes and optimized field supply units used. Depending on the mechanical conditions involved, the re-lubrication intervals for the bearings of DC/AC motors may be shorter than the useful lifetime of the brushes in DC motors.

Move profile

A move profile defines the desired acceleration rate, run time, speed, and deceleration rate of the load. For example, suppose with a system at rest (time = 0, Fig. 20), the motion controller issues a command to the motor (through the control) to start motion. At t = 0, with full power supply voltage and current applied, the motor has not yet started to move. At this instant, the feedback signal is zero, but the error signal is large. As friction and torque are overcome, the motor and load begin to accelerate. As the motor approaches the commanded speed, the error signal is reduced and, in turn, voltage applied to the motor is reduced. As the system stabilizes at running speed, only nominal power (voltage and current) are required to overcome friction. At t = 1, the load approaches the desired position and begins to decelerate.

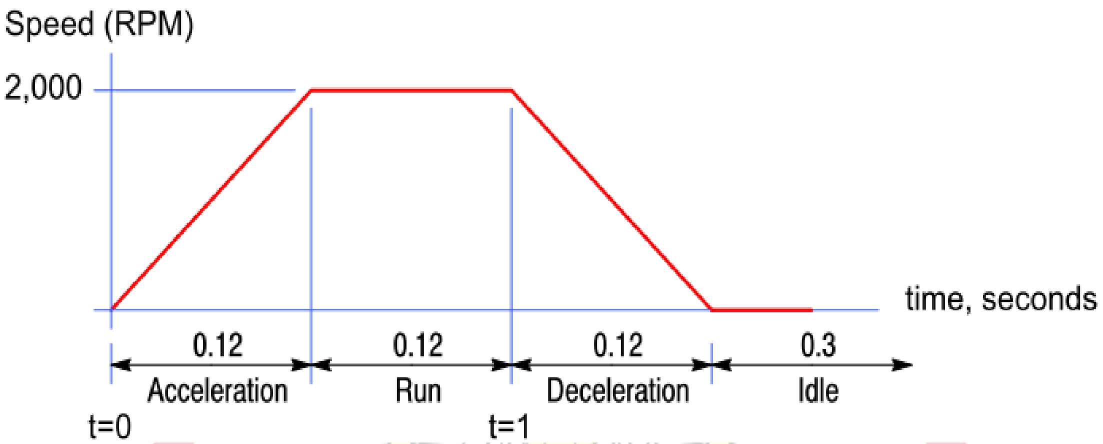


Fig. 20: Move profile

Determining acceleration rate is the first step. For example, with a movement profile as shown in Fig. 20, the acceleration rate can be determined from the speed and acceleration time. (Dividing the motor speed expressed in RPM by 9.55 converts the speed to radians per second.)

$$\alpha_{acc} = \frac{S_m}{9.55t_{acc}} = \frac{2000}{9.55 \times 0.12} = 1745.2 \text{ rad./sec}^2 \quad (21)$$

Acceleration torque

The torque required to accelerate the load and overcome mechanical friction is:

$$T_{acc} = J_t(\alpha_{acc}) + T_f \qquad (22)$$

$$T_{acc} = (J_l + J_{ls} + J_m)(\alpha_{acc}) + T_f \qquad (23)$$

Example: Our application requires moving a load with a leadscrew, Fig. 6. The load parameters are: Weight of load (Wlb) = 200 lb, leadscrew inertia (Jls) = 0.00313 lb-in-sec2, friction torque (Tf) = 0.95 lb-in, acceleration rate (α acc) =1745.2 rad./ sec2. Typical motor parameters are: motor inertia (Jm) = 0.0037 lb-in-s2, continuous stall torque (Ts) = 14.4 lb-in, torque constant (Kt) = 4.8 lb-in/A and motor resistance (Rm) = 4.5 ohms. Acceleration torque can be determined by substituting in Equation (23) as T_{acc} = (.00052 +.00313 +.0037)1745.2 + 0.95 = 13.77 lb-in.

Duty cycle torque

In addition to acceleration torque, the motor must be able to provide sufficient torque over the entire duty cycle or move profile. This includes a certain amount of constant torque during the run phase, and a deceleration torque during the stopping phase. Running torque is equal to friction torque (T_f), in our example, 0.95 lb-in During the stopping phase, deceleration torque is given by:

$$T_{dec} = -J_t(\alpha_{acc}) + T_f \qquad (24)$$

In the example,

$$T_{dec} = -(.00052 + .00313 + .0037)1745.2 + 0.95 = -11.87 \text{ lb-in}$$

Now, the root mean squared (RMS) value of torque required over the move profile can be calculated using:

$$T_{RMS} = \sqrt{\frac{T_{acc}^{\,2}(t_{acc}) + T_{run}^{\,2}(t_{run}) + T_{dec}^{\,2}(t_{dec})}{t_{acc} + t_{run} + t_{dec} + t_{idle}}} \qquad (25)$$

In the example,

$$T_{RMS} = \sqrt{\frac{(13.77)^2(.12) + (.95)^2(.12) + (11.87)^2(.12)}{.12 + .12 + .12 + .3}} = 7.75 \text{ lb–in}$$

The motor selected for this application can supply a continuous stall torque of 14.4 lb-in, which is adequate for the application.

Control requirements

Determining a suitable control (amplifier) is the next step. The control must be able to supply sufficient accelerating current (I_{acc}), as well as continuous current (I_{RMS}) for the application's duty cycle requirements. The required acceleration current that must be supplied to the motor is:

$$I_{acc} = \frac{T_{acc}}{K_t} \qquad (26)$$

$$= \frac{13.77}{4.8} = 2.86\text{A}$$

Current over the duty cycle, which the control must be able to supply to the motor, is:

$$I_{RMS} = \frac{T_{RMS}}{K_t} \qquad (27)$$

$$= \frac{7.75}{4.8} = 1.61\text{A}$$

Power requirements

The control must supply sufficient power for both the acceleration portion of the movement profile, as well as for the overall duty cycle requirements. The two aspects of power requirements include:

1. Power to move the load, "P_{del}" →

$$P_{del} = \frac{T(S_m)(746)}{63,025} \qquad (28)$$

2. Power losses dissipated in the motor, "P_{diss}". Power dissipated in the motor is a function of the motor current. Thus, during acceleration, the value depends on the acceleration current (I_{acc}); and while running, it is a function on the RMS current (I_{RMS}). Therefore, the appropriate value is used in place of "I" in the following equation.→

$$P_{diss} = I^2(R_m) \qquad (29)$$

The sum of these P_{del} and P_{diss} determine total power requirements. In the example, the power required during the acceleration portion of the movement profile is,

$$P_{del} = \frac{13.77(2,000)}{63,025}(746) = 325W$$
$$P_{diss} = (2.86)^2(4.5)(1.5) = 55W$$
$$P = P_{del} + P_{diss} = 325 + 55 = 380W$$

Note: The factor of 1.5 in the P_{diss} calculation is a factor used to make the motor's winding resistance "hot." This is a worst case analysis, assuming the winding is at 155 °C.
The continuous power required for the duty cycle is:

$$P_{del} = \frac{7.75(2,000)}{63,025}(746) = 183W$$
$$P_{diss} = (1.61)^2(4.5)(1.5) = 17W$$
$$P = P_{del} + P_{diss} = 183 + 17 = 200W$$

Chapter 2

Switches, Relays, Contactors, and Ladder Diagrams

Objectives

This chapter provides a detailed presentation of various electromechanical and digital switches, and relays used in control systems. In addition, the chapter introduces the ladder logic and diagrams are specialized schematics commonly used to document industrial control logic systems. The chapter also provides some practical examples of the motor control circuits for various applications, and the fail-safe relay logic design.

Electrical/Electromechanical Switches

An electrical switch is any device used to interrupt the flow of electrons (current) in a circuit. Switches are essentially binary devices: they are either completely on ("closed") or completely off ("open"). There are many different types of switches, and we will explore some of these types in this chapter.

The simplest type of switch is one where two electrical conductors are brought in contact with each other by the motion of an actuating mechanism. Other switches are more complex, containing electronic circuits able to turn on or off depending on some physical stimulus (such as light or magnetic field) sensed. In any case, the final output of any switch will be (at least) a pair of wire-connection terminals that will either be connected together by the switch's internal contact mechanism ("closed"), or not connected together ("open").

Switch Types

Switch types can be subdivided into three groups:

I. Hand switches.
II. Limit switches.
III. Indicating switches.

I. Hand Switches

Any switch designed to be operated manually by a person is generally called a hand switch, and they are manufactured in several varieties; Fig. 1:

1. Toggle Switches

Toggle switches are actuated by a lever angled in one of two or more positions. The common light switch used in household wiring is an example of a toggle switch. Most toggle switches will come to rest in any of their lever positions, while others have an internal spring mechanism returning the lever to a certain normal position, allowing for what is called "momentary" operation.

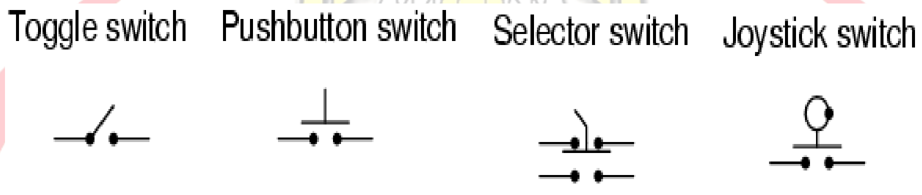


Fig. 1: Hand Type Switches

2. Pushbutton switch

Pushbutton switches are two-position devices actuated with a button that is pressed and released. Most pushbutton switches have an internal spring mechanism returning the button to its "out," or "un-pressed," position, for momentary operation. Some pushbutton switches will latch alternately on or off with every push of the button. Other pushbutton switches will stay in their "in," or "pressed," position until the button is pulled back out. This last type of pushbutton switches usually have a mushroom-shaped button for easy push-pull action.

3. Selector Switch

Selector switches are actuated with a rotary knob or lever of some sort to select one of two or more positions. Like the toggle switch, selector switches can either rest in any of their positions or contain spring-return mechanisms for momentary operation.

4. Joystick switch

A joystick switch is actuated by a lever free to move in more than one axis of motion. One or more of several switch contact mechanisms are actuated depending on which way the lever is pushed, and sometimes by how far it is pushed. The circle-and-dot notation on the switch symbol represents the direction of joystick lever motion required to actuate the contact. Joystick hand switches are commonly used for crane and robot control.

II. Limit Switches

Some switches are specifically designed to be operated by the motion of a machine rather than by the hand of a human operator. These motion-operated switches are commonly called limit switches, because they are often used to limit the motion of a machine by turning off the actuating power to a component if it moves too far. As with hand switches, limit switches come in several varieties; Fig. 2:

Fig. 2: Limit Switches

1. Lever Actuator Limit Switch

These limit switches closely resemble rugged toggle or selector hand switches fitted with a lever pushed by the machine part. Often, the levers are tipped with a small roller bearing, preventing the lever from being worn off by repeated contact with the machine part.

2. Proximity Switch

Proximity switches sense the approach of a metallic machine part either by a magnetic or high-frequency electromagnetic field. Simple proximity switches use a permanent magnet to actuate a sealed switch mechanism whenever the machine part gets close (typically 1 inch or less). More complex proximity switches work like a metal detector, energizing a coil of wire with a high-frequency current, and electronically monitoring the magnitude of that current. If a metallic part (not necessarily magnetic) gets close enough to the coil, the current will increase, and trip the monitoring circuit. The symbol shown here for the proximity switch is of the electronic variety, as indicated by the diamond-shaped box surrounding the switch. A non-electronic proximity switch would use the same symbol as the lever-actuated limit switch. Another form of proximity switch is the optical switch, comprised of a light source and photocell. Machine position is detected by either the interruption or reflection of a light beam. Optical switches are also useful in safety applications, where beams of light can be used to detect personnel entry into a dangerous area.

III. Indicating Switches

In many industrial processes, it is necessary to monitor various physical quantities with switches. Such switches can be used to sound alarms, indicating that a process variable has exceeded normal parameters, or they can be used to shut down processes or equipment if those variables have reached dangerous or destructive levels There are many different types of process switches:

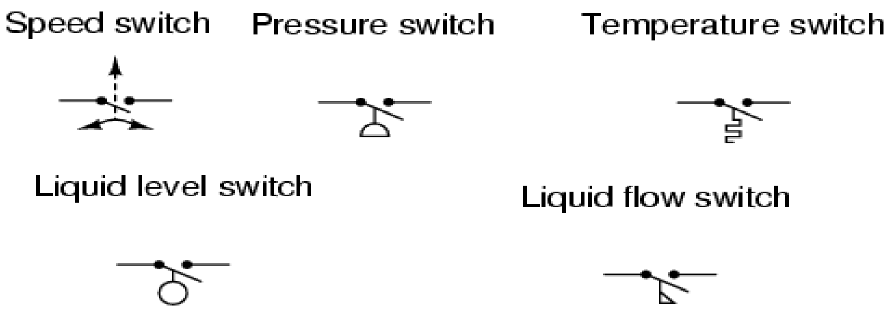


Fig. 3: Indicating Switches

1. Speed Switches

These switches sense the rotary speed of a shaft either by a centrifugal weight mechanism mounted on the shaft, or by some kind of non-contact detection of shaft motion such as optical or magnetic.

2. Pressure Switches

Gas or liquid pressure can be used to actuate a switch mechanism if that pressure is applied to a piston, diaphragm, or bellows, which converts pressure to mechanical force

3. Temperature Switches

An inexpensive temperature-sensing mechanism is the "bimetallic strip:" a thin strip of two metals, joined back-to-back, each metal having a different rate of thermal expansion. When the strip heats or cools, differing rates of thermal expansion between the two metals causes it to bend. The bending of the strip can then be used to actuate a switch contact mechanism. Other temperature switches use a brass bulb filled with either a liquid or gas, with a tiny tube connecting the bulb to a pressure-sensing switch. As the bulb is heated, the gas or liquid expands, generating a pressure increase which then actuates the switch mechanism.

4. Liquid Level Switch

A floating object can be used to actuate a switch mechanism when the liquid level in a tank rises past a certain point. If the liquid is electrically conductive, the liquid itself can be used as a conductor to bridge between two metal probes inserted into the tank at the required depth. The conductivity technique is usually implemented with a special design of relay triggered by a small amount of current through the conductive liquid. In most cases it is impractical and dangerous to switch the full load current of the circuit through a liquid. Level switches can also be designed to detect the level of solid materials such as wood chips, grain, coal, or animal feed in a storage silo, bin, or hopper. A common design for this application is a small paddle wheel, inserted into the bin at the desired height, which is slowly turned by a small electric motor. When the solid material fills the bin to that height, the material prevents the paddle wheel from turning. The torque response of the small motor than trips the switch mechanism.

5. Liquid Flow Switch

Inserted into a pipe, a flow switch will detect any gas or liquid flow rate in excess of a certain threshold, usually with a small paddle or vane which is pushed by the flow. Other flow switches are constructed as differential pressure switches, measuring the pressure drop across a restriction built into the pipe.

Switch Contact Design

A switch can be constructed with any mechanism bringing two conductors into contact with each other in a controlled manner. This can be as simple as allowing two copper wires to touch each other by the motion of a lever, or by directly pushing two metal strips into contact. However, a good switch design must be rugged and reliable, and avoid presenting the operator with the possibility of electric shock.

The conductive parts in a switch used to make and break the electrical connection are called contacts. Contacts are typically made of silver or silver-cadmium alloy, whose conductive properties are not significantly compromised by surface corrosion or oxidation. Gold contacts exhibit the best corrosion resistance, but are limited in current-carrying capacity and may "cold weld" if brought together with high mechanical force. Whatever the choice of metal, the switch contacts are guided by a mechanism ensuring square and even contact, for maximum reliability and minimum resistance.

Contacts such as these can be constructed to handle extremely large amounts of electric current, up to thousands of amps in some cases. The limiting factors for switch contact ampacity are as follows:

1) Heat generated by current through metal contacts (while closed).
2) Sparking caused when contacts are opened or closed.
3) The voltage across open switch contacts (potential of current jumping across the gap).

One major disadvantage of standard switch contacts is the exposure of the contacts to the surrounding atmosphere. In a nice, clean, control-room environment, this is generally not a problem. However, most industrial environments are not this benign. The presence of corrosive chemicals in the air can cause contacts to deteriorate and fail prematurely. Even more troublesome is the possibility of regular contact sparking causing flammable or explosive chemicals to ignite. When such environmental concerns exist, other types of contacts can be considered for small switches. These other types of contacts are sealed from contact with the outside air, and therefore do not suffer the same exposure problems that standard contacts do.

A common type of sealed-contact switch is the mercury switch. Mercury is a metallic element, liquid at room temperature. Being a metal, it possesses excellent conductive properties. Being a liquid, it can be brought into contact with metal probes (to close a circuit) inside of a sealed chamber simply by tilting the chamber so that the probes are on the bottom. Many industrial switches use small glass tubes containing mercury which are tilted one way to close the contact, and tilted another way to open. Aside from the problems of tube breakage and spilling mercury (which is a toxic material), and susceptibility to vibration, these devices are an excellent alternative to open-air switch contacts wherever environmental exposure problems are a concern.

Another sealed-contact type of switch is the magnetic reed switch. Like the mercury switch, a reed switch's contacts are located inside a sealed tube. Unlike the mercury switch which uses liquid metal as the contact medium, the reed switch is simply a pair of very thin, magnetic, metal strips (hence the name "reed") which are brought into contact with each other by applying a strong magnetic field outside the sealed tube. The source of the magnetic field in this type of switch is usually a permanent magnet, moved closer to or further away from the tube by the actuating mechanism. Due to the small size of the reeds, this type of contact is typically rated at lower currents and voltages than the average mercury switch. However, reed switches typically handle vibration better than mercury contacts because there is no liquid inside the tube to splash around.

It is common to find a general-purpose switch contact voltage and current ratings to be greater on any given switch or relay if the electric power being switched is AC instead of DC. The reason for this is the self-extinguishing tendency of an alternating-current arc across an air gap. Because the 50 Hz (or the 60 Hz) power line current actually stops and reverses direction 100 times (or 120 times) per second, there are many opportunities for the ionized air of an arc to lose enough temperature to stop conducting current, to the point where the arc will not re-start on the next voltage peak. DC, on the other hand, is a continuous, uninterrupted flow of electrons which tends to maintain an arc across an air gap much better. Therefore, switch contacts of any kind incur more wear when switching a given value of direct current than for the same value of alternating current. The problem of switching DC is exaggerated when the load has a significant amount of inductance, as there will be very high voltages generated across the switch's contacts when the circuit is opened (the inductor doing its best to maintain circuit current at the same magnitude as when the switch was closed).

With both AC and DC, contact arcing can be minimized with the addition of a "snubber" circuit (a capacitor and resistor wired in series) in parallel with the contact, like this:

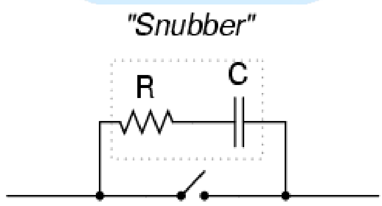


Fig. 4: Snubber circuits

A sudden rise in voltage across the switch contact caused by the contact opening will be tempered by the capacitor's charging action (the capacitor opposing the increase in voltage by drawing current). The resistor limits the amount of current that the capacitor will discharge through the contact when it closes again. If the resistor were not there, the capacitor might actually make the arcing during contact closure worse than the arcing during contact opening without a capacitor! While this addition to the circuit helps mitigate contact arcing, it is not without disadvantage: a prime consideration is the possibility of a failed (shorted) capacitor/resistor combination providing a path for electrons to flow through the circuit at all times, even when the contact is open and current is not desired. The risk of this failure, and the severity of the resulting consequences must be considered against the increased contact wear (and inevitable contact failure) without the snubber circuit.

The use of snubbers in DC switch circuits is nothing new: automobile manufacturers have been doing this for years on engine ignition systems, minimizing the arcing across the switch contact "points" in the distributor with a small capacitor called a condenser. As any mechanic can tell you, the service life of the distributor's "points" is directly related to how well the condenser is functioning.

With all this discussion concerning the reduction of switch contact arcing, one might be led to think that less current is always better for a mechanical switch. This, however, is not necessarily so. It has been found that a small amount of periodic arcing can actually be good for the switch contacts, because it keeps the contact faces free from small amounts of dirt and corrosion. If a mechanical switch contact is operated with too little current, the contacts will tend to accumulate excessive resistance and may fail prematurely! This minimum amount of electric current necessary to keep a mechanical switch contact in good health is called the wetting current.

Normally, a switch's wetting current rating (wetting current is the minimum electric current needing to flow through a contact to break through the surface film resistance; the film of oxidation occurs often in areas with high humidity.) is far below its maximum current rating, and well below its normal operating current load in a properly designed system. However, there are applications where a mechanical switch contact may be required to routinely handle currents below normal wetting current limits (for instance, if a mechanical selector switch needs to open or close a digital logic or analog electronic circuit where the current value is extremely small). In these applications, is it highly recommended that gold-plated switch contacts be specified. Gold is a "noble" metal and does not corrode as other metals will. Such contacts have extremely low wetting current requirements as a result. Normal silver or copper alloy contacts will not provide reliable operation if used in such low-current service!

Contact Normal-State and Make/Break Sequence

Any kind of switch contact can be designed so that the contacts "close" (establish continuity) when actuated, or "open" (interrupt continuity) when actuated. For switches that have a spring-return mechanism in them, the direction that the spring returns it to with no applied force is called the normal position. Therefore, contacts that are open in this position are called normally-open and contacts that are closed in this position are called normally-closed.

For process switches, the normal position, or state, is that which the switch is in when there is no process influence on it. An easy way to figure out the normal condition of a process switch is to consider the state of the switch as it sits on a storage shelf, uninstalled. Here are some examples of "normal" process switch conditions:

- Speed switch: Shaft not turning
- Pressure switch: Zero applied pressure
- Temperature switch: Ambient (room) temperature
- Level switch: Empty tank or bin
- Flow switch: Zero liquid flow

It is important to differentiate between a switch's "normal" condition and its "normal" use in an operating process. Consider the example of a liquid flow switch that serves as a low-flow alarm in a cooling water system. The normal, or properly-operating, condition of the cooling water system is to have fairly constant coolant flow going through this pipe. If we want the flow switch's contact to close in the event of a loss of coolant flow (to complete an electric circuit which activates an alarm siren, for example), we would want to use a flow switch with normally-closed rather than normally-open contacts. When there's adequate flow through the pipe, the switch's contacts are forced open; when the flow rate drops to an abnormally low level, the contacts return to their normal (closed) state. This is confusing if you think of "normal" as being the regular state of the process, so be sure to always think of a switch's "normal" state as that which it's in as it sits on a shelf.

The schematic symbology for switches vary according to the switch's purpose and actuation. A normally-open switch contact is drawn in such a way as to signify an open connection, ready to close when actuated. Conversely, a normally-closed switch is drawn as a closed connection which will be opened when actuated. Note the following symbols:

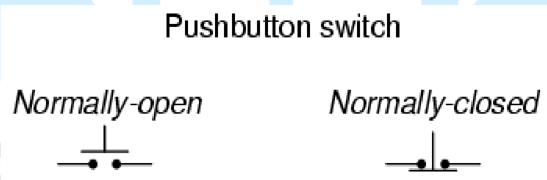


Fig. 5: Pushbutton switches

There is also a generic symbology for any switch contact, using a pair of vertical lines to represent the contact points in a switch. Normally-open contacts are designated by the lines not touching, while normally-closed contacts are designated with a diagonal line bridging between the two lines. Compare the two:

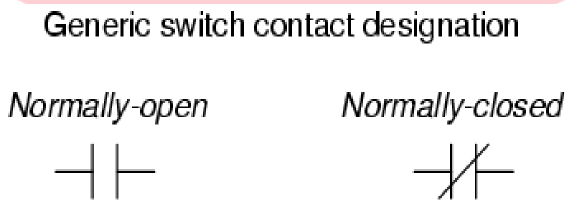
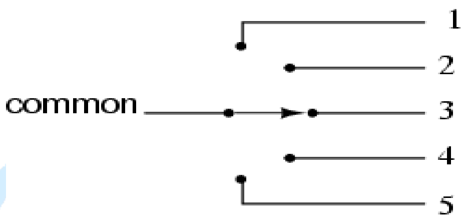


Fig. 6:Switch contact designation

The switch on the left will close when actuated, and will be open while in the "normal" (un-actuated) position. The switch on the right will open when actuated, and is closed in the "normal" (un-actuated) position. If switches are designated with these generic symbols, the type of switch usually will be noted in text immediately beside the symbol. Please note that the symbol on the left is not to be confused with that of a capacitor.

With multiple-position selector switches, another design factor must be considered: that is, the sequence of breaking old connections and making new connections as the switch is moved from position to position, the moving contact touching several stationary contacts in sequence.

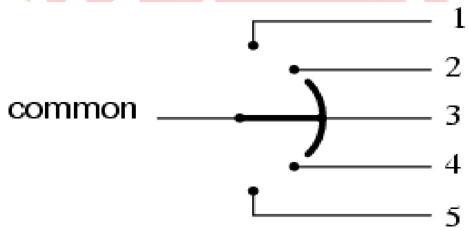


Multiple position selector switch

Fig. 7: Multiple position selector switch

The selector switch shown above switches a common contact lever to one of five different positions, to contact wires numbered 1 through 5. The most common configuration of a multi-position switch like this is one where the contact with one position is broken before the contact with the next position is made. This configuration is called break-before-make. To give an example, if the switch were set at position number 3 and slowly turned clockwise, the contact lever would move off of the number 3 position, opening that circuit, move to a position between number 3 and number 4 (both circuit paths open), and then touch position number 4, closing that circuit.

There are applications where it is unacceptable to completely open the circuit attached to the "common" wire at any point in time. For such an application, a make-before-break switch design can be built, in which the movable contact lever actually bridges between two positions of contact (between number 3 and number 4, in the above scenario) as it travels between positions. The compromise here is that the circuit must be able to tolerate switch closures between adjacent position contacts (1 and 2, 2 and 3, 3 and 4, 4 and 5) as the selector knob is turned from position to position. Such a switch is shown here:



Make-before-break switch

Fig. 8: Make-before-break multiple position selector switch

When movable contact(s) can be brought into one of several positions with stationary contacts, those positions are sometimes called throws. The number of movable contacts is sometimes called poles. Both selector switches shown above with one moving contact and five stationary contacts would be designated as "single-pole, five-throw" switches.

If two identical single-pole, five-throw switches were mechanically ganged together so that they were actuated by the same mechanism, the whole assembly would be called a "double-pole, five-throw" switch:

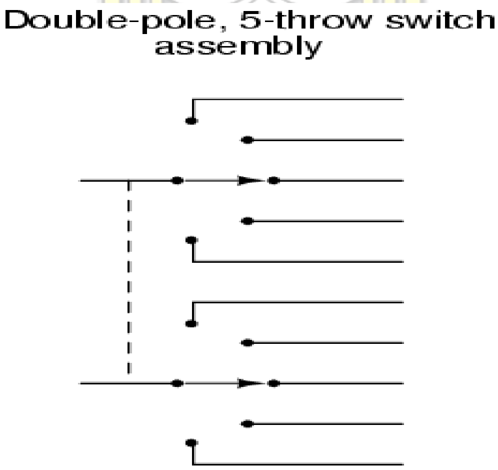


Fig. 9: Double-pole, five-throw switch

Here are a few common switch configurations and their abbreviated designations

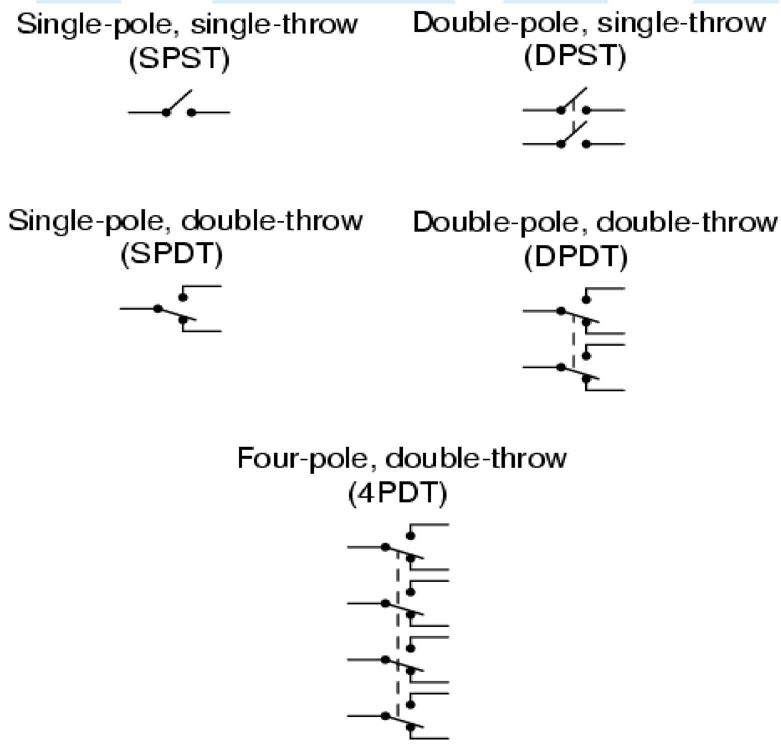


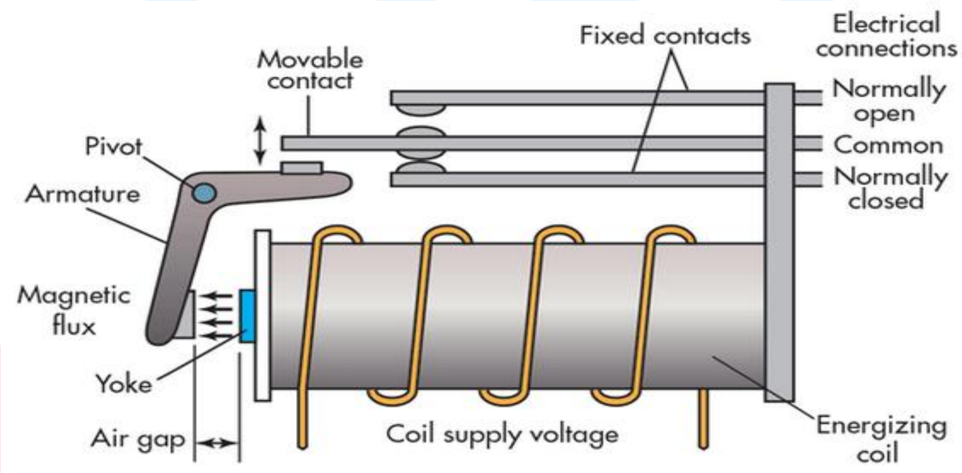
Fig. 10: Common switch configurations and their designations

Contact Bounce

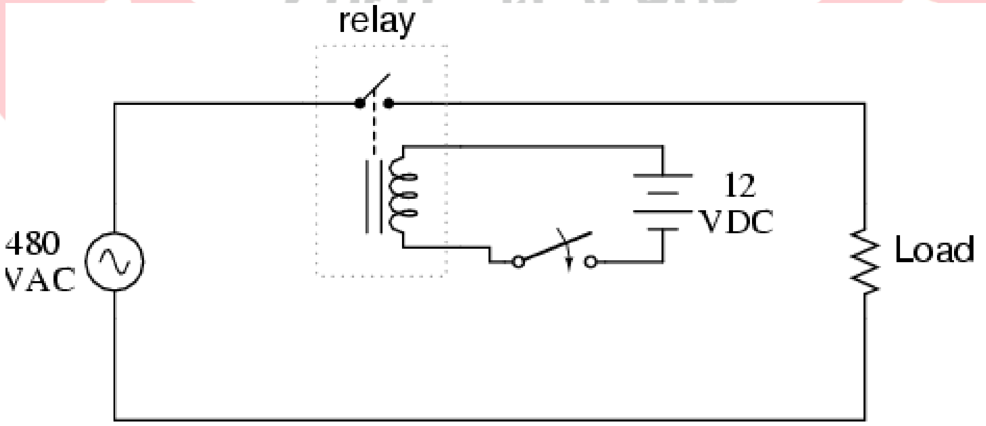
When a switch is actuated and contacts touch one another under the force of actuation, they are supposed to establish continuity in a single, crisp moment. Unfortunately, though, switches do not exactly achieve this goal. Due to the mass of the moving contact and any elasticity inherent in the mechanism and/or contact materials, contacts will "bounce" upon closure for a period of milliseconds before coming to a full rest and providing unbroken contact. In many applications, switch bounce is of no consequence: it matters little if a switch controlling an incandescent lamp "bounces" for a few cycles every time it is actuated. Since the lamp's warm-up time greatly exceeds the bounce period, no irregularity in lamp operation will result; however, if the switch is used to send a signal to an electronic amplifier or some other circuit with a fast response time, contact bounce may produce very noticeable and undesired effects.

Relays

A relay is an electrically operated switch. Many relays use an electromagnet to mechanically operate a switch, but other operating principles are also used, such as solid-state relays (SSRs) (see below figure). Relays are used where it is necessary to control a high-power circuit by a separate low-power signal, or where several circuits must be controlled by one signal. A type of relay that can handle the high power required to directly control an electric motor or other loads is called a contactor.

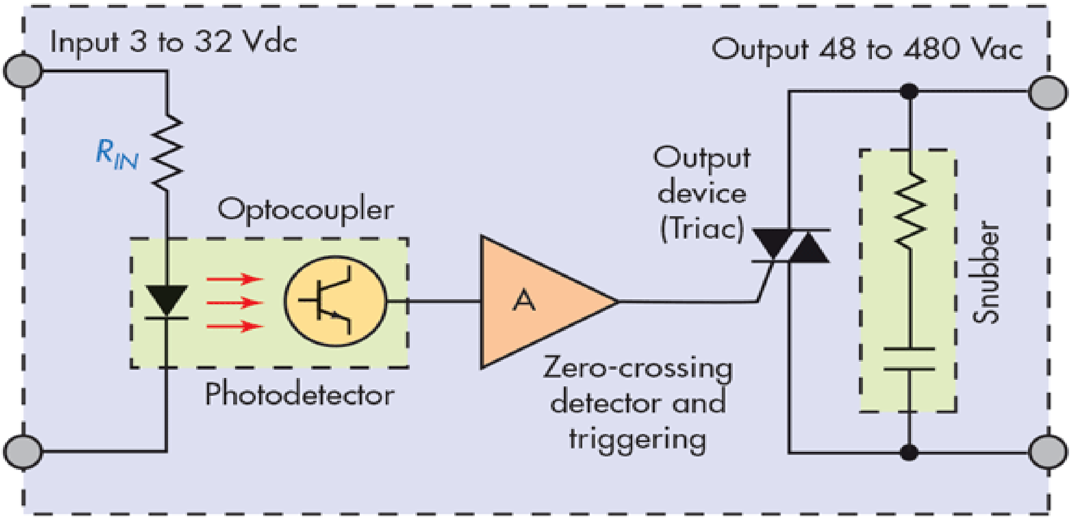


(a) Layout

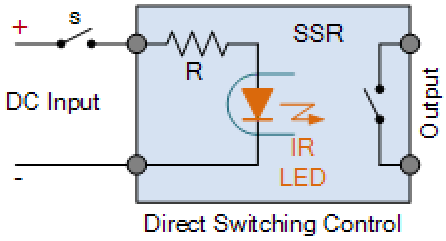


(b) Operation concept

Fig. 11: A typical schematic of a simplified electromechanical relay



(a) Simplified AC SSR



(b) DC SSR with direct switching control
Fig. 12: A typical schematic of solid-state relay (SSRs)

Relays are extremely useful when we have a need to control a large amount of current and/or voltage with a small electrical signal. The relay coil which produces the magnetic field may only consume fractions of a watt of power, while the contacts closed or opened by that magnetic field may be able to conduct hundreds of times that amount of power to a load. In effect, a relay acts as a binary (on or off) amplifier. Just as with transistors, the relay's ability to control one electrical signal with another finds application in the construction of logic functions. This topic will be covered in greater detail in another lesson. For now, the relay's "amplifying" ability will be explored.

Electromechanical relays open and close electrical contacts to turn a load off and on. Most electromechanical relays contain a moving component called an armature that is attracted by the magnetic field the coil generates (Fig. 11). An electric current through a conductor will produce a magnetic field at right angles to the direction of electron flow. If that conductor is wrapped into a coil shape, the magnetic field produced will be oriented along the length of the coil. The greater the current, the greater the strength of the magnetic field. Inductors react against changes in current because of the energy stored in this magnetic field. When we construct a transformer from two inductor coils around a common iron core, we use this field to transfer energy from one coil to the other. However, there are simpler and more direct uses for electromagnetic fields than the applications we've seen with inductors and transformers. The magnetic field produced by a coil of current-carrying wire can be used to exert a mechanical force on any magnetic object, just as we can use a permanent magnet to attract magnetic objects, except that this magnet (formed by the coil) can be turned on or off by switching the current on or off through the coil. If we place a magnetic object near such a coil for the purpose of making that object move when we energize the coil with electric current, we have what is called a solenoid. The movable magnetic object is called an armature, and most armatures can be moved with either direct current (DC) or alternating current (AC) energizing the coil. The polarity of the magnetic field is irrelevant for the purpose of attracting an iron armature. Solenoids can be used to electrically open door latches, open or shut valves, move robotic limbs, and even actuate electric switch mechanisms. However, if a solenoid is used to actuate a set of switch contacts, we have a device so useful it deserves its own name: the relay.

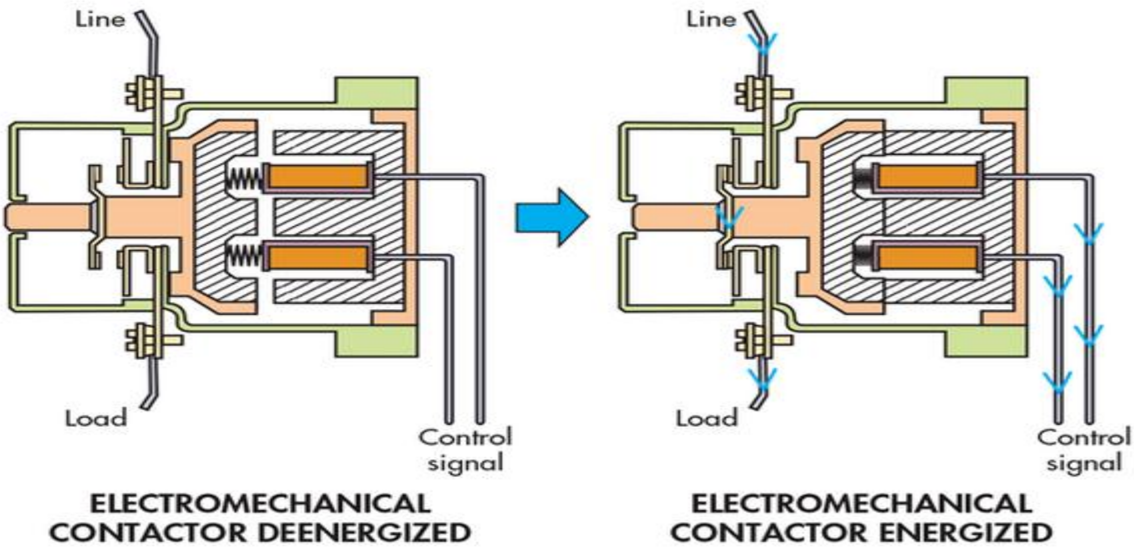


Fig. 13: On/off operation of an electromechanical relay

Usually, relays are usually supplied from dc sources. A dc relay uses a single coil of wire wound around the iron core to make the electromagnet. When the dc coil energizes, the core generates a steady magnetic field that holds the armature closed (see Fig. 13). In theory, ac can be used to operate a dc relay. But ac drops to zero every half cycle. Thus, the relay armature tends to release every half cycle. This continual movement of the armature tends to result in an audible buzz and can open and close the contacts as the armature moves. To make a relay compatible with ac, most manufacturers install a shader ring (or shader coil) on the top of the coil core. The shader ring forces the magnetism developed in part of the core to lag that of the remainder of the core. Thus, there is a slight phase displacement between the magnetism in the two parts of the core. The purpose of the shader ring is to ensure some magnetic energy remains in the core during each half cycle when ac current drops to zero. The energy holds the armature closed until energy in the unshaded portion of the core builds up again. Most ac applications are for 50-Hz or 60-Hz current. Telephone relays operate on 20-Hz current but are similar in construction. For 400-Hz current, as found in aircraft, a radical departure from the 60-Hz relay construction is necessary. Reliable performance is attained by rectifying the 400-Hz ac to dc and using a dc relay motor.

Electromechanical are often used because they cost less than corresponding electronic switches. But some or their qualities are superior to those of SSRs. For example, electromechanical relays can have numerous contacts electrically isolated one from another. Electromechanical relays also have a contact resistance that tends to be lower than that of SSRs (tens of milliohms versus about 100 Ω). Contact capacitance is also less, which may benefit high-frequency circuits. Electromechanical relays are less likely to be turned on by transients than SSRs and may be less easily damaged by brief short circuits or overloads. Electromechanical relays differ in other important ways from SSRs. First, relay coils are highly inductive, and the inductance value is not constant. Inductance is low immediately after energization and rises as current approaches a steady-state level and the relay armature closes. In contrast, SSRs have mainly resistive inputs and a constant input current. Second, electromechanical relays switch much more slowly than SSRs (typically 5 to 15 msec versus about 1 msec). Coil inductance is the primary cause, but the mass of armature and contact structures are also factors. Third, relay coil inductance can produce high-voltage transients when the device deenergizes. Snubber circuits can reduce the transients but can delay relay dropout as well. Arcs at the contacts of electromechanical relays can produce EMI when a contact bounces during opening or closing.

A solid-state relay (SSR) is an electronic switching device that switches on or off when a small external voltage is applied across its control terminals. SSRs consist of a sensor which responds to an appropriate input (control signal), a solid-state electronic switching device which switches power to the load circuitry, and a coupling mechanism to enable the control signal to activate this switch without mechanical parts (see Fig. 12). The relay may be designed to switch either AC or DC to the load. It serves the same function as an electromechanical relay, but has no moving parts as the semiconductor devices perform the switching function(s).

In all SSRs, the control signal must be coupled to the controlled circuit in a way which provides galvanic isolation between the two circuits. Galvanic isolation is a principle of isolating functional sections of electrical systems to prevent current flow; no direct conduction path is permitted. Many SSRs use optical coupling as shown in Fig. 12. The control voltage energizes an internal LED which illuminates and switches on a photo-sensitive diode (photo-voltaic); the diode current turns on a back-to-back thyristor, SCR, or MOSFET to switch the load. The optical coupling allows the control circuit to be electrically isolated from the load.

AC SSRs use SCR or TRIAC to inherently switch off at the points of zero load current. The circuit will never be interrupted in the middle of a sine wave peak, preventing the large transient voltages that would otherwise occur due to the sudden collapse of the magnetic field around the inductance. With the addition of a zero-point detector (and no adverse circuit inductance and resultant back-e.m.f.), the individual SCR's can be switched back on at the start of a new wave. This feature is called zero-crossover switching (Fig. 12(a)).

DC SSRs (Fig. 12(b)) are based on a single MOSFET, or multiple MOSFETs in a paralleled array, can work well for DC loads. MOSFETs have an inherent substrate diode that conducts in the reverse direction, so a single MOSFET cannot block current in both directions. For AC (bi-directional) operation two MOSFETs are arranged back-to-back with their source pins tied together. Their drain pins are connected to either side of the output. The substrate diodes are alternately reverse biased to block current when the relay is off. When the relay is on, the common source is always riding on the instantaneous signal level and both gates are biased positive relative to the source by the photo-diode. It is common to provide access to the common source so that multiple MOSFETs can be wired in parallel if switching a DC load. Usually a network is provided to speed the turn-off of the MOSFET when the control input is removed.

Relays with calibrated operating characteristics and sometimes multiple operating coils are used to protect electrical circuits from overload or faults; in modern electric power systems these functions are performed by digital instruments still called "protective relays".

Advantages of SSRs over electromechanical relays

- An SSR is inherently smaller and slimmer profile than an equivalent electromechanical relay of similar specification, allowing tighter packing.
- Totally silent operation.
- SSRs switch faster than electromechanical relays; the switching time of a typical optically coupled SSR is dependent on the time needed to power the LED on and off - of the order of microseconds to milliseconds.
- Increased lifetime, even if it is activated many times, as there are no moving parts to wear and no contacts to pit or build up carbon.
- Output resistance remains constant regardless of amount of use.
- Clean, bounce-less operation.
- No sparking, allows it to be used in explosive environments, where it is critical that no spark is generated during switching.
- Much less sensitive to storage and operating environment factors such as mechanical shock, vibration, humidity, and external magnetic fields. As previously, mentioned electromechanical

switches need wetting currents i.e. this minimum amount of electric current necessary to keep a mechanical switch contact in good health is called the wetting current

Disadvantages of SSRs

- Voltage/current characteristic of semiconductor rather than mechanical contacts:
  - When closed, higher resistance (generating heat), and increased electrical noise.
  - When open, lower resistance, and reverse leakage current (typically µA range)
  - Voltage/current characteristic is not linear (not purely resistive), distorting switched waveforms to some extent. An electromechanical relay has the low ohmic (linear) resistance of the associated mechanical switch when activated, and the exceedingly high resistance of the air gap and insulating materials when open.
- Some types have polarity-sensitive output circuits. Electromechanical relays are not affected by polarity.
- Possibility of spurious switching due to voltage transients (due to much faster switching than mechanical relay)
- Isolated bias supply required for gate charge circuit
- Higher transient reverse recovery time (Trr) due to the presence of the body diode
- Tendency to fail "shorted" on their outputs, while electromechanical relay contacts tend to fail "open".

Contactors

When a relay is used to switch a large amount of electrical power through its contacts, it is designated by a special name: contactor. Contactors typically have multiple contacts, and those contacts are usually (but not always) normally-open, so that power to the load is shut-off when the coil is de-energized. Perhaps the most common industrial use for contactors is the control of electric motors as shown in Fig. 14.

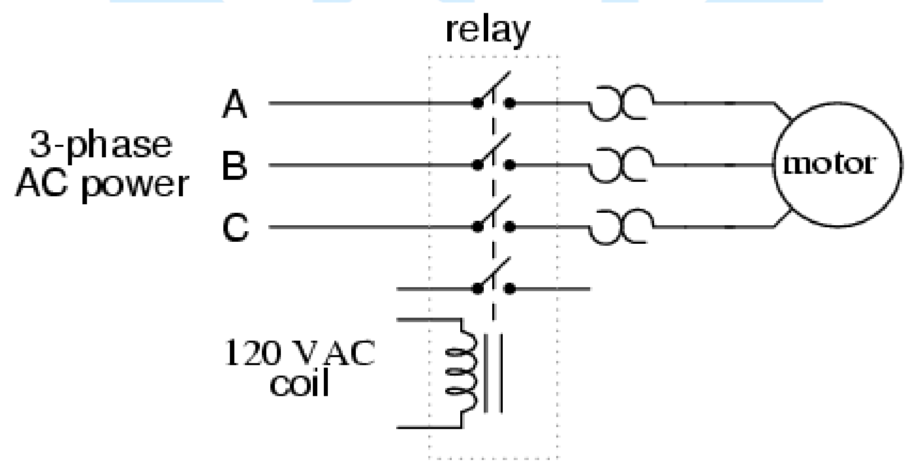


Fig. 14: Contactors, and motor control

In Fig. 14, the top three contacts switch the respective phases of the incoming 3-phase AC power, typically at least 480 Volts for motors 1 horsepower or greater. The lowest contact is an "auxiliary" contact which has a current rating much lower than that of the large motor power contacts, but is actuated by the same armature as the power contacts. The auxiliary contact is often used in a relay logic circuit, or for some other part of the motor control scheme, typically switching 120 Volt AC power instead of the motor voltage. One contactor may have several auxiliary contacts, either normally-open or normally-closed, if required.

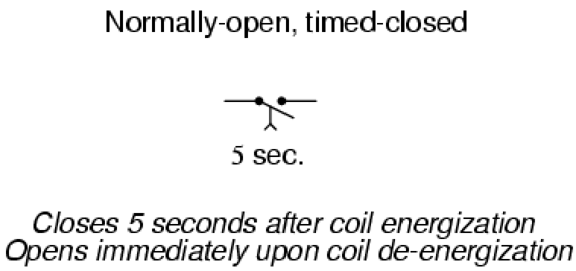
The three "opposed-question-mark" shaped devices in series with each phase going to the motor are called overload heaters. Each "heater" element is a low-resistance strip of metal intended to heat up as the motor draws current. If the temperature of any of these heater elements reaches a critical point (equivalent to a moderate overloading of the motor), a normally-closed switch contact (not shown in the diagram) will spring open. This normally-closed contact is usually connected in series with the relay coil, so that when it opens the relay will automatically de-energize, thereby shutting off power to the motor. We will see more of this overload protection wiring in the next chapter. Overload heaters are intended to provide overcurrent protection for large electric motors, unlike circuit breakers and fuses which serve the primary purpose of providing overcurrent protection for power conductors.

Overload heater function is often misunderstood. They are not fuses; that is, it is not their function to burn open and directly break the circuit as a fuse is designed to do. Rather, overload heaters are designed to thermally mimic the heating characteristic of the particular electric motor to be protected. All motors have thermal characteristics, including the amount of heat energy generated by resistive dissipation (I^2R), the thermal transfer characteristics of heat "conducted" to the cooling medium through the metal frame of the motor, the physical mass and specific heat of the materials constituting the motor, etc. These characteristics are mimicked by the overload heater on a miniature scale: when the motor heats up toward its critical temperature, so will the heater toward its critical temperature, ideally at the same rate and approach curve. Thus, the overload contact, in sensing heater temperature with a thermo-mechanical mechanism, will sense an analogue of the real motor. If the overload contact trips due to excessive heater temperature, it will be an indication that the real motor has reached its critical temperature (or, would have done so in a short while). After tripping, the heaters are supposed to cool down at the same rate and approach curve as the real motor, so that they indicate an accurate proportion of the motor's thermal condition, and will not allow power to be re-applied until the motor is truly ready for start-up again.

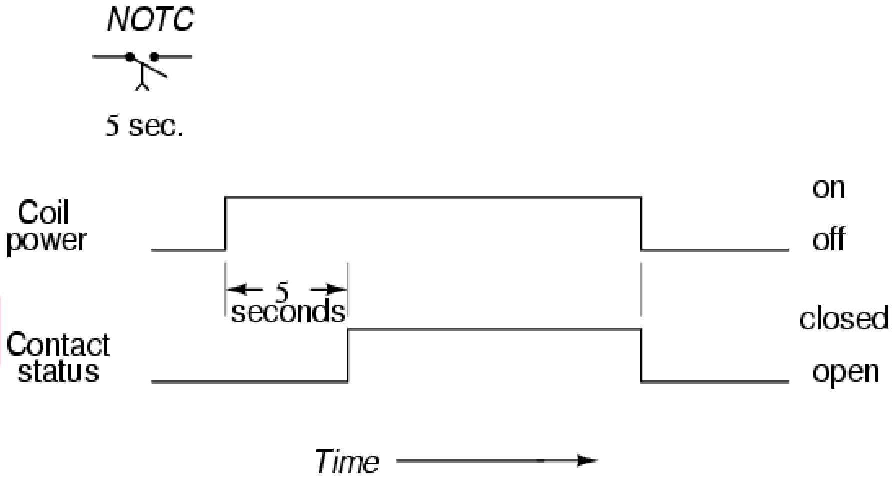
Time-Delay Relays

Some relays are constructed with a kind of "shock absorber" mechanism attached to the armature which prevents immediate, full motion when the coil is either energized or de-energized. This addition gives the relay the property of time-delay actuation. Time-delay relays can be constructed to delay armature motion on coil energization, de-energization, or both. Time-delay relay contacts must be specified not only as either normally-open or normally-closed, but whether the delay operates in the direction of closing or in the direction of opening. The following is a description of the four basic types of time-delay relay contacts.

First we have the normally-open, timed-closed (NOTC) contact; Fig. 15. The symbol of this contact is shown in Fig. 15(a), while the timing diagram of this relay contact is shown in Fig. 15(b). This type of contact is normally open when the coil is un-powered (de-energized). The contact is closed by the application of power to the relay coil, but only after the coil has been continuously powered for the specified amount of time. In other words, the direction of the contact's motion (either to close or to open) is identical to a regular NO contact, but there is a delay in closing direction. Because the delay occurs in the direction of coil energization, this type of contact is alternatively known as a normally-open, on-delay:



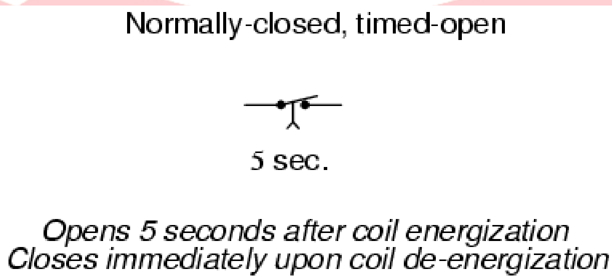
(a) Symbol and its designation



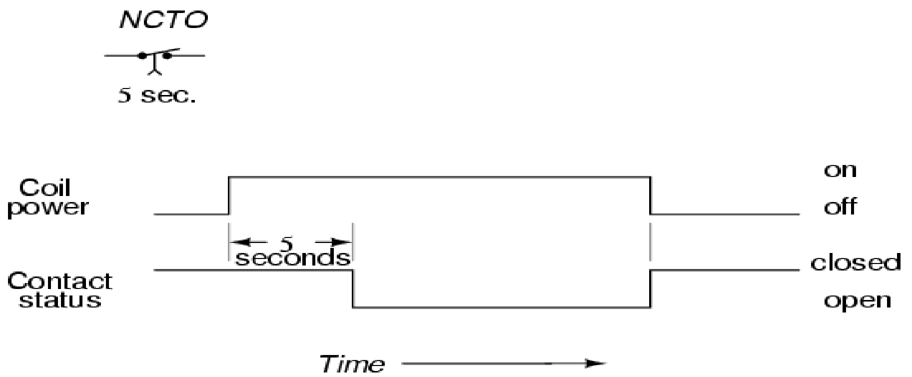
(b) Timing diagram

Fig. 15: Normally-open, timed-closed (NOTC) contact

Next we have the normally-closed, timed-open (NCTO) contact (Fig. 16). This type of contact is normally closed when the coil is unpowered (de-energized). The contact is opened with the application of power to the relay coil, but only after the coil has been continuously powered for the specified amount of time. In other words, the direction of the contact's motion (either to close or to open) is identical to a regular NC contact, but there is a delay in the opening direction. Because the delay occurs in the direction of coil energization, this type of contact is alternatively known as a normally-closed, on-delay:



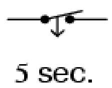
(a) Symbol and its designation



(b) Timing diagram

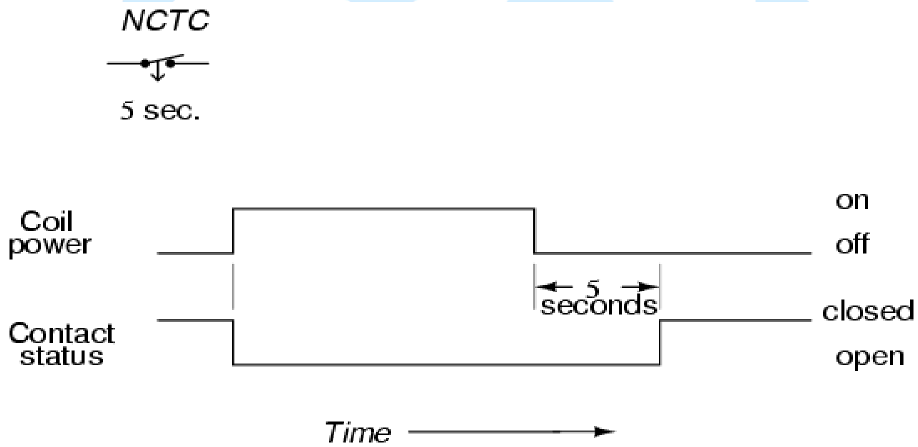
Fig. 16: Normally-closed, timed-open (NCTO) contact

Normally-closed, timed-closed



Opens immediately upon coil energization
Closes 5 seconds after coil de-energization

(a) Symbol and its designation



(b) Timing diagram

Fig. 17: Normally-closed, timed-close (NCTC) contact

Finally we have the normally-closed, timed-closed (NCTC) contact (Fig. 17). Like the NCTO contact, this type of contact is normally closed when the coil is unpowered (de-energized), and opened by the application of power to the relay coil. However, unlike the NCTO contact, the timing action occurs upon *de-energization* of the coil rather than upon energization. Because the delay occurs in the direction of coil de-energization, this type of contact is alternatively known as a normally-closed, *off*-delay.

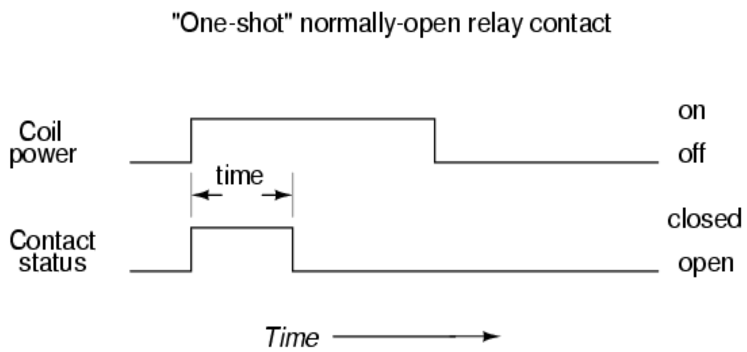
Time-delay relays are very important for use in industrial control logic circuits. Some examples of their use include:

- Flashing light control (time on, time off): two time-delay relays are used in conjunction with one another to provide a constant-frequency on/off pulsing of contacts for sending intermittent power to a lamp.
- Engine auto-start control: Engines that are used to power emergency generators are often equipped with "auto-start" controls that allow for automatic start-up if the main electric power fails. To properly start a large engine, certain auxiliary devices must be started first and allowed some brief time to stabilize (fuel pumps, pre-lubrication oil pumps) before the engine's starter motor is energized. Time-delay relays help sequence these events for proper start-up of the engine.
- Furnace safety purge control: Before a combustion-type furnace can be safely lit, the air fan must be run for a specified amount of time to "purge" the furnace chamber of any potentially flammable or explosive vapors. A time-delay relay provides the furnace control logic with this necessary time element.
- Motor soft-start delay control: Instead of starting large electric motors by switching full power from a dead stop condition, reduced voltage can be switched for a "softer" start and less inrush current. After a prescribed time delay (provided by a time-delay relay), full power is applied.
- Conveyor belt sequence delay: when multiple conveyor belts are arranged to transport material, the conveyor belts must be started in reverse sequence (the last one first and the first one last) so that material doesn't get piled on to a stopped or slow-moving conveyor. In order to get large belts up to full speed, some time may be needed (especially if soft-start motor controls are used). For this reason, there is usually a time-delay circuit arranged on each conveyor to give it adequate time to attain full belt speed before the next conveyor belt feeding it is started.

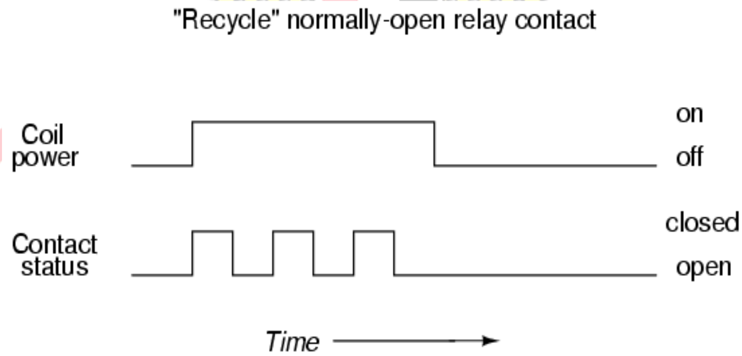
The older, mechanical time-delay relays used pneumatic dashpots or fluid-filled piston/cylinder arrangements to provide the "shock absorbing" needed to delay the motion of the armature. Newer designs of time-delay relays use electronic circuits with resistor-capacitor (RC) networks to generate a time delay, and then energize a normal (instantaneous) electromechanical relay coil with the electronic circuit's output. The electronic-timer relays are more versatile than the older, mechanical models, and less prone to failure.

Many models provide advanced timer features (Fig. 18) such as "one-shot" (one measured output pulse for every transition of the input from de-energized to energized), "recycle" (repeated on/off output cycles for as long as the input connection is energized) and "watchdog" which changes state if the input signal does not repeatedly cycle on and off.

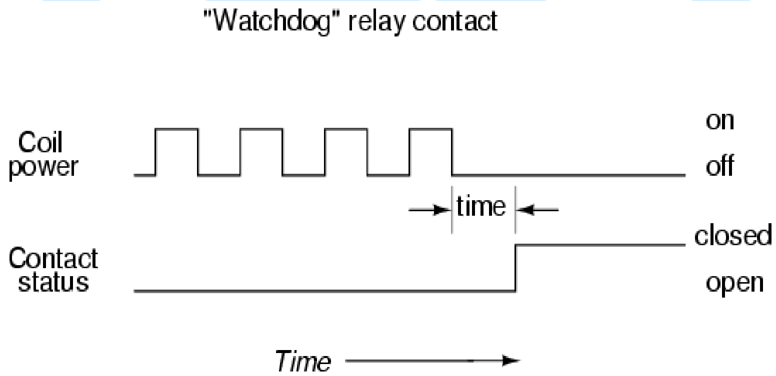
The "watchdog" timer is especially useful for monitoring of computer systems. If a computer is being used to control a critical process, it is usually recommended to have an automatic alarm to detect computer "lockup" (an abnormal halting of program execution due to any number of causes). An easy way to set up such a monitoring system is to have the computer regularly energize and de-energize the coil of a watchdog timer relay (similar to the output of the "recycle" timer). If the computer execution halts for any reason, the signal it outputs to the watchdog relay coil will stop cycling and freeze in one or the other state. A short time thereafter, the watchdog relay will "time out" and signal a problem.



(a) One-shot NO relay contact



(b) Recycle NO relay contact



(c) Washdog relay contact

Fig. 18: Models providing advanced timer features

Protective Relays

A special type of relay is one which monitors the current, voltage, frequency, or any other type of electric power measurement either from a generating source or to a load for the purpose of triggering a circuit breaker to open in the event of an abnormal condition. These relays are referred to in the electrical power industry as protective relays.

The circuit breakers which are used to switch large quantities of electric power on and off are actually electromechanical relays, themselves. Unlike the circuit breakers found in residential and commercial use which determine when to trip (open) by means of a bimetallic strip inside that bends when it gets too hot from overcurrent, large industrial circuit breakers must be "told" by an external device when to open. Such breakers have two electromagnetic coils inside: one to close the breaker contacts and one to open them. The "trip" coil can be energized by one or more protective relays, as well as by hand switches, connected to switch 125 Volt DC power. DC power is used because it allows for a battery bank to supply close/trip power to the breaker control circuits in the event of a complete (AC) power failure.

Protective relays can monitor large AC currents by means of current transformers (CT's), which encircle the current-carrying conductors exiting a large circuit breaker, transformer, generator, or other device. Current transformers step down the monitored current to a secondary (output) range of 0 to 5 amps AC to power the protective relay. The current relay uses this 0-5 amp signal to power its internal mechanism, closing a contact to switch 125 Volt DC power to the breaker's trip coil if the monitored current becomes excessive.

Likewise, (protective) voltage relays can monitor high AC voltages by means of voltage, or potential, transformers (PT's) which step down the monitored voltage to a secondary range of 0 to 120 Volts AC, typically. Like (protective) current relays, this voltage signal powers the internal mechanism of the relay, closing a contact to switch 125 Volt DC power to the breaker's trip coil is the monitored voltage becomes excessive.

There are many types of protective relays, some with highly specialized functions. Not all monitor voltage or current, either. They all, however, share the common feature of outputting a contact closure signal which can be used to switch power to a breaker trip coil, close coil, or operator alarm panel. Most protective relay functions have been categorized into an ANSI standard number code. Here are a few examples from that code list:

ANSI protective relay designation numbers

12 = Overspeed
24 = Overexcitation
25 = Syncrocheck
27 = Bus/Line undervoltage
32 = Reverse power (anti-motoring)
38 = Stator overtemp (RTD)
39 = Bearing vibration
40 = Loss of excitation
46 = Negative sequence undercurrent (phase current imbalance)
47 = Negative sequence undervoltage (phase voltage imbalance)
49 = Bearing overtemp (RTD)
50 = Instantaneous overcurrent
51 = Time overcurrent
51V = Time overcurrent -- voltage restrained
55 = Power factor
59 = Bus overvoltage
60FL = Voltage transformer fuse failure
67 = Phase/Ground directional current
79 = Autoreclose
81 = Bus over/underfrequency

Ladder Logic

Ladder diagrams are specialized schematics commonly used to document industrial control logic systems. They are called "ladder" diagrams because they resemble a ladder, with two vertical rails (supply power) and as many "rungs" (horizontal lines) as there are control circuits to represent. If we wanted to draw a simple ladder diagram showing a lamp that is controlled by a hand switch, it would look like Fig. 19.

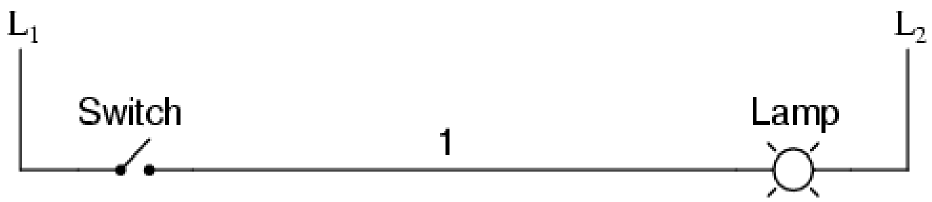


Fig. 19: A simple ladder diagram showing a lamp that is controlled by a hand switch

The "L_1" and "L_2" designations refer to the two poles of the AC supply (e.g. 120 VAC supply). *Generally, so long as the switch contacts and relay coils are all adequately rated, it really does not matter what level of voltage is chosen for the system to operate with.* L_1 is the "hot" conductor, and L_2 is the grounded ("neutral") conductor. These designations have nothing to do with inductors, just to make things confusing. The actual transformer or generator supplying power to this circuit is omitted for simplicity. In reality, the circuit looks something like Fig. 20.

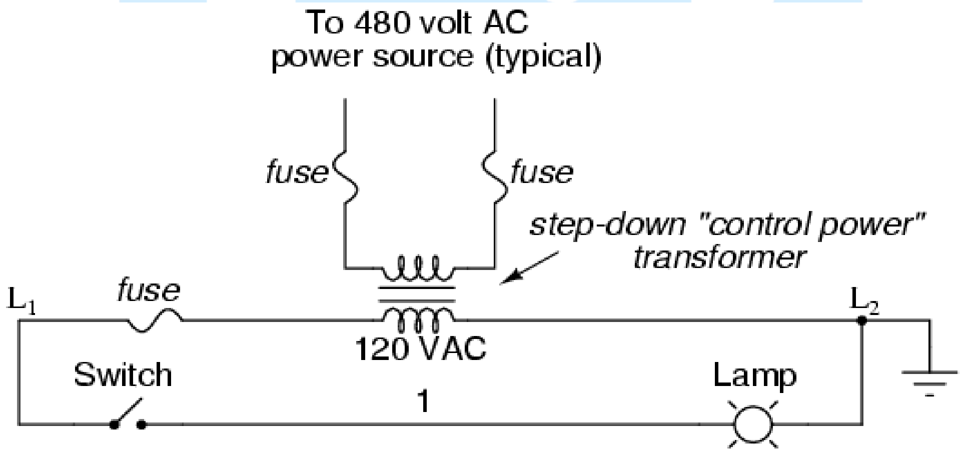


Fig. 20: A ladder diagram with the power source included

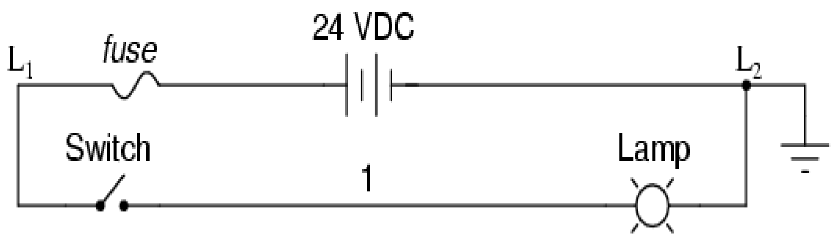


Fig. 21: Ladder diagram with DC power source

Typically in industrial relay logic circuits, but not always, the operating voltage for the switch contacts and relay coils will be 120 volts AC. Lower voltage AC and even DC systems are sometimes built and documented according to "ladder" diagrams; see Fig. 21.

In Fig. 21, note the number "1" on the wire between the switch and the lamp. In the real world, that wire would be labeled with that number, using heat-shrink or adhesive tags, wherever it was convenient to identify. Wires leading to the switch would be labeled "L_1" and "1," respectively. Wires leading to the lamp would be labeled "1" and "L_2," respectively. These wire numbers make assembly and maintenance very easy. Each conductor has its own unique wire number for the control system that it's used in. Wire numbers do not change at any junction or node, even if wire size, color, or length changes going into or out of a connection point. Of course, it is preferable to maintain consistent wire colors, but this is not always practical. What matters is that any one, electrically continuous point in a control circuit possesses the same wire number. Take this circuit section, for example, with wire #25 as a single, electrically continuous point threading to many different devices as shown in Fig. 22.

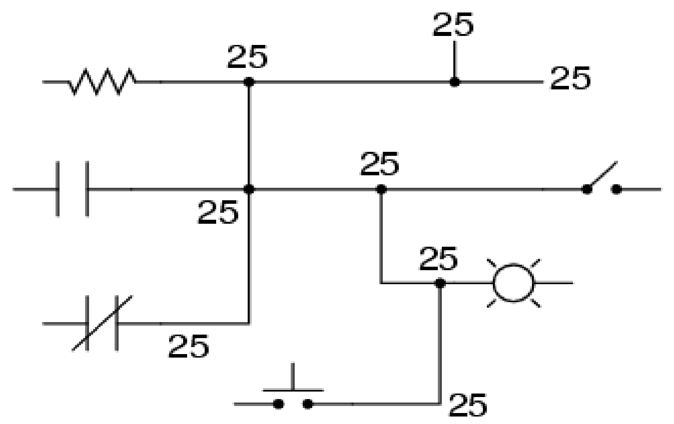
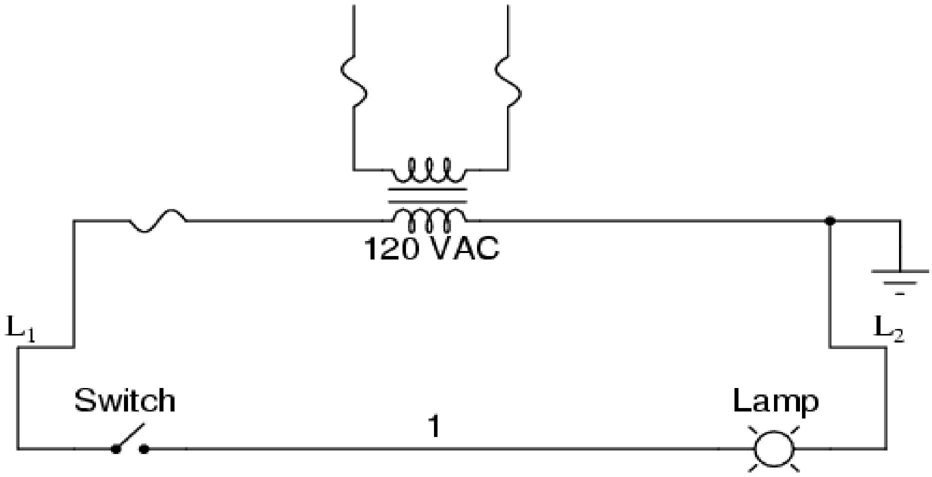
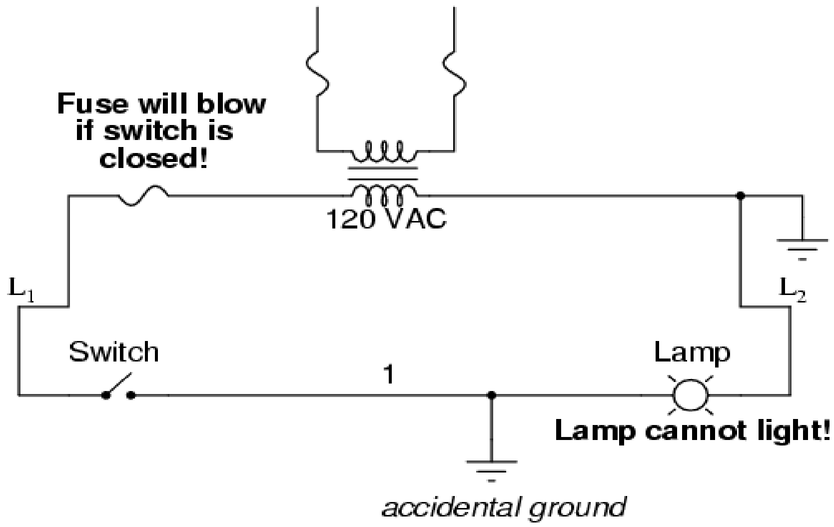


Fig. 22: Electrically continuous point threading to many different devices

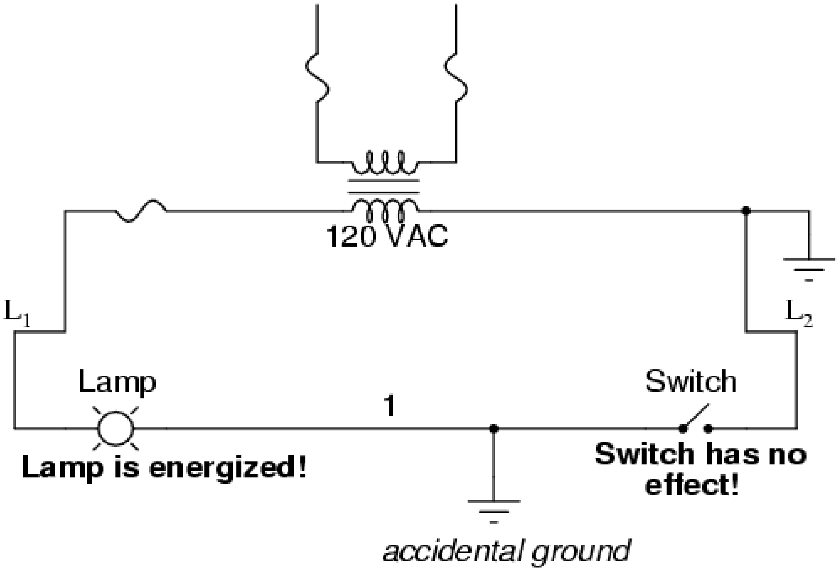
In ladder diagrams, the load device (lamp, relay coil, solenoid coil, etc.) is almost always drawn at the right-hand side of the rung. While it doesn't matter electrically where the relay coil is located within the rung, it *does* matter which end of the ladder's power supply is grounded, for reliable operation. For example, consider the circuit shown in Fig. 23(a). Here, the lamp (load) is located on the right-hand side of the rung, and so is the ground connection for the power source. This is no accident or coincidence; rather, it is a purposeful element of good design practice. Suppose that wire #1 were to accidentally come in contact with ground, the insulation of that wire having been rubbed off so that the bare conductor came in contact with grounded, metal conduit. Our circuit would now function like Fig. 23(b).



(a) Ladder logic example



(b) A wire failure both sides of the lamp connected to ground



(c) A wire failure both sides of the switch connected to ground

Fig. 23: Fail analysis of a ladder logic

With both sides of the lamp connected to ground, the lamp will be "shorted out" and unable to receive power to light up. If the switch were to close, there would be a short-circuit, immediately blowing the fuse (Fig. 23(b)); however, consider what would happen to the circuit with the same fault (wire #1 coming in contact with ground), except this time we'll swap the positions of switch and fuse (L_2 is still grounded) as shown in Fig. 23(c). This time the accidental grounding of wire #1 will force power to the lamp while the switch will have no effect. It is much safer to have a system that blows a fuse in the event of a ground fault than to have a system that uncontrollably energizes lamps, relays, or solenoids in the event of the same fault. For this reason, the load(s) must always be located nearest the grounded power conductor in the ladder diagram.

Permissive and Interlock Circuits

A practical application of switch and relay logic is in control systems where several process conditions have to be met before a piece of equipment is allowed to start. A good example of this is burner control for large combustion furnaces; Fig. 24. In order for the burners in a large furnace to be started safely, the control system requests "permission" from several process switches, including high and low fuel pressure, air fan flow check, exhaust stack damper position, access door position, etc. Each process condition is called a *permissive*, and each permissive switch contact is wired in series, so that if any one of them detects an unsafe condition, the circuit will be opened:

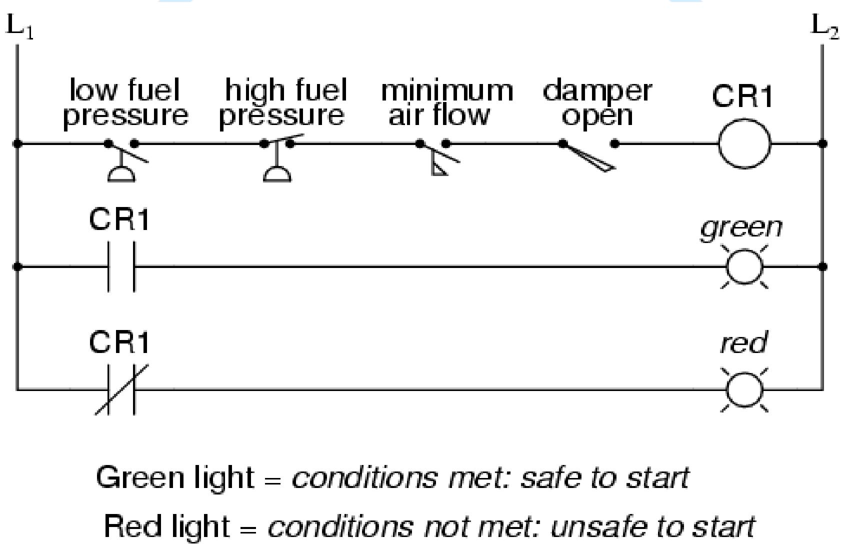
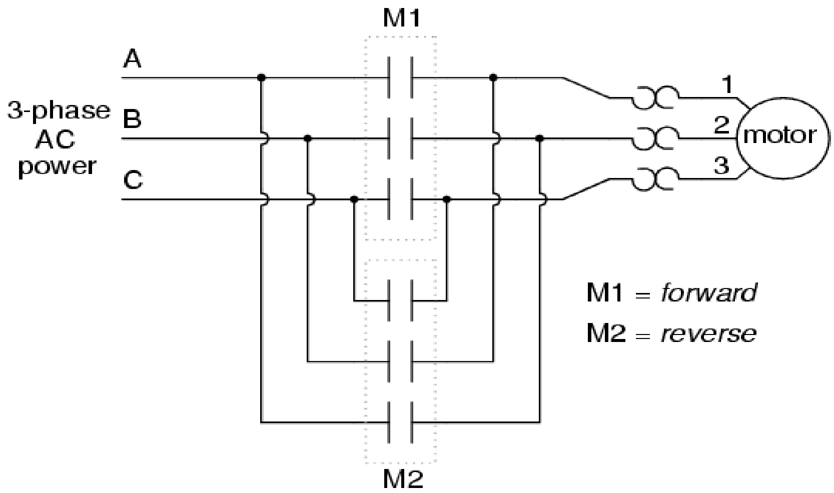


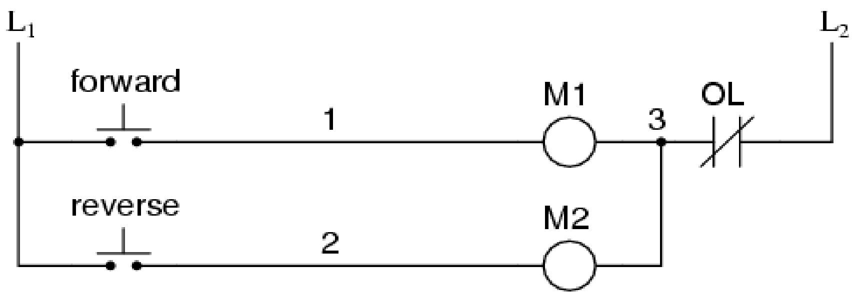
Fig. 24: Permissive ladder/relay logic concepts for large combustion furnaces

If all permissive conditions are met, CR_1 will energize and the green lamp will be lit. In real life, more than just a green lamp would be energized: usually a control relay or fuel valve solenoid would be placed in that rung of the circuit to be energized when all the permissive contacts were "good:" that is, all closed. If any one of the permissive conditions are not met, the series string of switch contacts will be broken, CR_2 will de-energize, and the red lamp will light. Note that the high fuel pressure contact is normally-closed. This is because we want the switch contact to open if the fuel pressure gets too high. Since the "normal" condition of any pressure switch is when zero (low) pressure is being applied to it, and we want this switch to open with excessive (high) pressure, we must choose a switch that is closed in its normal state.

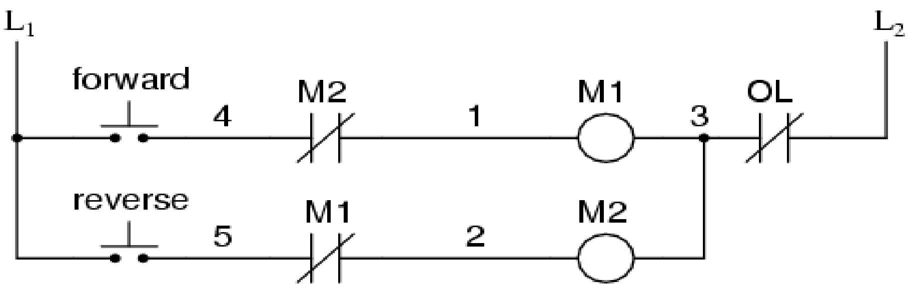
Another practical application of relay logic is in control systems where we want to ensure two incompatible events cannot occur at the same time. An example of this is in reversible motor control (Fig. 25), where two motor contactors are wired to switch polarity (or phase sequence) to an electric motor, and we do not want the forward and reverse contactors energized simultaneously.



(a) Circuit layout



(b) Relay logic without interlock



(c) Relay logic with interlock

Fig. 25: Ladder/relay logic concepts for motor rotation reversal control circuit

When contactor M_1 is energized, the 3 phases (A, B, and C) are connected directly to terminals 1, 2, and 3 of the motor, respectively. However, when contactor M_2 is energized, phases A and B are reversed, A going to motor terminal 2 and B going to motor terminal 1. This reversal of phase wires results in the motor spinning the opposite direction. Let's examine the control circuit for these two contactors.

In Fig. 25(b), take note of the normally-closed "OL" contact, which is the thermal overload contact activated by the "heater" elements wired in series with each phase of the AC motor. If the heaters get too hot, the contact will change from its normal (closed) state to being open, which will prevent either contactor from energizing. This control system will work fine, so long as no one pushes both buttons at the same time. If someone were to do that, phases A and B would be short-circuited together by virtue of the fact that contactor M_1 sends phases A and B straight to the motor and contactor M_2 reverses them; phase A would be shorted to phase B and visa-versa. Obviously, this is a bad control system design, and an interlock is essentially required for preventing requesting both rotation directions simultaneously.

To prevent this occurrence from happening, we can design the circuit with an interlock (Fig. 25(c)) so that the energization of one contactor prevents the energization of the other. This is called interlocking, and it is accomplished through the use of auxiliary contacts on each contactor. Now, when M_1 is energized, the normally-closed auxiliary contact on the second rung will be open, thus preventing M_2 from being energized, even if the "Reverse" pushbutton is actuated. Likewise, M_1's energization is prevented when M_2 is energized. Note, as well, how additional wire numbers (4 and 5) were added to reflect the wiring changes.

It should be noted that this is not the only way to interlock contactors to prevent a short-circuit condition. Some contactors come equipped with the option of a mechanical interlock: a lever joining the armatures of two contactors together so that they are physically prevented from simultaneous closure. For additional safety, electrical interlocks may still be used, and due to the simplicity of the circuit there is no good reason not to employ them in addition to mechanical interlocks.

Motor Control Circuits (MCC)

The interlock contacts installed in the previous section's motor control circuit (fig. 25(c)) work fine, but the motor will run only as long as each pushbutton switch is held down. If we wanted to keep the motor running even after the operator takes his or her hand off the control switch(es), we could change the circuit in a couple of different ways:

- We could replace the pushbutton switches with toggle switches, or
- We could add some more relay logic to "latch" the control circuit with a single, momentary actuation of either switch.

Let's see how the second approach is implemented (Fig. 26) , since it is commonly used in industry:

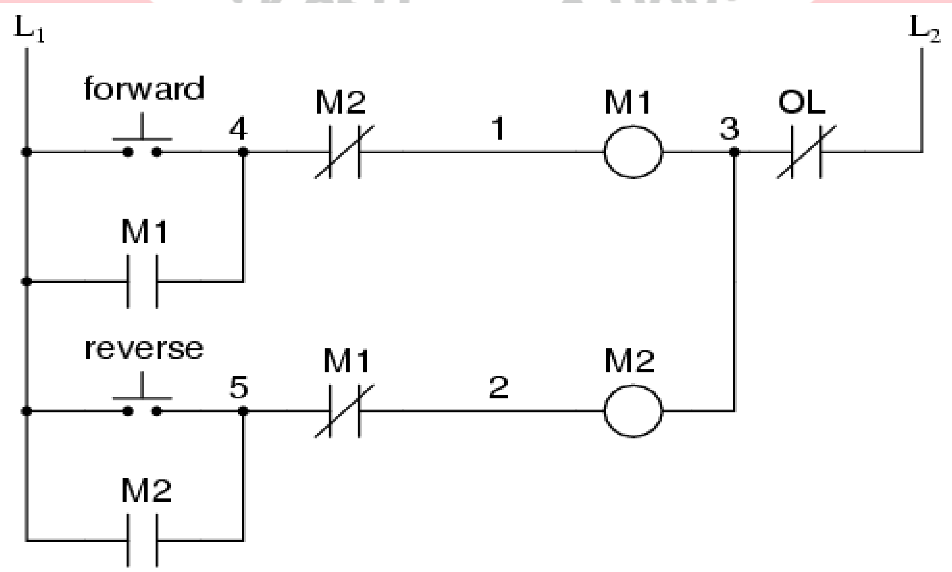


Fig. 26: Interlocking, and latching of the MCC shown in Fig. 25(a)

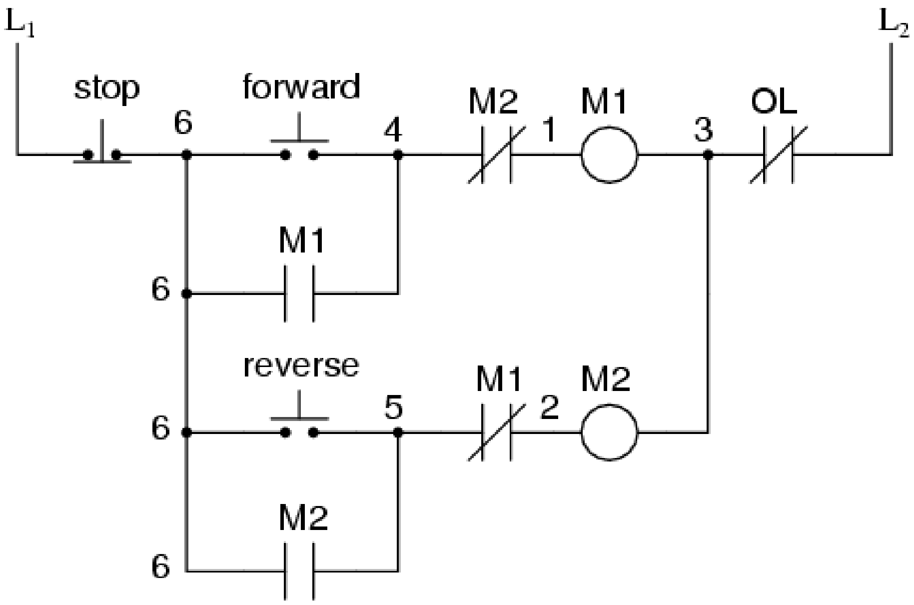


Fig. 27: Adding “stop” logic to the MCC logic of Fig. 26

When the "Forward" pushbutton is actuated, M_1 will energize, closing the normally-open auxiliary contact in parallel with that switch. When the pushbutton is released, the closed M_1 auxiliary contact will maintain current to the coil of M_1, thus latching the "Forward" circuit in the "on" state. The same sort of thing will happen when the "Reverse" pushbutton is pressed. These parallel auxiliary contacts are sometimes referred to as seal-in contacts, the word "seal" meaning essentially the same thing as the word latch; however, this creates a new problem: how to stop the motor! As the circuit exists right now, the motor will run either forward or backward once the corresponding pushbutton switch is pressed, and will continue to run as long as there is power. To stop either circuit (forward or backward), we require some means for the operator to interrupt power to the motor contactors. We'll call this new switch, Stop as shown in Fig. 27.

Now, if either forward or reverse circuits are latched, they may be "unlatched" by momentarily pressing the "Stop" pushbutton, which will open either forward or reverse circuit, de-energizing the energized contactor, and returning the seal-in contact to its normal (open) state. The "Stop" switch, having normally-closed contacts, will conduct power to either forward or reverse circuits when released.

Let's consider another practical aspect of our motor control scheme before we quit adding to it. If our hypothetical motor turned a mechanical load with a lot of momentum, such as a large air fan, the motor might continue to *coast* or *slew* for a substantial amount of time after the stop button had been pressed. This could be problematic if an operator were to try to reverse the motor direction without waiting for the fan to stop turning. If the fan was still coasting forward and the "Reverse" pushbutton was pressed, the motor would struggle to overcome that inertia of the large fan as it tried to begin turning in reverse, drawing excessive current and potentially reducing the life of the motor, drive mechanisms, and fan.

What we might like to have is some kind of a time-delay function in this motor control system to prevent such a premature startup from happening.

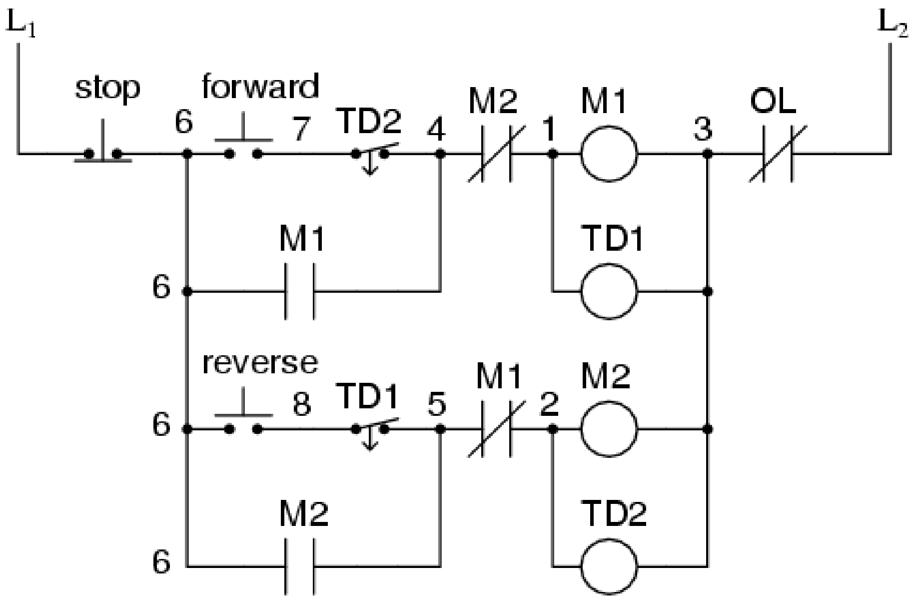


Fig. 28: Consideration of motor coasting in the relay logic of Fig. 27

Let's begin by adding a couple of *time-delay relay coils*, one in parallel with each motor contactor coil as shown in Fig. 28. If we use contacts that delay returning to their normal state, these relays will provide us a "memory" of which direction the motor was last powered to turn. What we want each time-delay contact to do is to open the starting-switch leg of the opposite rotation circuit for several seconds, while the fan coasts to a halt.

If the motor has been running in the forward direction, both M_1 and TD_1 will have been energized. This being the case, the normally-closed, timed-closed contact of TD_1 between wires 8 and 5 will have immediately opened the moment TD_1 was energized. When the stop button is pressed, contact TD_1 waits for the specified amount of time before returning to its normally-closed state, thus holding the reverse pushbutton circuit open for the duration so M_2 can't be energized. When TD_1 times out, the contact will close and the circuit will allow M_2 to be energized, if the reverse pushbutton is pressed. In like manner, TD_2 will prevent the "Forward" pushbutton from energizing M_1 until the prescribed time delay after M_2 (and TD_2) have been de-energized.

The careful observer will notice that the time-interlocking functions of TD_1 and TD_2 render the M_1 and M_2 interlocking contacts redundant. We can get rid of auxiliary contacts M_1 and M_2 for interlocks and just use TD_1 and TD_2's contacts, since they immediately open when their respective relay coils are energized, thus "locking out" one contactor if the other is energized. Each time delay relay will serve a dual purpose: preventing the other contactor from energizing while the motor is running, and preventing the same contactor from energizing until a prescribed time after motor shutdown. The resulting circuit has the advantage of being simpler, and cheaper than the previous example.

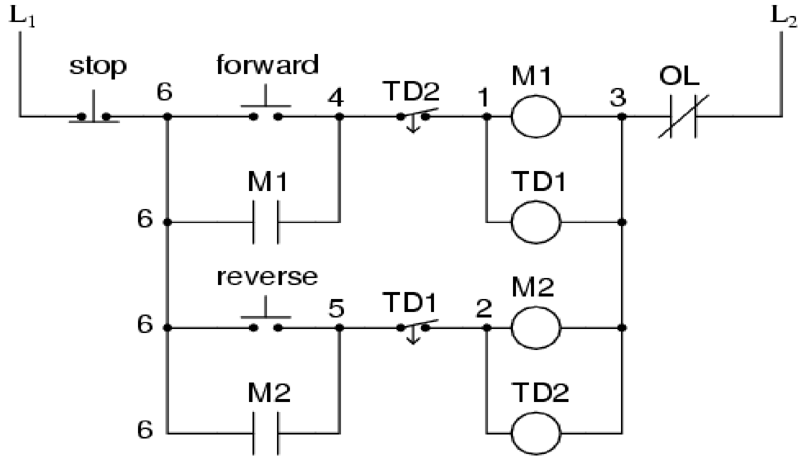


Fig. 29: Cost reduction of the relay logic of Fig. 28 by removing redundant interlocking

Fail-Safe Design

Logic circuits, whether comprised of electromechanical relays or solid-state gates, can be built in many different ways to perform the same functions. There is usually no one "correct" way to design a complex logic circuit, but there are usually ways that are better than others. In control systems, safety is (or at least should be) an important design priority. If there are multiple ways in which a digital control circuit can be designed to perform a task, and one of those ways happens to hold certain advantages in safety over the others, then that design is the better one to choose.

Let's take a look at the simple system and consider how it might be implemented in relay logic. Suppose that a large laboratory or industrial building is to be equipped with a fire alarm system, activated by any one of several latching switches installed throughout the facility. The system should work so that the alarm siren will energize if any one of the switches is actuated. At first glance it seems as though the relay logic should be incredibly simple: just use normally-open switch contacts and connect them all in parallel with each other as shown in Fig. 30.

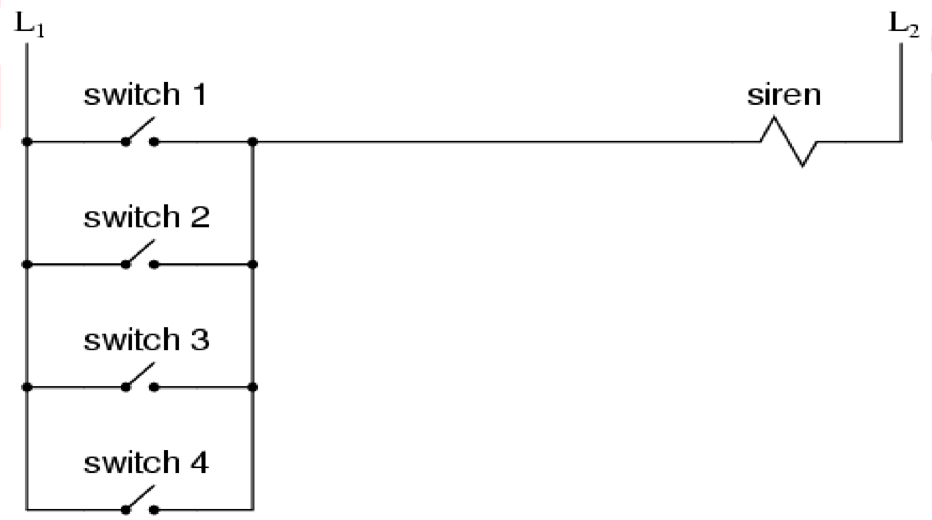


Fig. 30: Fail-safe analysis of simple relay logic

Essentially, this is the OR logic function implemented with four switch inputs. We could expand this circuit to include any number of switch inputs, each new switch being added to the parallel network, but we will limit it to four in this example to keep things simple. At any rate, it is an elementary system and there seems to be little possibility of trouble. Except in the event of a wiring failure, that is. The nature of electric circuits is such that "open" failures (open switch contacts, broken wire connections, open relay coils, blown fuses, etc.) are statistically more likely to occur than any other type of failure. With that in mind, it makes sense to engineer a circuit to be as tolerant as possible to such a failure. Let's suppose that a wire connection for Switch #2 were to fail open a shown in Fig. 31.

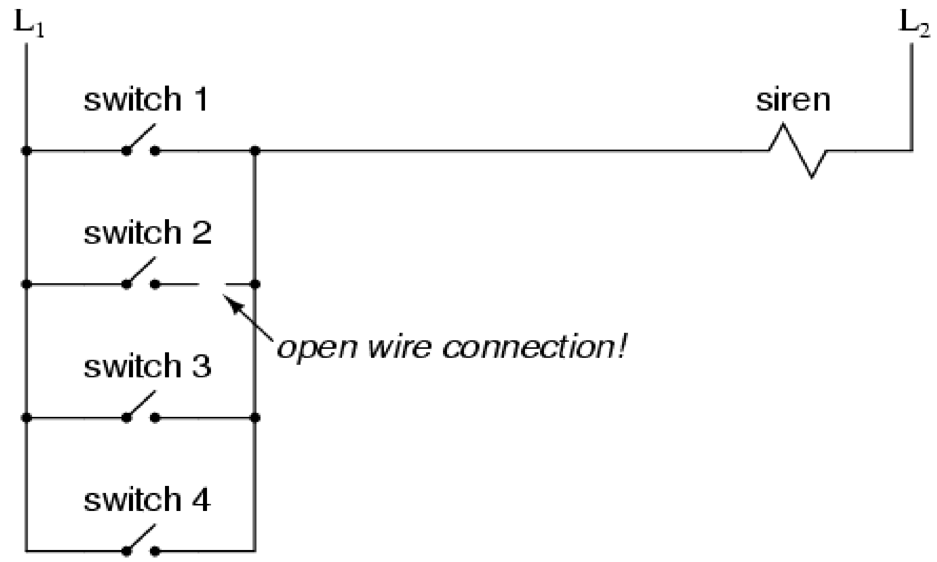


Fig. 31: Analysis of an open wire fault

If this failure were to occur, the result would be that Switch #2 would no longer energize the siren if actuated. This, obviously, is not good in a fire alarm system. Unless the system were regularly tested (a good idea anyway), no one would know there was a problem until someone tried to use that switch in an emergency.

What if the system were re-engineered so as to sound the alarm in the event of an open failure? That way, a failure in the wiring would result in a false alarm (Fig. 32), a scenario much more preferable than that of having a switch silently fail and not function when needed. In order to achieve this design goal, we would have to re-wire the switches so that an open contact sounded the alarm, rather than a closed contact. That being the case, the switches will have to be normally-closed and in series with each other, powering a relay coil which then activates a normally-closed contact for the siren:

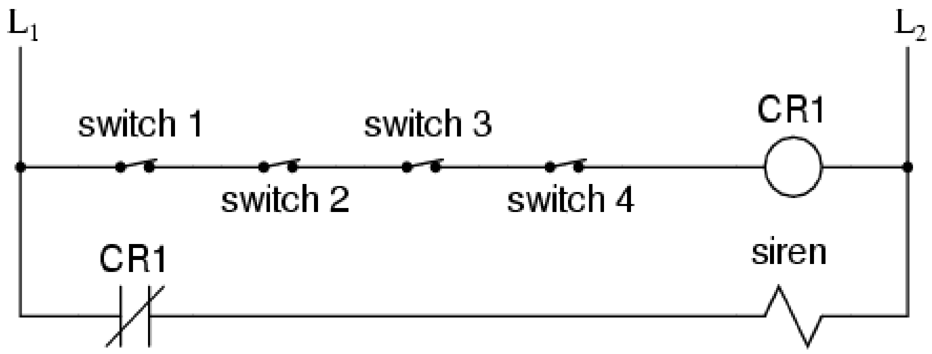


Fig. 32: Fail-safe design of the example of Fig. 30

When all switches are un-actuated (the regular operating state of this system), relay CR_1 will be energized, thus keeping contact CR_1 open, preventing the siren from being powered. However, if any of the switches are actuated, relay CR_1 will de-energize, closing contact CR_1 and sounding the alarm. Also, if there is a break in the wiring anywhere in the top rung of the circuit, the alarm will sound. When it is discovered that the alarm is false, the workers in the facility will know that something failed in the alarm system and that it needs to be repaired. Granted, the circuit is more complex than it was before the addition of the control relay, and the system could still fail in the "silent" mode with a broken connection in the bottom rung, but it's still a safer design than the original circuit, and thus preferable from the standpoint of safety.

This design of circuit is referred to as fail-safe, due to its intended design to default to the safest mode in the event of a common failure such as a broken connection in the switch wiring. Fail-safe design always starts with an assumption as to the most likely kind of wiring or component failure, and then tries to configure things so that such a failure will cause the circuit to act in the safest way, the "safest way" being determined by the physical characteristics of the process.

Take for example an electrically-actuated (solenoid) valve for turning on cooling water to a machine. Energizing the solenoid coil will move an armature which then either opens or closes the valve mechanism, depending on what kind of valve we specify. A spring will return the valve to its "normal" position when the solenoid is de-energized. We already know that an open failure in the wiring or solenoid coil is more likely than a short or any other type of failure, so we should design this system to be in its safest mode with the solenoid de-energized.

If it's cooling water we're controlling with this valve, chances are it is safer to have the cooling water turn on in the event of a failure than to shut off, the consequences of a machine running without coolant usually being severe. This means we should specify a valve that turns on (opens up) when de-energized and turns off (closes down) when energized. This may seem "backwards" to have the valve set up this way, but it will make for a safer system in the end.

One interesting application of fail-safe design is in the power generation and distribution industry, where large circuit breakers need to be opened and closed by electrical control signals from protective relays. If a 50/51 relay (instantaneous and time overcurrent) is going to command a circuit breaker to trip (open) in the event of excessive current, should we design it so that the relay closes a switch contact to send a "trip" signal to the breaker, or opens a switch contact to interrupt a regularly "on" signal to initiate a breaker trip? We know that an open connection will be the most likely to occur, but what is the safest state of the system: breaker open or breaker closed?

At first, it would seem that it would be safer to have a large circuit breaker trip (open up and shut off power) in the event of an open fault in the protective relay control circuit, just like we had the fire alarm system default to an alarm state with any switch or wiring failure. However, things are not so simple in the world of high power. To have a large circuit breaker indiscriminately trip open is no small matter, especially when customers are depending on the continued supply of electric power to supply hospitals, telecommunications systems, water treatment systems, and other important infrastructures. For this reason, power system engineers have generally agreed to design protective relay circuits to output a closed contact signal (power applied) to open large circuit breakers, meaning that any open failure in the control wiring will go unnoticed, simply leaving the breaker in the status quo position.

Is this an ideal situation? Of course it is not. If a protective relay detects an overcurrent condition while the control wiring is failed open, it will not be able to trip open the circuit breaker. Like the first fire alarm system design, the "silent" failure will be evident only when the system is needed. However, to engineer the control circuitry the other way -- so that any open failure would immediately shut the circuit breaker off, potentially blacking out large potions of the power grid -- really isn't a better alternative.

An entire book could be written on the principles and practices of good fail-safe system design. At least here, you know a couple of the fundamentals: that wiring tends to fail open more often than shorted, and that an electrical control system's (open) failure mode should be such that it indicates and/or actuates the real-life process in the safest alternative mode. These fundamental principles extend to non-electrical systems as well: identify the most common mode of failure, then engineer the system so that the probable failure mode places the system in the safest condition.

Chapter 3

Fundamentals of electric and electronic circuits

Objectives

- To review the basic electrical quantities, elements and laws
- To demonstrate the waveforms of single and three phase sources
- To explain the operation of basic electronic switches

Electrical Quantities

In describing the operation of electric circuits, one should be familiar with such electrical quantities as charge, current, and voltage. The material of this section will serve as a review.

Conductors and Insulators

In order to put charge in motion so that it becomes an electric current, one must provide a path through which it can flow easily by the movement of electrons. Materials through which charge flows readily are called *conductors*. Examples include most metals, such as silver, gold, copper, and aluminum. Copper is used extensively for the conductive paths on electric circuit boards and for the fabrication of electrical wires.

Electrical Quantities

Insulators are materials that do not allow charge to move easily. Examples include glass, plastic, ceramics, and rubber. Electric current cannot be made to flow through an insulator, since a charge has great difficulty moving through it. One sees insulating (or *dielectric*) materials often wrapped around the center conducting core of a wire.

Although the term resistance will be formally defined later, one can say qualitatively that a conductor has a very low resistance to the flow of charge, whereas an insulator has a very high resistance to the flow of charge. Charge-conducting abilities of various materials vary in a wide range. *Semiconductors* fall in the middle between conductors and insulators, and have a moderate resistance to the flow of charge. Examples include silicon, germanium, and gallium arsenide.

Current

The rate of movement of net positive charge per unit of time through a cross section of a conductor is known as *current*,

$$i(t) = \frac{dq}{dt} \quad (1)$$

The SI unit of current is the ampere (A), which represents 1 coulomb per second. In most metallic conductors, such as copper wires, current is exclusively the movement of free electrons in the wire. Since electrons are negative, and since the direction designated for the current is that of the net positive charge movement, the charges in the wire are thus moving in the direction opposite to the direction of the current designation. The net charge transferred at a particular time is the net area under the current-time curve from the beginning of time to the present.

Electric Potential and Voltage

When electrical forces act on a particle, it will possess potential *energy*. In order to describe the potential energy that a particle will have at a point x, the *electric potential* at point *x* is defined as

$$v(x) = \frac{dw(x)}{dq} \quad (2)$$

where *w(x)* is the potential energy that a particle with charge *q* has when it is located at the position *x*. The zero point of potential energy can be chosen arbitrarily since only differences in energy have practical meaning. The point where electric potential is zero is known as the *reference point* or *ground point*, with respect to which potentials at other points are then described. The *potential difference* is known as the *voltage* expressed in volts (V) or joules per coulomb (J/C).

If the potential at *B* is higher than that at *A*,

$$v_{BA} = v_B - v_A \quad (3)$$

which is positive. Obviously voltages can be either positive or negative numbers, and it follows that

$$v_{BA} = -v_{AB} \quad (4)$$

The voltage at point *A*, designated as *vA*, is then the potential at point *A* with respect to the ground.

Energy and Power

If a charge *dq* gives up energy *dw* when going from point *a* to point *b*, then the voltage across those points is defined as

$$v = \frac{dw}{dq} \quad (5)$$

If *dw*/*dq* is positive, point *a* is at the higher potential. The voltage between two points is the work per unit positive charge required to move that charge between the two points. If *dw* and *dq* have the same sign, then energy is *delivered* by a positive charge going from *a* to *b* (or a negative charge going the other way). Conversely, charged particles *gain* energy inside a *source* where *dw* and *dq* have opposite polarities. The *load* and *source* conventions are shown in Figure (1), in which point *a* is at a higher potential than point *b*. The load *receives* or *absorbs* energy because a positive charge goes in the direction of the current arrow from higher to lower potential. The source has a capacity to *supply* energy. The *voltage source* is sometimes known as an *electromotive force*, or *emf*, to convey the notation that it is a force that drives the current through the circuit. The *instantaneous power p* is defined as the rate of doing work or the rate of change of energy *dw/dt*,

$$p = \frac{dw}{dt} = \left(\frac{dw}{dq}\right)\left(\frac{dq}{dt}\right) = vi \qquad (6)$$

The electric power consumed or produced by a circuit element is given by its voltage-current product, expressed in volt-amperes (VA) or watts (W). The energy over a time interval is found by integrating power,

$$w = \int_0^T p\, dt \qquad (7)$$

which is expressed in watt-seconds or joules (J), or commonly in electric utility bills in kilowatthours (kWh). Note that 1 kWh equals 3.6 × 106 J.

Sources and Loads

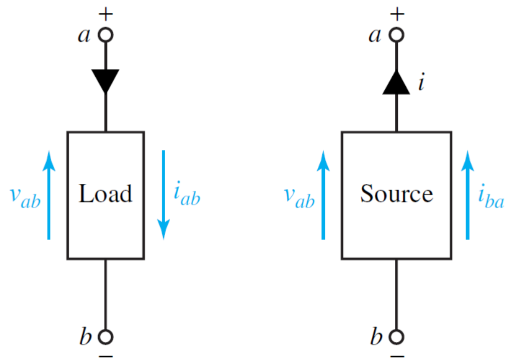


Figure (1) Load and source conventions

A source-load combination is represented in Figure (2). A *node* is a point at which two or more components or devices are connected together. A part of a circuit containing only one component, source, or device between two nodes is known as a *branch*. A voltage *rise* indicates an electric source, with the charge being raised to a higher potential, whereas a voltage *drop* indicates a load, with a charge going to a lower potential. The voltage *across* the source is the same as the voltage across the load in Figure (2) . The current delivered by the source goes *through* the load. Ideally, with no losses, the power *(p = vi)* delivered by the source is consumed by the load.

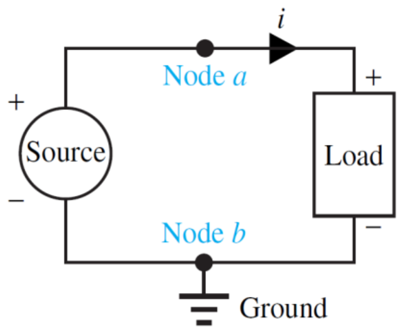


Figure (2) Source-Load combination

When current flows out of the positive terminal of an electric source, it implies that nonelectric energy has been transformed into electric energy. Examples include mechanical energy transformed into electric energy as in the case of a generator source, chemical energy changed into electric energy as in the case of a battery source, and solar energy converted into electric energy as in the case of a solar-cell source. On the other hand, when current flows in the direction of voltage drop, it implies that electric energy is transformed into nonelectric energy.

These are *voltage sources*. An *ideal voltage source* is one whose terminal voltage *v* is a specified function of time, regardless of the current *i* through the source. An ideal battery has a constant voltage *V* with respect to time, as shown in Figure (3). It is known as a dc source, because $i = I$ is a direct current. Figure (3) shows the symbol and time variation for a *sinusoidal voltage source* with $v = V_m \cos \omega t$.

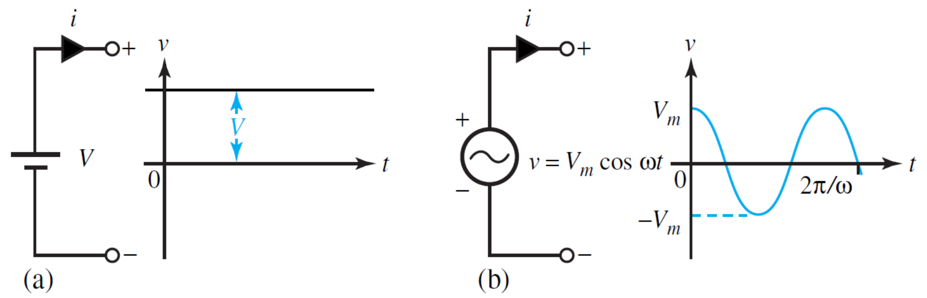


Figure (3) Voltage sources.
(a) Ideal dc source (battery) **(b)** Ideal sinusoidal ac source.

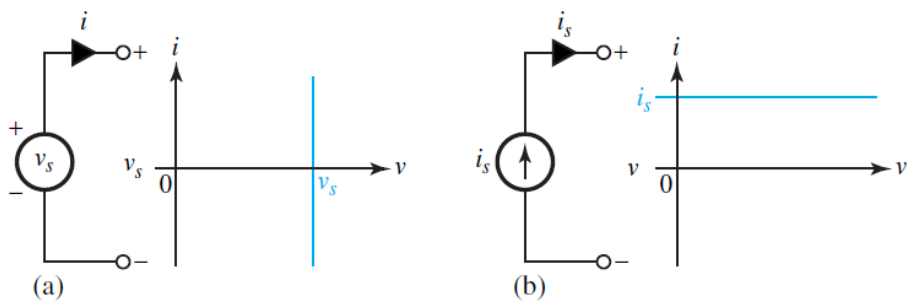


Figure (4) Circuit symbols and *i*-*v* curves.
(a) Ideal voltage source. **(b)** Ideal current source.

The positive sign on the source symbol indicates instantaneous polarity of the terminal at the higher potential whenever $\cos \omega t$ is positive. A sinusoidal source is generally termed an ac source because such a voltage source tends to produce an alternating current. The concept of an *ideal current source*, although less familiar but useful as we shall see later, is defined as one whose current *i* is a specified function of time, regardless of the voltage across its terminals. The circuit symbols and the corresponding *i*-*v* curves for the ideal voltage and current sources are shown in Figure (4).

Even though ideal sources could theoretically produce infinite energy, one should recognize that infinite values are physically impossible. Various circuit laws and device representations or *models* are approximations of physical reality, and significant limitations of the idealized concepts or models need to be recognized. Simplified representations or models for physical devices are the most powerful tools in electrical engineering. As for ideal sources, the concept of constant *V* or constant *I* for dc sources and the general idea of *v* or *i* being a specified function of time should be understood. When the source voltage or current is independent of all other voltages and currents, such sources are known as *independent sources*.

Waveforms

We are often interested in *waveforms*, which may not be constant in time. Of particular interest is a *periodic waveform*, which is a *time-varying waveform* repeating itself over intervals of time *T* >0.

$$f(t) = f(t \pm nT) \qquad n = 1,\ 2,\ 3, \cdots \quad (8)$$

The repetition time *T* of the waveform is called the *period* of the waveform. For a waveform to be periodic, it must continue indefinitely in time. The dc waveform of Figure (3) can be considered to be periodic with an infinite period. The *frequency* of a periodic waveform is the reciprocal of its period,

$$f = \frac{1}{T}\ \text{Hertz (Hz)} \quad (9)$$

A sinusoidal or cosinusoidal waveform is typically described by

$$f(t) = A\ \sin(\omega t + \phi) \quad (10)$$

where *A* is the amplitude, φ is the phase offset, and $\omega = 2\pi f = 2\pi/T$ is the radian frequency of the wave. When $\varphi = 0$, a sin wave results, and when $\varphi = 90^\circ$, a cosine wave results. The *average value* of a periodic waveform is the net positive area under the curve for one period, divided by the period,

$$F_{\text{av}} = \frac{1}{T}\int_0^T f(t)\,dt \quad (11)$$

The *effective*, or *root-mean square* (rms), value is the square root of the average of the square of function

$$F_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T f^2(t)\,dt} \quad (12)$$

Determining the square of the function *f (t)*, then finding the mean (average) value, and finally taking the square root yields the rms value, known as effective value. This concept will be seen to be useful in comparing the effectiveness of different sources in delivering power to a resistor. The effective value of a periodic current, for example, is a constant, or dc value, which delivers the same average power to a resistor, as will be seen later.

For the special case of a dc waveform, the following holds:

$$f(t) = F; \qquad F_{av} = F_{rms} = F \quad (13)$$

For the sinusoid or cosinusoid, it can be seen that

$$f(t) = A\sin(\omega t + \phi); \qquad F_{av} = 0; \qquad F_{rms} = A/\sqrt{2} \cong 0.707\,A \quad (14)$$

Lumped-Circuit Elements

Electric *circuits* or *networks* are formed by interconnecting various devices, sources, and components. Although the effects of each element (such as heating effects, electric-field effects, or magnetic-field effects) are distributed throughout space, one often lumps them together as *lumped elements*. The *passive* components are the *resistance R* representing the heating effect, the *capacitance C* representing the electric-field effect, and the *inductance L* representing the magnetic-field effect. Their characteristics will be presented in this section. The capacitor models the relation between voltage and current due to changes in the accumulation of electric charge, and the inductor models the relation due to changes in magnetic flux linkages, as will be seen later.While these phenomena are generally distributed throughout an electric circuit, under certain conditions they can be considered to be concentrated at certain points and can therefore be represented by lumped parameters.

Resistance

An *ideal resistor* is a circuit element with the property that the current through it is linearly proportional to the potential difference across its terminals,

$$i = v/R = Gv, \text{ or } v = iR \quad (15)$$

which is known as *Ohm's law*, published in 1827. *R* is known as the resistance of the resistor with the SI unit of *ohms* (Ω), and *G* is the reciprocal of resistance called *conductance*, with the SI unit of *siemens* (S). The circuit symbols of fixed and variable resistors are shown in Figure (5), along with an illustration of Ohm's law. Most resistors used in practice are good approximations to *linear* resistors for large ranges of current, and their *i*-*v* characteristic (current versus voltage plot) is a straight line.

The value of resistance is determined mainly by the physical dimensions and the *resistivity ρ* of the material of which the resistor is composed. For a bar of resistive material of length *l* and cross-sectional area *A* the resistance is given by

$$R = \frac{\rho l}{A} = \frac{l}{\sigma A} \quad (16)$$

where *ρ* is the resistivity of the material in ohm-meters *(Ω · m)*, and *σ* is the *conductivity* of the material in S/m, which is the reciprocal of the resistivity. Metal wires are often considered as ideal.

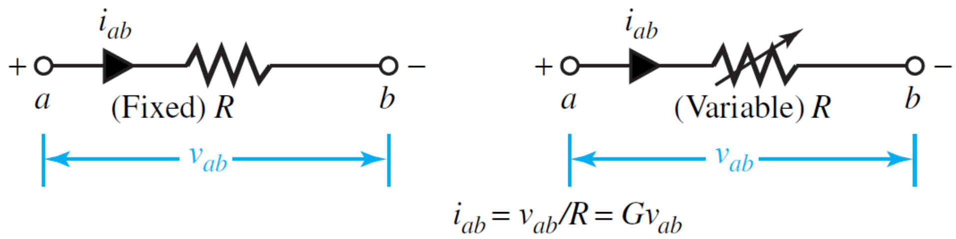


Figure (5) Circuit symbols of fixed and variable resistors and illustration of Ohm's law.

An important property of the resistor is its ability to convert energy from electrical form into heat. The manufacturer generally states the maximum power dissipation of the resistor in watts. If more power than this is converted to heat by the resistor, the resistor will be damaged due to verheating. The instantaneous power absorbed by the resistor is given by

$$p(t) = v(t)i(t) = i^2R = v^2/R = v^2G \quad (17)$$

where v is the voltage drop across the resistance and i is the current through the resistance. It can be shown that the average value of Equation (17) is given by

$$P_{\text{av}} = V_{\text{rms}}I_{\text{rms}} = I_{\text{rms}}^2R = V_{\text{rms}}^2/R = V_{\text{rms}}^2G \quad (18)$$

for periodically varying current and voltage as a function of time. Equation (18) gives the expression for the power converted to heat by the resistor. *Series* and *parallel* combinations of resistors occur very often. Figure (6) illustrates these combinations. Figure (6) (a) shows two resistors $R1$ and $R2$ in series. When $R1$ and $R2$ are in series,

$$R_{\text{eq}} = R_1 + R_2 \quad (19)$$

Figure (6) (b) shows two resistors in parallel. When $R1$ and $R2$ are in parallel,

$$R_{\text{eq}} = \frac{R_1R_2}{R_1 + R_2} \quad \text{or} \quad \frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} \quad (20)$$

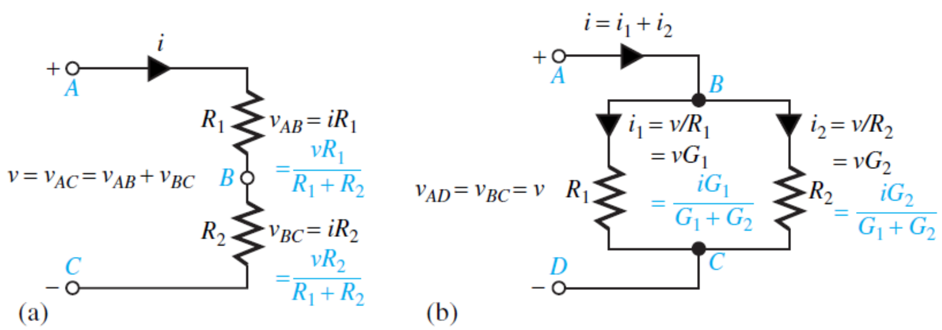


Figure (6) Resistances in series and in parallel.
(a) $R1$ and $R2$ in series. **(b)** $R1$ and $R2$ in parallel.

Capacitance

An *ideal capacitor* is an energy-storage circuit element (with no loss associated with it) representing the electric-field effect. The capacitance in farads (F) is defined by

$$C = q/v \tag{21}$$

where q is the charge on each conductor, and v is the potential difference between the two perfect conductors. the current entering one terminal of the capacitor is equal to the rate of buildup of charge

$$i(t) = \frac{dq}{dt} = C\frac{dv}{dt} \tag{22}$$

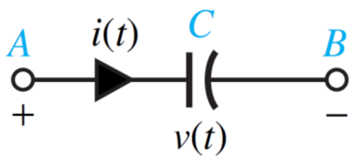


Figure (7) Capacitor symbol.

When $C1$ and $C2$ are in series,

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} \quad \text{or} \quad \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} \tag{23}$$

When $C1$ and $C2$ are in parallel,

$$C_{eq} = C_1 + C_2 \tag{24}$$

Note that capacitors in parallel combine as resistors in series, and capacitors in series combine as resistors in parallel.

Inductance

An *ideal inductor* is also an energy-storage circuit element (with no loss associated with it) like a capacitor, but representing the magnetic-field effect. The inductance in henrys (H) is defined by

$$L = \frac{\lambda}{i} = \frac{N\psi}{i} \tag{25}$$

where λ is the magnetic-flux linkage in weber-turns (Wb·t), N is the number of turns of the coil, and $N\psi$ is the magnetic flux in webers (Wb) produced by the current i in amperes (A). Figure (8) (a) illustrates a single inductive coil or an inductor of N turns carrying a current i that is linked by its own flux.

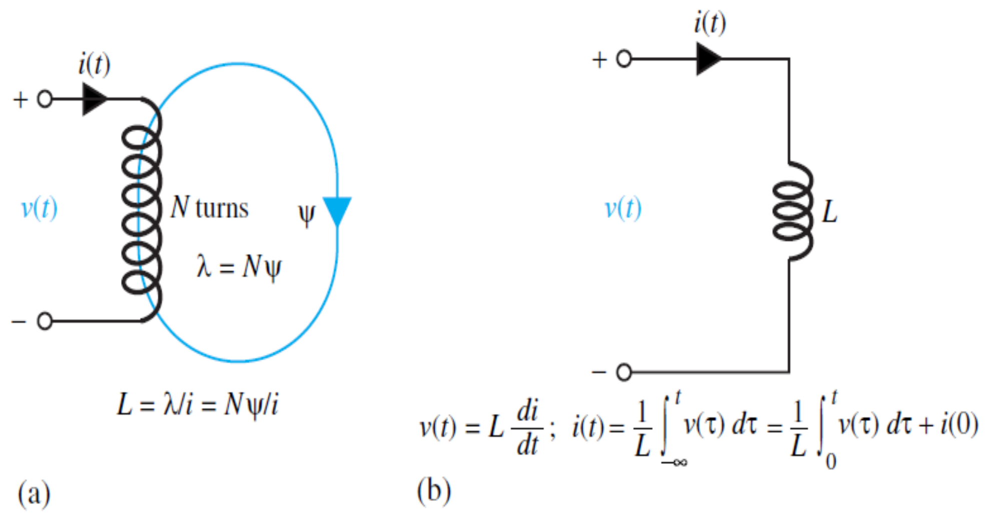


Figure (8) (a) A single inductive coil of *N* turns. **(b)** Circuit symbol.

The general circuit symbol for an inductor is shown in Figure (8)(b). According to Faraday's law of induction, one can write

$$v(t) = \frac{d\lambda}{dt} = \frac{d(N\psi)}{dt} = N\frac{d\psi}{dt} = \frac{d(Li)}{dt} = L\frac{di}{dt} \quad (26)$$

where *L* is assumed to be a constant and not a function of time (which could be if the physical shape of the coil changed with time). Mathematically, by looking at Equations (22) and (26), the inductor is the *dual* of the capacitor. That is to say, the terminal relationship for one circuit element can be obtained from that of the other by interchanging *v* and *i*, and also by interchanging *L* and *C*. Under dc conditions, an ideal inductor acts like an ideal wire, or short circuit. Note that the current through an inductor cannot change value instantaneously. However, there is no reason to rule out an instantaneous change in the value of the inductor voltage. The student should justify the statements made here by recalling Equation (26).

If the medium in the flux path has a linear magnetic characteristic (i.e., constant permeability), then the relationship between the flux linkages λ and the current *i* is *linear*, and the slope of the linear λ-*i* characteristic gives the *self-inductance*, defined as flux linkage per ampere by Equation (25). While the inductance in general is a function of the geometry and permeability of the material medium, in a linear system it is independent of voltage, current, and frequency. If the inductor coil is wound around a ferrous core such as iron, the λ-*i* relationship will be *nonlinear* and even multivalued because of hysteresis. In such a case the inductance becomes a function of the current, and the inductor is said to be nonlinear. However, we shall consider only linear inductors here.

Series and parallel combinations of inductors are often encountered. Figure (9) illustrates these combinations. Inductors in series combine like resistors in series and capacitors in parallel; while inductors in parallel combine like resistors in parallel and capacitors in series. Thus, when L_1 and L_2 are in series,

$$L_{eq} = L_1 + L_2 \quad (27)$$

and when L_1 and L_2 are in parallel,

$$L_{eq} = \frac{L_1 L_2}{L_1 + L_2} \quad \text{or} \quad \frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} \tag{28}$$

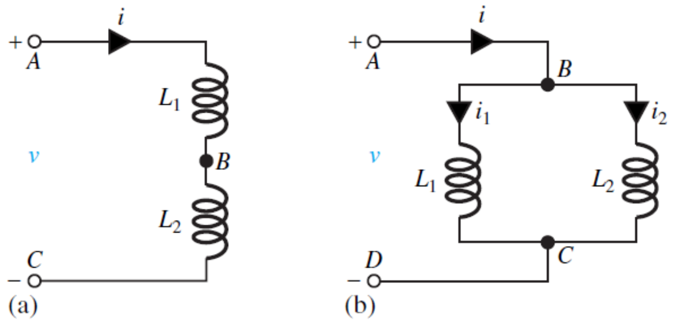


Figure (9) Inductors in series and parallel.
(a) L_1 and L_2 in series. **(b)** L_1 and L_2 in parallel.

Kirchhoff's Laws

The basic laws that must be satisfied among circuit currents and circuit voltages are known as Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). These are fundamental for the systematic analysis of electric circuits. KCL states that, at any node of any circuit and at any instant of time, the sum of all currents entering the node is equal to the sum of all currents leaving the node. That is, the algebraic sum of all currents (entering or leaving) at any node is zero, or no node can accumulate or store charge. Figure (10) illustrates Kirchhoff's current law, in which at node a,

$$(i_1 - i_2 + i_3 + i_4 - i_5 = 0) \; or \; (-i_1 + i_2 - i_3 - i_4 + i_5 = 0) \; or \; (i_1 + i_3 + i_4 = i_2 + i_5) \quad (29)$$

Note that so long as one is consistent, it does not matter whether the currents directed toward the node are considered positive or negative.

KVL states that the algebraic sum of the voltages (drops or rises) encountered in traversing any loop (which is a closed path through a circuit in which no electric element or node is encountered more than once) of a circuit in a specified direction must be zero. In other words, the sum of the voltage rises is equal to the sum of the voltage drops in a loop. A loop that contains no other loops is known as a mesh. KVL implies that moving charge around a path and returning to the starting point should require no net expenditure of energy. Figure (11) illustrates the Kirchhoff's voltage law.

For the mesh shown in Figure (11), which depicts a portion of a network, starting at node a and returning back to it while traversing the closed path abcdea in either clockwise or anticlockwise direction, Kirchhoff's voltage law yields

$$(-v_1 + v_2 - v_3 - v_4 + v_5 = 0) \text{ or } (v_1 - v_2 + v_3 + v_4 - v_5 = 0) \text{ or } (v_1 + v_3 + v_4 = v_2 + v_5) \; (30)$$

Note that so long as one is consistent, it does not matter whether the voltage drops are considered positive or negative. Also notice that the currents labeled in Figure (11) satisfy KCL at each of the nodes.

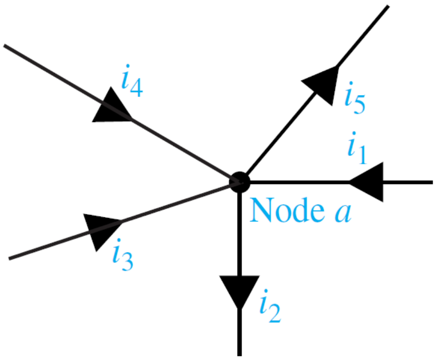


Figure **(10)** Illustration of Kirchoff's current law.

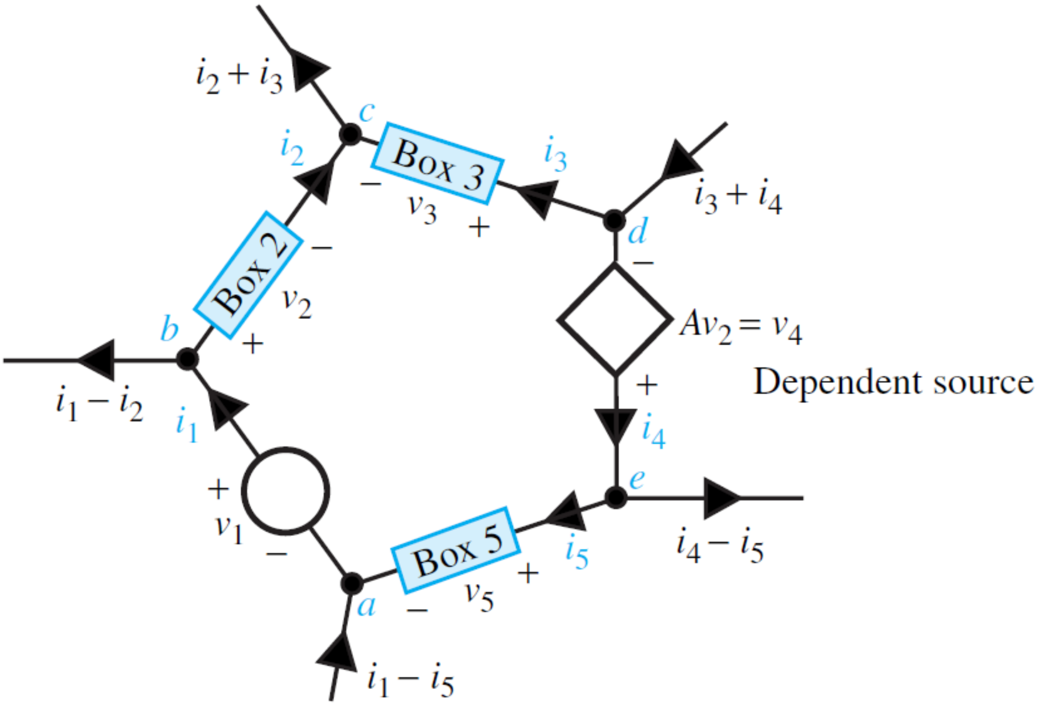


Figure **(11)** Illustration of Kirchoff's voltage law.

Three-Phase Source Voltages And Phase Sequence

The elementary three-phase, two-pole generator shown in Figure (12) has three identical stator coils (*aa*', *bb*', and *cc*') of one or more turns, displaced by 120° in space from each other. The rotor carries a field winding excited by the dc supply through brushes and slip rings. When the rotor is driven at a constant speed, voltages of equal amplitude but different phase angle will be generated in the three phases in accordance with Faraday's law. Each of the three stator coils constitutes one phase of this single generator.

If the field structure is so designed that the flux is distributed sinusoidally over the poles, the flux linking any phase will vary sinusoidally with time, and sinusoidal voltages will be induced in the three phases. These three induced voltage waves will be displaced by 120° electrical degrees in time because the stator phases are displaced by 120° in space. When the rotor is driven counterclockwise, Figure (13) shows the wave forms of the three voltages. The time origin and the reference axis are chosen on the basis of analytical convenience. In a balanced system, all three phase voltages are equal in magnitude but differ from each other in phase by 120°.

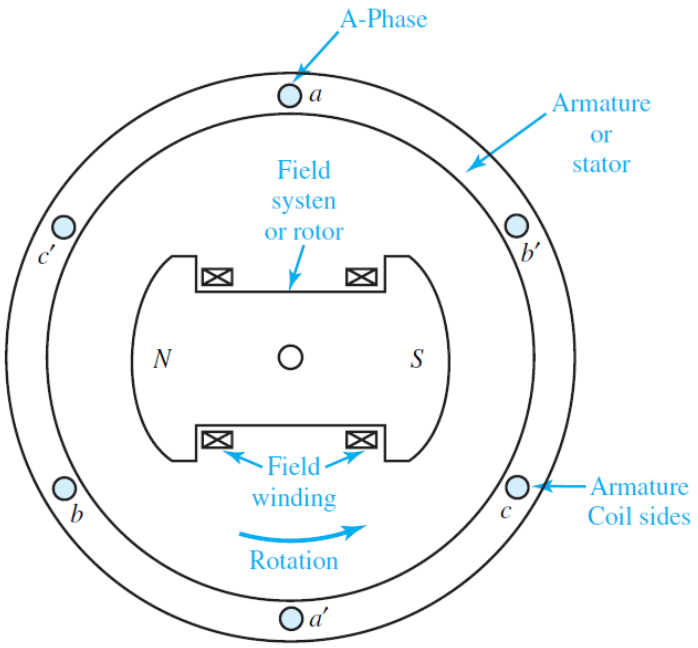


Figure (12) Elementary three-phase, twopole ac generator.

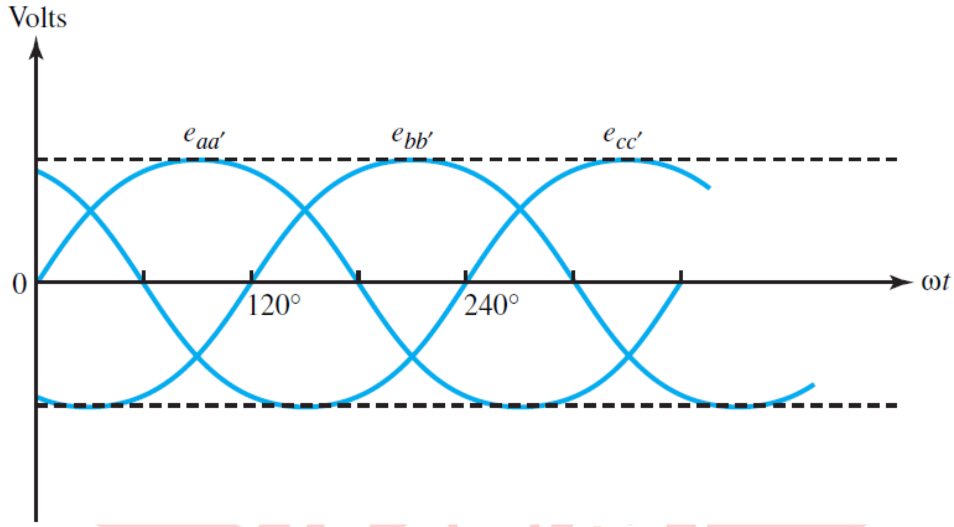


Figure (13) Three phase waveforms in time domain.

The stator phase windings may be connected in either wye (also known as star or symbolically represented as Y) or delta (also known as mesh or symbolically represented as Δ), as shown schematically in Figure (14). Almost all ac generators (otherwise known as alternators) have their stator phase windings connected in wye. By connecting together either all three primed terminals or all three unprimed terminals to form the *neutral* of the wye, a wye connection results. If a neutral conductor is brought out, the system is known as a *four-wire, three-phase system*; otherwise it is a *three-wire, three-phase system*. A delta connection is effected for the armature of the generator by connecting terminals *a'* to *b*, *b'* to *c*, and *c'* to *a*.

The generator terminals *A, B, C* (and sometimes *N* for a wye connection) are brought out as shown in Figure (14). In the delta-connection, no neutral exists, and hence only a three-wire, three-phase system can be formed. Note that a phase is one of the three branch circuits making up a three-phase circuit. In a wye connection, a phase consists of those circuit elements connected between one line and neutral; in a delta circuit, a phase consists of those circuit elements connected between two lines. From the nature of the connections shown in Figure (14) it can be seen that the line-to-line voltages ($V_{L\text{-}L}$ or V_L) are equal to the phase voltage V_{ph} for the delta connection, and the line current is equal to the phase current for the wye connection.

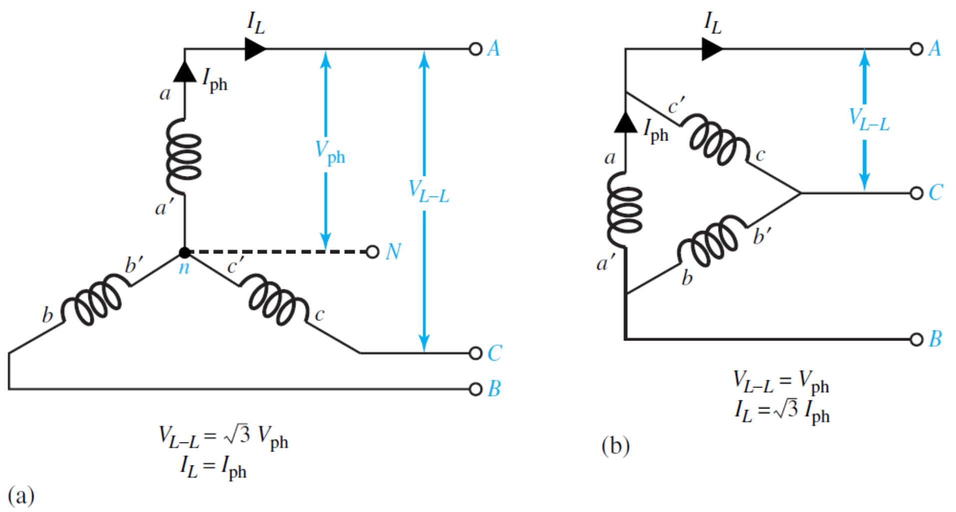


Figure (14) Schematic representation of generator windings.
(a) Balanced wye connection. **(b)** Balanced delta connection.

The one-line equivalent circuit of the balanced wye-connected three-phase source is shown in Figure (15). The line-to-neutral (otherwise known as phase) voltage is used; it may be taken as a reference with a phase angle of zero for convenience. This procedure yields the equivalent single-phase circuit in which all quantities correspond to those of one phase in the three-phase circuit. Except for the 120° phase displacements in the currents and voltages, the conditions in the other two phases are the same, and there is no need to investigate them individually. Line currents in the three-phase system are the same as in the single-phase circuit, and total three-phase real power, reactive power, and volt-amperes are three times the corresponding quantities in the single-phase circuit. Line-to-line voltages, in magnitude, can be obtained by multiplying voltages in the single-phase circuit by √3. When a system of sources is so large that its voltage and frequency remain constant regardless of the power delivered or absorbed, it is known as an *infinite bus*. Such a bus has a voltage and a frequency that are unaffected by external disturbances. The infinite bus is treated as an ideal voltage source. Figure (16) shows the Notation of subscripts that will be used in this book.

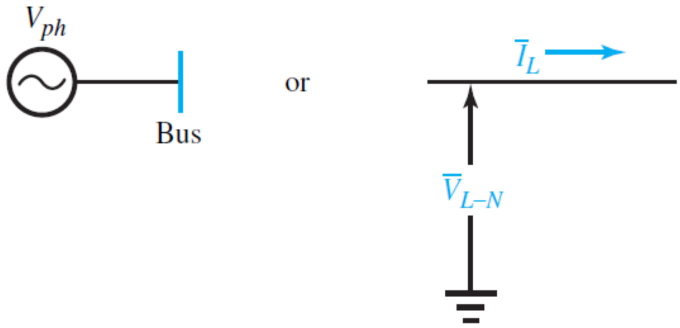


Figure (15) Single-line equivalent circuit.

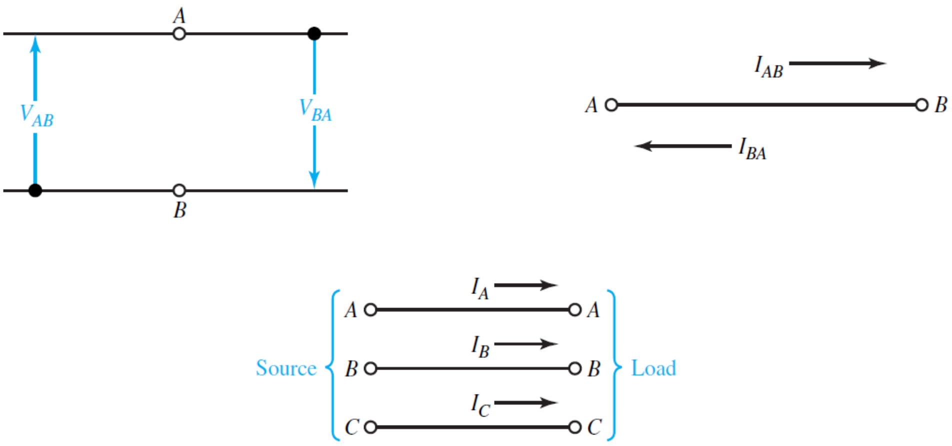


Figure (16) Notation using subscripts

Balanced Three-Phase Loads

Three-phase loads can be connected in either wye (also known as star or Y) or delta (otherwise known as mesh orΔ). If the load impedances in each of the three phases are the same in both magnitude and phase angle, the load is said to be balanced.

Power in Balanced Three-Phase Circuits

The total power delivered by a three-phase source, or consumed by a three-phase load, is found simply by adding the power in each of the three phases. In a balanced circuit, however, this is the same as multiplying the average power in any one phase by 3, since the average power is the same for all phases. Thus one has

$$P = 3\, V_{ph} I_{ph}\, \cos\, \phi \quad (31)$$

where V_{ph} and I_{ph} are the magnitudes of any phase voltage and phase current, cos φ is the load power factor, and φ is the power factor angle between the phase voltage . Vph and the phase current . Iph corresponding to any phase. In view of the relationships between the line and phase quantities for balanced wye- or delta-connected loads, Equation (31) can be rewritten in terms of the line-to-line voltage and the line current for either wye- or delta-connected balanced loading as follows:

$$P = \sqrt{3}\, V_L I_L \cos\phi \quad (32)$$

where V_L and I_L are the magnitudes of the line-to-line voltage and the line current. φ is still the load power factor angle as in Equation (32), namely, the angle between the phase voltage and the corresponding phase current. The real power P is expressed in watts when voltage and current are expressed in volts and amperes, respectively. You may recall that the instantaneous power in single-phase ac circuits absorbed by a pure inductor or capacitor has a zero average value. The instantaneous power absorbed by a pure resistor has a nonzero average value. The instantaneous reactive power is alternately positive and negative, indicating the reversible flow of energy to and from the reactive component of the load. Its amplitude or maximum value is known as the reactive power.

The total reactive power Q (expressed as reactive volt-amperes, or VARs) and the voltamperes for either wye- or delta-connected balanced loadings are given by

$$Q = 3\, V_{ph} I_{ph} \sin\phi \quad (33)$$

or

$$Q = \sqrt{3}\, V_L I_L \sin\phi \quad (34)$$

and

$$S = |\bar{S}| = \sqrt{P^2 + Q^2} = 3\, V_{ph} I_{ph} = \sqrt{3}\, V_L I_L \quad (35)$$

where the complex power S is given by

$$\bar{S} = P + jQ \quad (36)$$

In speaking of a three-phase system, unless otherwise specified, balanced conditions are assumed. The terms voltage, current, and power, unless otherwise identified, are conventionally understood to imply the **line-to-line voltage** (rms value), the **line current** (rms value), and the total power of all three phases. In general, the ratio of the real or average power P to the apparent power or the magnitude of the complex power S is the power factor, which happens to be cos φ in the sinusoidal case.

The Power Diode

Among all the static switching devices used in Power Electronics (PE), the power diode is perhaps the simplest. Its circuit symbol is shown in Fig. (17). It is a two terminal device, and terminal A is known as the anode whereas terminal K is known as the cathode. If terminal A experiences a higher potential compared to terminal K, the device is said to be forward biased and a current called forward current (I_F) will flow through the device in the direction as shown. This causes a small voltage drop across the device (<1V), which in ideal condition is usually ignored. On the contrary, when a diode is reverse biased, it does not conduct and a practical diode does experience a small current flowing in the reverse direction called the leakage current. Both the forward voltage drop and the leakage current are ignored in an ideal diode. Usually in PE applications a diode is considered to be an **ideal static switch**.

The characteristics of a practical diode show a departure from the ideals of zero forward and infinite reverse impedance, as shown in Fig. (18). In the forward direction, a potential barrier associated with the distribution of charges in the vicinity of the junction, together with other effects, leads to a voltage drop. This, in the case of silicon, is in the range of 1V for currents in the normal range. In reverse, within the normal operating range of voltage, a very small current flows which is largely independent of the voltage. For practical purposes, the static characteristics is often represented by Fig. (19). In the figure, the forward characteristic is expressed as a threshold voltage *Vo* and a linear incremental or slope resistance, *r*. The reverse characteristic remains the same over the range of possible leakage currents irrespective of voltage within the normal working range.

From the forward and reverse biased condition characteristics, one can notice that when the diode is forward biased, current rises rapidly as the voltage is increased. Current in the reverse biased region is significantly small until the breakdown voltage of the diode is reached. Once the applied voltage is over this limit, the current will increase rapidly to a very high value limited only by an external resistance.

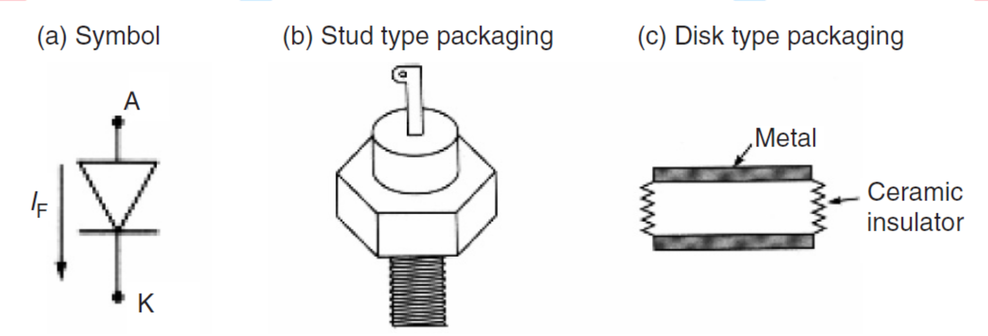


FIGURE (17) Power diode: (a) symbol; (b) and (c) types of packaging.

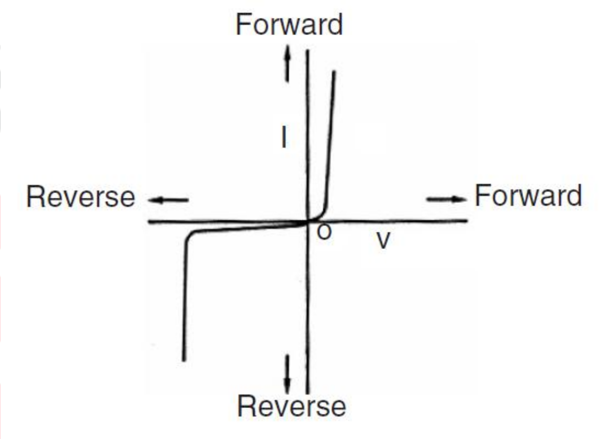


FIGURE (18) Typical static characteristic of a power diode
(forward and reverse have different scale).

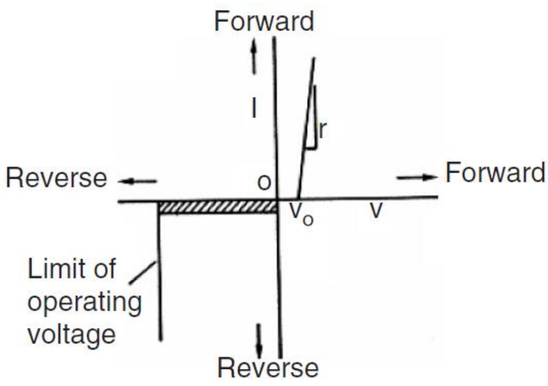


FIGURE (19) Practical representation of the static characteristic of a power diode.

Thyristors

Thyristors are usually three-terminal devices that have four layers of alternating *p*-type and *n*-type material (i.e. three *p*–*n* junctions) comprising its main power handling section. The control terminal of the thyristor, called the gate (*G*) electrode, may be connected to an integrated and complex structure as a part of the device. The other two terminals, called the anode (*A*) and cathode (*K*), handle the large applied potentials (often of both polarities) and conduct the major current through the thyristor. The anode and cathode terminals are connected in series with the load to which power is to be controlled.

Thyristors are used to approximate ideal closed (no voltage drop between anode and cathode) or open (no anode current flow) switches for control of power flow in a circuit. Thyristor circuits must have the capability of delivering large currents and be able to withstand large externally applied voltages. All thyristor types are controllable in switching from a forward-blocking state (positive potential applied to the anode with respect to the cathode, with correspondingly little anode current flow) into a forward-conduction state (large forward anode current flowing, with a small anode–cathode potential drop). Most thyristors have the characteristic that after switching from a forward-blocking state into the forward-conduction state, the gate signal can be removed and the thyristor will remain in its forward-conduction mode. This property is termed “latching” and is an important distinction between thyristors and other types of power electronic devices.

Figure (20) shows a conceptual view of a typical thyristor with the three *p*–*n* junctions and the external electrodes labeled. Also shown in the figure is the thyristor circuit symbol used in electrical schematics.

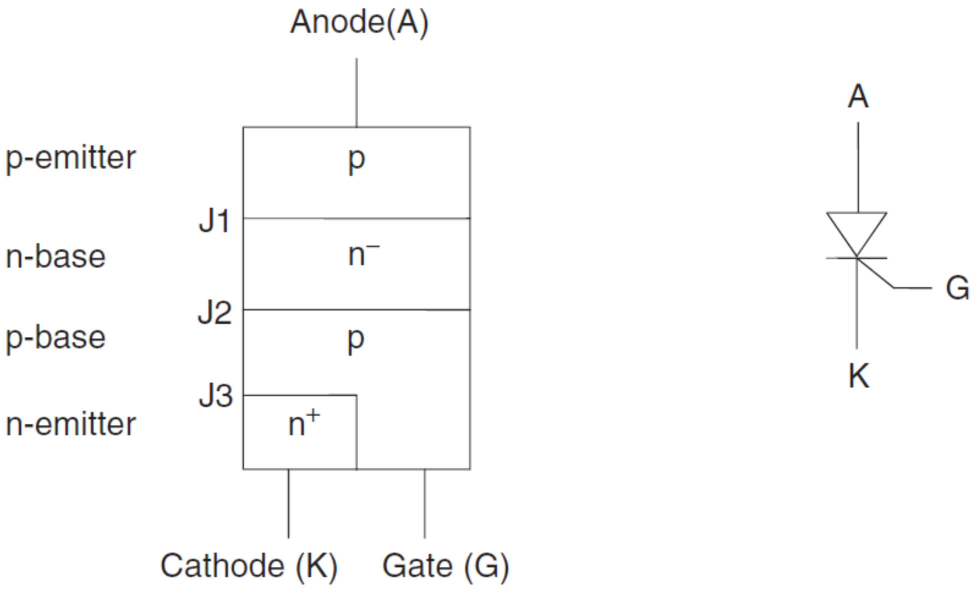


FIGURE (20) Simple cross section of a typical thyristor
and the associated electrical schematic symbols.

Operation of thyristors is as follows. When a positive voltage is applied to the anode (with respect to cathode), the thyristor is in its forward-blocking state. The center junction, J_2 is reverse biased. In this operating mode the gate current is held to zero (open circuit). In practice, the gate electrode is biased to a small negative voltage (with respect to the cathode) to reverse bias the GK-junction J3 and prevent charge-carriers from being injected into the *p*-base. In this condition only thermally generated leakage current flows through the device and can often be approximated as zero in value (the actual value of the leakage current is typically many orders of magnitude lower than the conducted current in the on-state).

When a positive gate current is injected into the device, J_3 becomes forward biased and electrons are injected from the *n*-emitter into the *p*-base. Some of these electrons diffuse across the *p*-base and get collected in the *n*-base. This collected charge causes a change in the bias condition of J_1. The change in bias of J_1 causes holes to be injected from the *p*-emitter into the *n*-base. These holes diffuse across the *n*-base and are collected in the *p*-base. The addition of these collected holes in the *p*-base acts the same as gate current. The entire process is regenerative and will cause the increase in charge carriers until J_2 also becomes forward biased and the thyristor is latched in its on-state (forward-conduction). The regenerative action will take place as long as the gate current is applied in sufficient amount and for a sufficient length of time. This mode of turn-on is considered to be the desired one as it is controlled by the gate signal. Once the thyristor has moved into forward-conduction, any applied gate current is superfluous. The thyristor is latched.

Current-Voltage Curves for Thyristors

A plot of the anode current (i_A) as a function of anode– cathode voltage (v_{AK}) is shown in Fig. (21). The forward-blocking mode is shown as the low-current portion of the graph (solid curve around operating point “1”).With zero gate current and positive v_{AK} , the forward characteristic in the forward blocking-state is determined by the center junction J_2,which is reverse biased. At operating point "1" very little current flows (*Ico* only) through the device. However, if the applied voltage exceeds the forward-blocking voltage, the thyristor switches to its on- or conducting-state (shown as operating point "2") because of carrier multiplication. The effect of gate current is to lower the blocking voltage at which switching takes place. The thyristor moves rapidly along the negatively sloped portion of the curve until it reaches a stable operating point determined by the external circuit (point "2"). The portion of the graph indicating forward-conduction shows the large values of *iA* that may be conducted at relatively low values of v_{AK} , similar to a power diode.

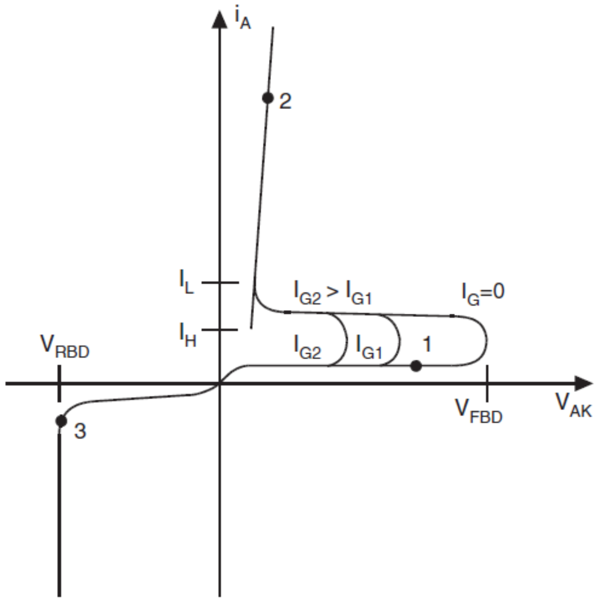


FIGURE (21) Static characteristic *i-v* curve typical of thyristors.

As the thyristor moves from forward-blocking to forward-conduction, the external circuit must allow sufficient anode current to flow to keep the device latched. The minimum anode current that will cause the device to remain in forward-conduction as it switches from forward-blocking is called the latching current I_L. If the thyristor is already in forward-conduction and the anode current is reduced, the device can move its operating mode from forward-conduction back to forward-blocking. The minimum value of anode current necessary to keep the device in forward-conduction after it has been operating at a high anode current value is called the holding current *IH*. The holding current value is lower than the latching current value as indicated in Fig. (21). The reverse thyristor characteristic, quadrant III of Fig. (21), is determined by the outer two junctions (J_1 and J_3), which are reverse biased in this operating mode (applied v_{AK} is negative).

Insulated Gate Bipolar Transistor (IGBT)

The Insulated Gate Bipolar Transistor (IGBT) is a three-terminal power semiconductor switch used to control the electrical energy. Figure (22) shows the symbol of IGBT. Many new applications would not be economically feasible without IGBT's. Typical forward characteristics of an IGBT as a function of gate potential and IGBT transfer characteristics are shown in Fig. (23). The IGBT is in the off-state if the gate-emitter potential is below the threshold voltage. For gate voltages greater than the threshold voltage, the transfer curve is linear over most of the drain current range. To turn-off the IGBT, gate is shorted to the emitter.

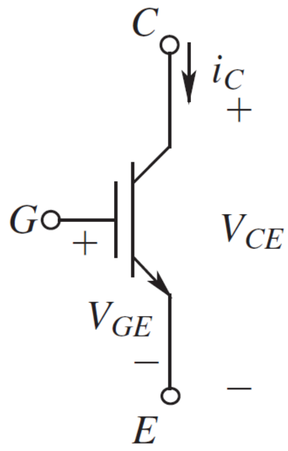


FIGURE (22) Symbol of IGBT

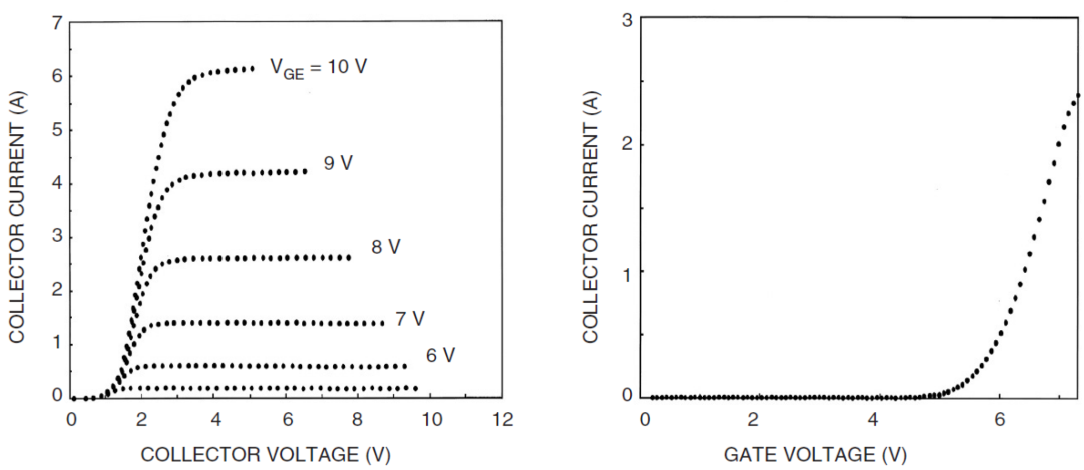


FIGURE (23) IGBT: (a) forward characteristics (b) transfer characteristics.

Chapter 4

Electronic Converters

Objectives

- To explain the operation of uncontrolled and controlled three phase rectifiers
- To demonstrate the waveforms and calculations of three phase rectifiers
- To explain the operation of single-phase and three-phase inverters

Three-phase Diode Rectifiers

Three-phase or diode rectifiers are used for high power output, specifically, higher than 15kW. There are two types of three-phase diode rectifier that convert a three-phase ac supply into a dc voltage, namely, star rectifiers and bridge rectifiers. In the following subsections, the operations of these rectifiers are examined and their performances are analyzed. For the sake of simplicity, the diodes and the transformers are considered to be ideal, i.e. the diodes have zero forward voltage drop and reverse current, and the transformers possess no resistance and no leakage inductance. Furthermore, it is assumed that the load is purely resistive, such that the load voltage and the load current have similar waveforms.

Three-phase Star Rectifier Circuit

A basic three-phase star rectifier circuit is shown in Fig. (1). This circuit can be considered as three single-phase half-wave rectifiers combined together. Therefore it is sometimes referred to as a three-phase half-wave rectifier. The diode in a particular phase conducts during the period when the voltage on that phase is higher than that on the other two phases. The voltage waveforms of each phase and the load are shown in Fig. (2). It is clear that, unlike the single-phase rectifier circuit, the conduction angle of each diode is $2\pi/3$, instead of π. This circuit finds uses where the required dc output voltage is relatively low and the required output current is too large for a practical single-phase system.

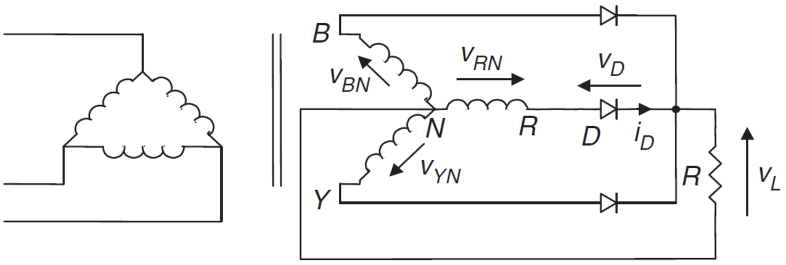


FIGURE (1) Three-phase star rectifier.

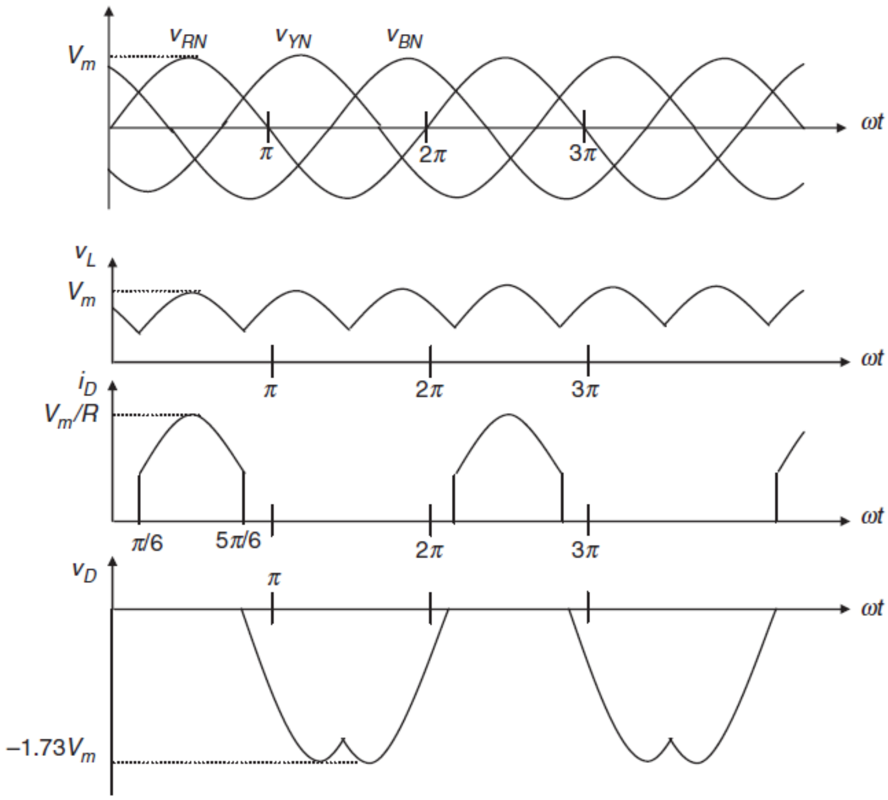


FIGURE (2) Waveforms of voltage and current of the three-phase star rectifier

Taking phase *R* as an example, diode *D* conducts from $\pi/6$ to $5\pi/6$. Therefore, the average value of the output can be found as

$$V_{dc} = \frac{1}{T}\int_0^T v_L(t)\,dt \tag{1}$$

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \sin\theta d\theta \tag{2}$$

$$V_{dc} = V_m \frac{3}{\pi}\frac{\sqrt{3}}{2} = 0.827V_m \tag{3}$$

Similarly, the rms value of the output voltage can be found as

$$V_L = \left[\frac{1}{T}\int_0^T v_L^2(t)dt\right]^{1/2} \tag{4}$$

$$V_L = \sqrt{\frac{3}{2\pi} \int_{\pi/6}^{5\pi/6} (V_m \sin\theta)^2 \, d\theta} \quad (5)$$

$$V_L = V_m \sqrt{\frac{3}{2\pi} \left(\frac{\pi}{3} + \frac{\sqrt{3}}{4} \right)} = 0.84 V_m \quad (6)$$

In addition, the rms current in each transformer secondary winding can also be found as

$$I_s = I_m \sqrt{\frac{1}{2\pi} \left(\frac{\pi}{3} + \frac{\sqrt{3}}{4} \right)} = 0.485 I_m \quad (7)$$

Note that the three-phase star rectifier shown in Fig. (1) has direct currents in the secondary windings that can cause a transformer core saturation problem. In addition, the currents in the primary do not sum to zero. Therefore it is preferable not to have star-connected primary windings.

Three-phase Bridge Rectifiers

Three-phase bridge rectifiers are commonly used for high power applications because they have the highest possible transformer utilization factor for a three-phase system. The circuit of a three-phase bridge rectifier is shown in Fig. (3).

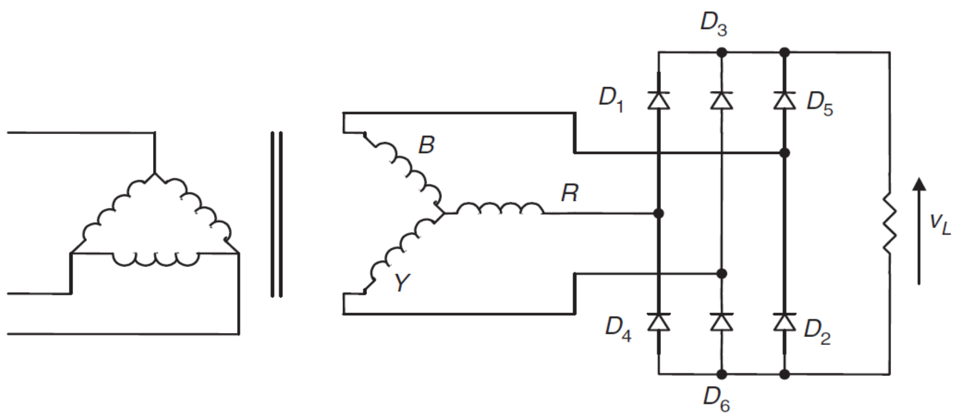


FIGURE (3) Three-phase bridge rectifier.

The diodes are numbered in the order of conduction sequences and the conduction angle of each diode is $2\pi/3$. The conduction sequence for diodes is 12, 23, 34, 45, 56, and 61. The voltage and the current waveforms of the three-phase bridge rectifier are shown in Fig. (4). The line voltage is 1.73 times the phase voltage of a three-phase star connected source. It is permissible to use any combination of star- or delta-connected primary and secondary windings because the currents associated with the secondary windings are symmetrical.

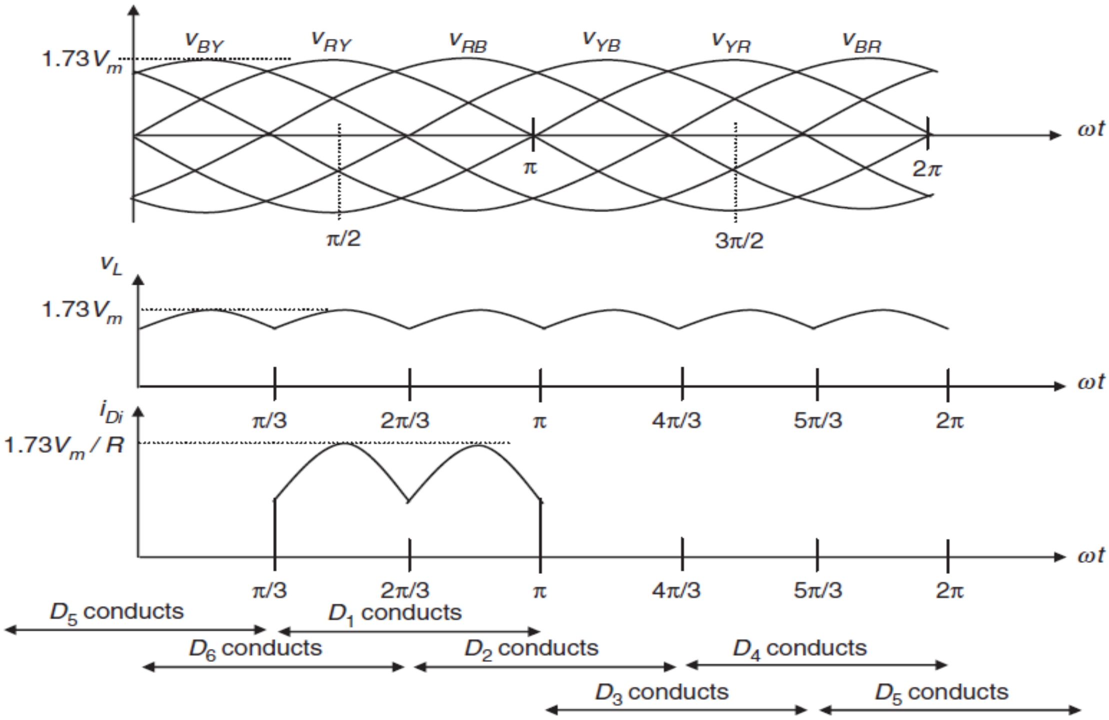


Figure (4) Voltage and current waveforms of the three-phase bridge rectifier.

Using Eq. (1) the average value of the output can be found as

$$V_{dc} = \frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} \sqrt{3}V_m \sin\theta d\theta \quad (8)$$

$$V_{dc} = V_m \frac{3\sqrt{3}}{\pi} = 1.654V_m \quad (9)$$

Similarly, using Eq. (4), the rms value of the output voltage can be found as

$$V_L = \sqrt{\frac{9}{\pi}\int_{\pi/3}^{2\pi/3} (V_m \sin\theta)^2 \, d\theta} \quad (10)$$

$$V_L = V_m\sqrt{\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}} = 1.655V_m \quad (11)$$

In addition, the rms current in each transformer secondary winding can also be found as

$$I_s = I_m\sqrt{\frac{2}{\pi}\left(\frac{\pi}{6} + \frac{\sqrt{3}}{4}\right)} = 0.78I_m \quad (12)$$

and the rms current through a diode is

$$I_D = I_m \sqrt{\frac{1}{\pi}\left(\frac{\pi}{6} + \frac{\sqrt{3}}{4}\right)} = 0.552 I_m \tag{13}$$

this three-phase bridge rectifier is very efficient and popular wherever both dc voltage and current requirements are high. In many applications, no additional filter is required because the output ripple voltage is only 4.2%. Even if a filter is required, the size of the filter is relatively small because the ripple frequency is increased to six times the input frequency.

Three-phase Controlled Rectifiers

Three-phase controlled rectifiers have a wide range of applications, from small rectifiers to large high voltage direct current (HVDC) transmission systems. They are used for electrochemical processes, many kinds of motor drives, traction equipment, controlled power supplies and many other applications.

Three-phase Half-wave controlled Rectifier

Figure (5) shows the three-phase half-wave rectifier topology. To control the load voltage, the half-wave rectifier uses three common-cathode thyristor arrangement. In this figure, the power supply and the transformer are assumed ideal. The thyristor will conduct (*ON* state), when the anode-to-cathode voltage v_{AK} is positive and a firing current pulse i_G is applied to the gate terminal. Delaying the firing pulse by an angle α controls the load voltage.

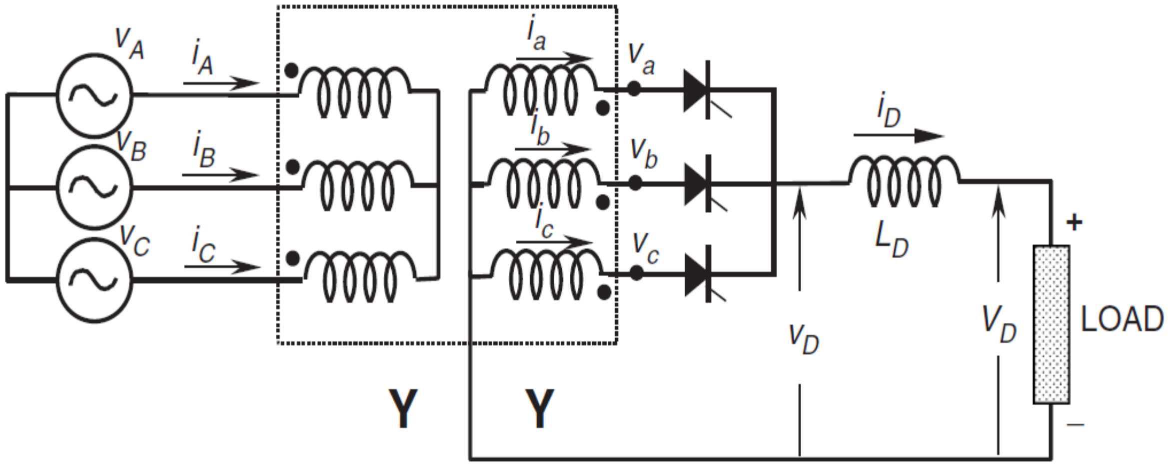


FIGURE (5) Three-phase half-wave rectifier.

As shown in Fig. (6), the firing angle α is measured from the crossing point between the phase supply voltages. At that point, the anode-to-cathode thyristor voltage v_{AK} begins to be positive.

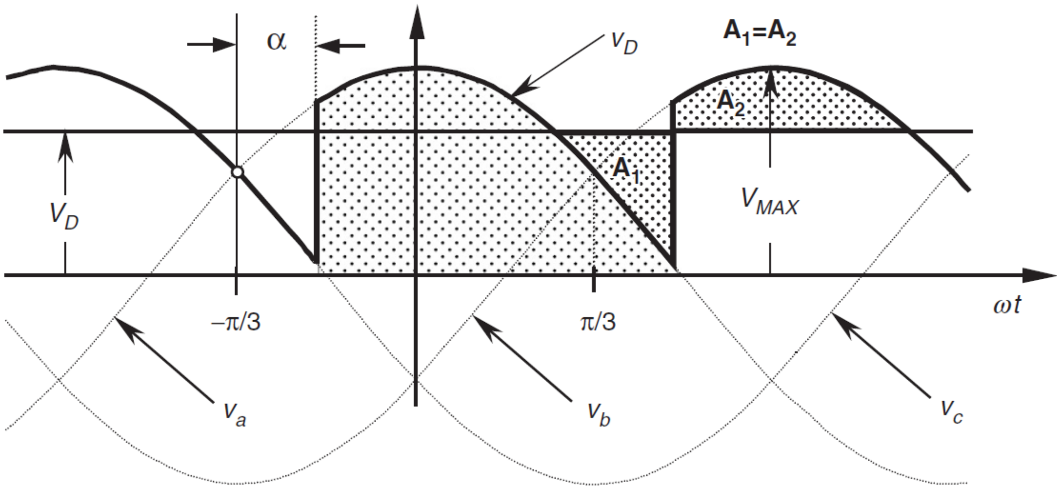


FIGURE (6) Instantaneous *dc* voltage v_D, average *dc* voltage V_D, and firing angle α.

As shown in Fig. (7), when the load is resistive, current i_d has the same waveform of the load voltage. As the load becomes more and more inductive, the current flattens and finally becomes constant. The thyristor goes to the non-conducting condition (*OFF* state) when the next thyristor is switched *ON*, or the current, tries to reach a negative value.

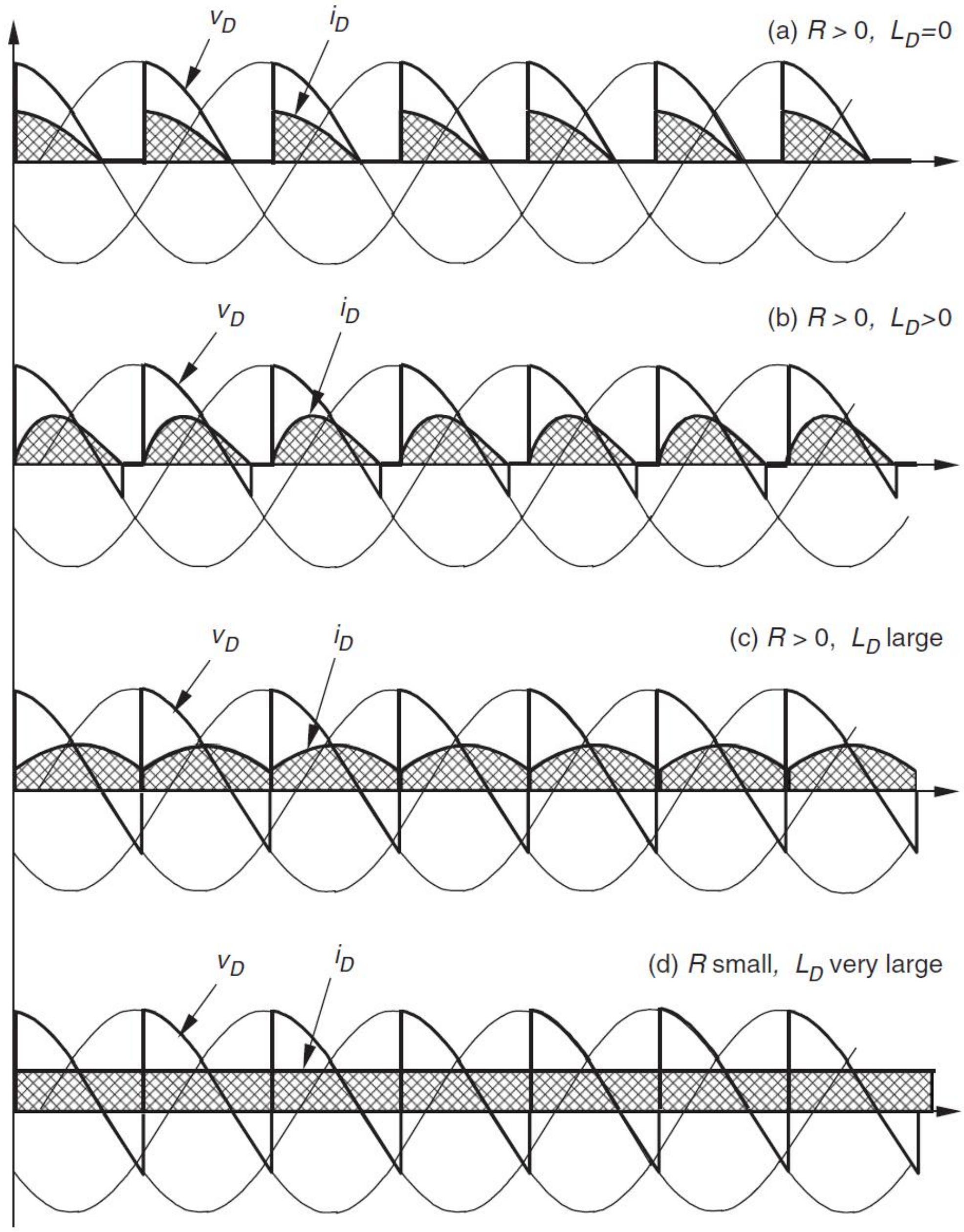


FIGURE (7) *DC* current waveforms.

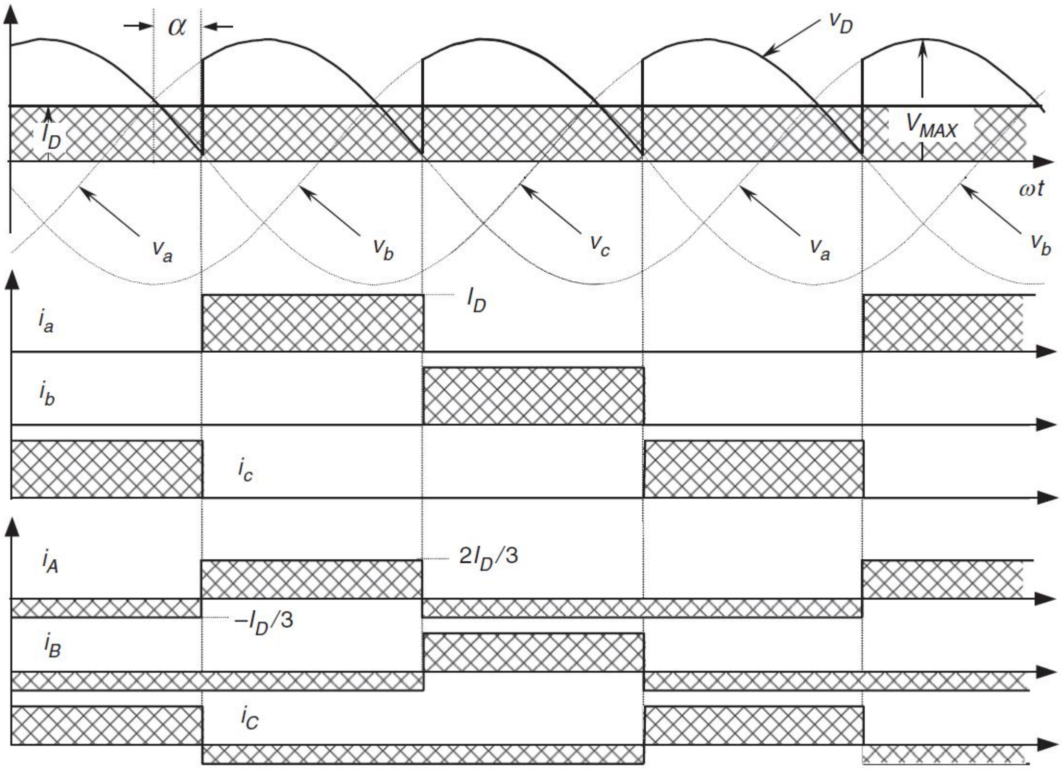


FIGURE (8) *AC* current waveforms for the half-wave rectifier.

With the help of Fig. (6), the load average voltage can be evaluated, and is given by:

$$V_D = \frac{V_{MAX}}{\frac{2}{3}\pi} \int_{-\pi/3+\alpha}^{\pi/3+\alpha} \cos\omega t \cdot d(\omega t)$$

$$= V_{MAX} \frac{\sin\frac{\pi}{3}}{\frac{\pi}{3}} \cdot \cos\alpha \approx 1.17 \cdot V_{f-N}^{rms} \cdot \cos\alpha \qquad (14)$$

where V_{MAX} is the secondary phase-to-neutral peak voltage, $V^{rms}{}_{f-N}$ its root mean square (*rms)* value and ω is the angular frequency of the main power supply. It can be seen from Eq. (13) that the load average voltage V_D is modified by changing firing angle α. When $\alpha < 90^\circ$, V_D is positive and when $\alpha > 90^\circ$, the average *dc* voltage becomes negative. In such a case, the rectifier begins to work as an inverter and the load needs to be able to generate power reversal by reversing its *dc* voltage.

Three-phase Full-wave Controlled Rectifier (Three-phase controlled Bridge)

The full-wave rectifier of is shown in Fig. (9). With this arrangement, it can be seen that the three common cathode valves generate a positive voltage with respect to the neutral, and the three common anode valves produce a negative voltage. The result is a *dc* voltage, twice the value of the half-wave rectifier. Each half of the bridge is a three-pulse converter group. This bridge connection is a two-way connection and alternating currents flow in the valve-side transformer windings during both half periods, avoiding *dc* components into the windings, and saturation in the transformer magnetic core. These characteristics make the so-called Three-phase bridge the most widely used thyristor rectifier. The configuration does not need any special transformer. The series characteristic of this rectifier produces a *dc* voltage twice the value of the half-wave rectifier.

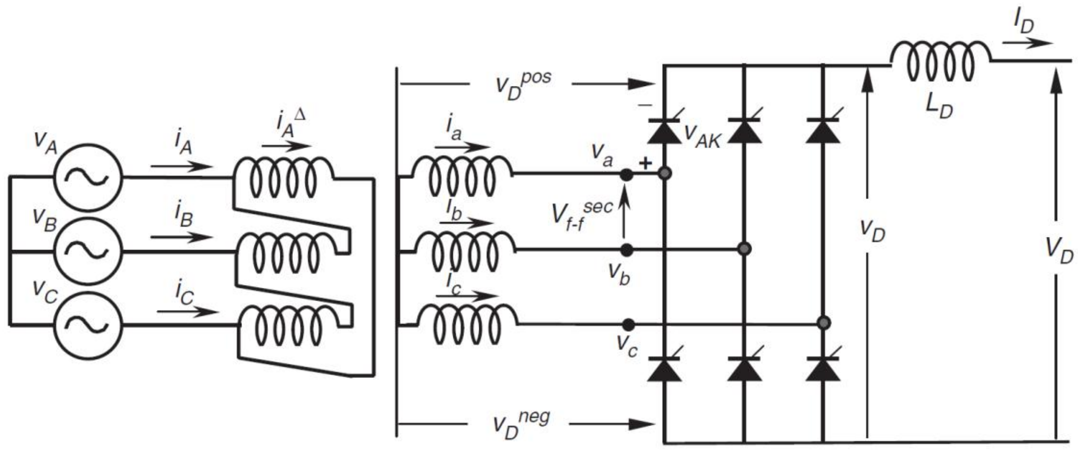


FIGURE (9) Three-phase full-wave controlled rectifier

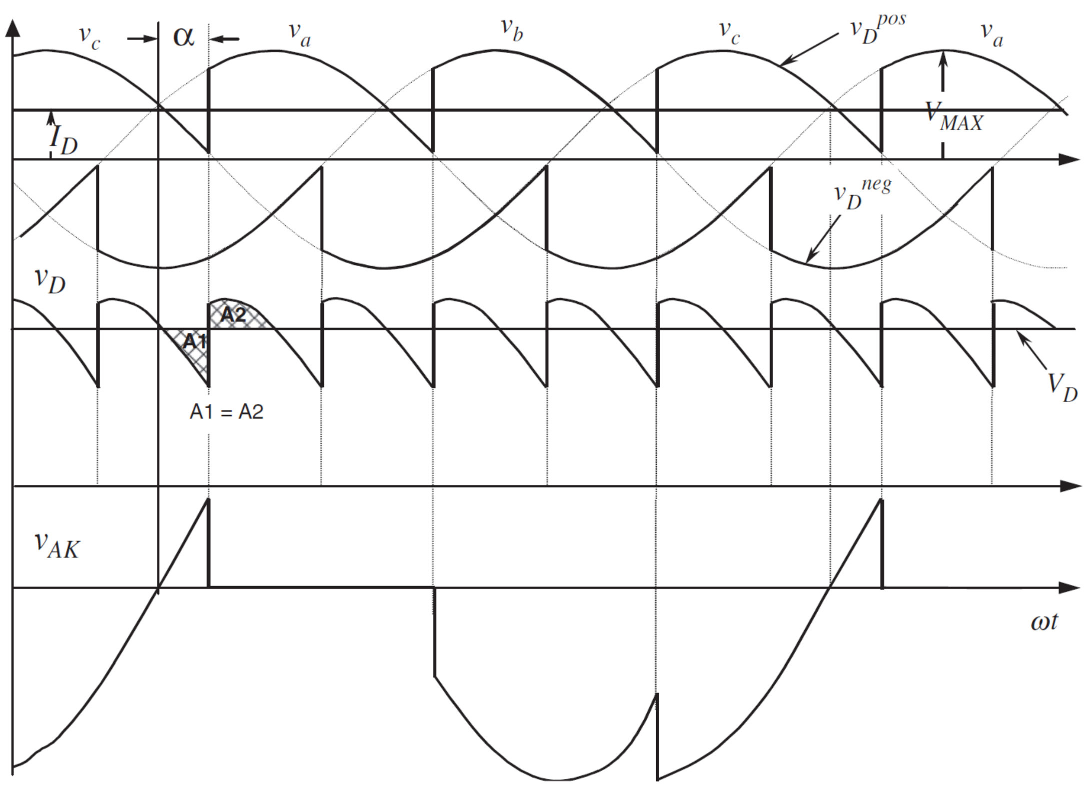


FIGURE (10) Voltage waveforms for the Three-phase bridge.

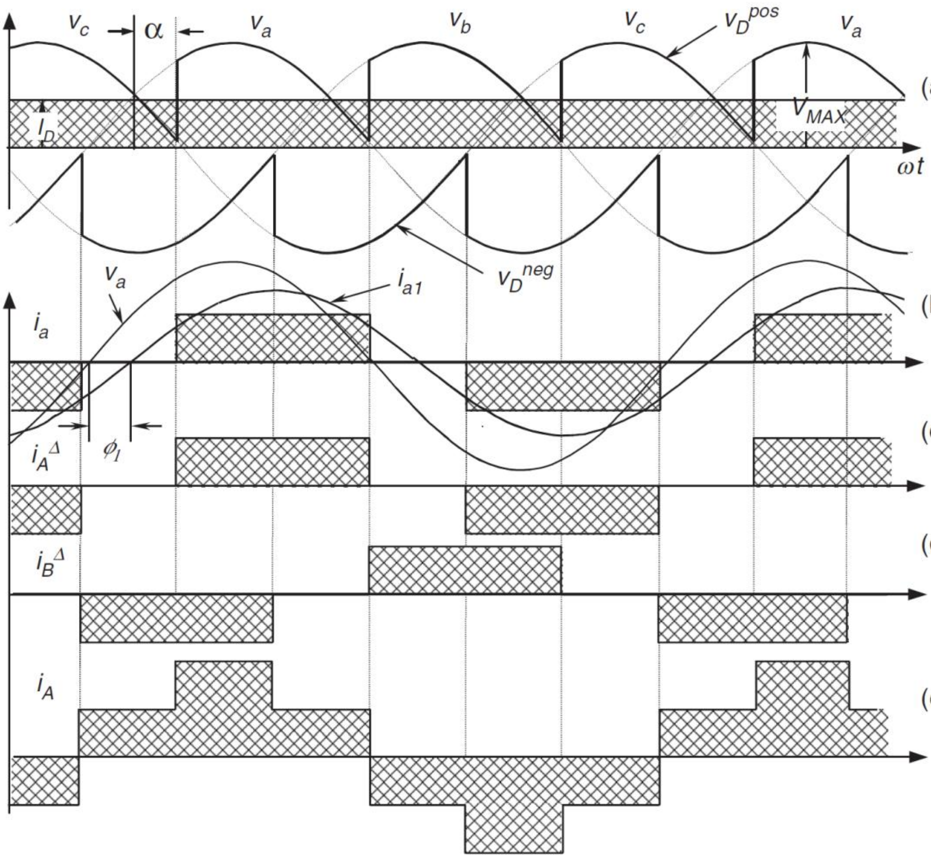


FIGURE (11) Current waveforms for the three-phase bridge.

The load average voltage is given by:

$$V_D = \frac{2 \cdot V_{MAX}}{\frac{2}{3}\pi} \int_{-\pi/3+\alpha}^{\pi/3+\alpha} \cos\omega t \cdot d(\omega t)$$

$$= 2 \cdot V_{MAX} \frac{\sin\frac{\pi}{3}}{\frac{\pi}{3}} \cdot \cos\alpha \approx 2.34 \cdot V_{f-N}^{rms} \cdot \cos\alpha \tag{15}$$

Or

$$V_D = \frac{3 \cdot \sqrt{2} \cdot V_{f-f}^{sec}}{\pi} \cos\alpha \approx 1.35 \cdot V_{f-f}^{sec} \cdot \cos\alpha \tag{16}$$

Figure (10) shows the voltages of each half-wave bridge of this topology, V_D^{pos} and V_D^{neg}, the total instantaneous *dc* voltage V_D, and the anode-to-cathode voltage V_{AK} in one of the bridge thyristors. The maximum value of V_{AK} is $\sqrt{3}\ V_{MAX}$, which is the same as that of the half-wave converter. The double star rectifier presents a maximum anode-to-cathode voltage of two times V_{MAX}. Figure **(11)** shows the currents of the rectifier, which assumes that L_D is large enough to keep the *dc* current smooth. The example is for the same *Y* transformer connection shown in the topology of Fig. (9). It can be noted that the secondary currents do not carry any *dc* component, thereby avoiding overdesign of the windings and transformer saturation. These two figures have been drawn for a firing angle, α of approximately 30°. The perfect symmetry of the currents in all windings and lines is one of the reasons why this rectifier is the most popular of its type. Figure (12) shows a three-phase bridge with a Free-Wheeling Diode (FWD), which eliminates the negative portions of the load voltage leading to a significant increase.

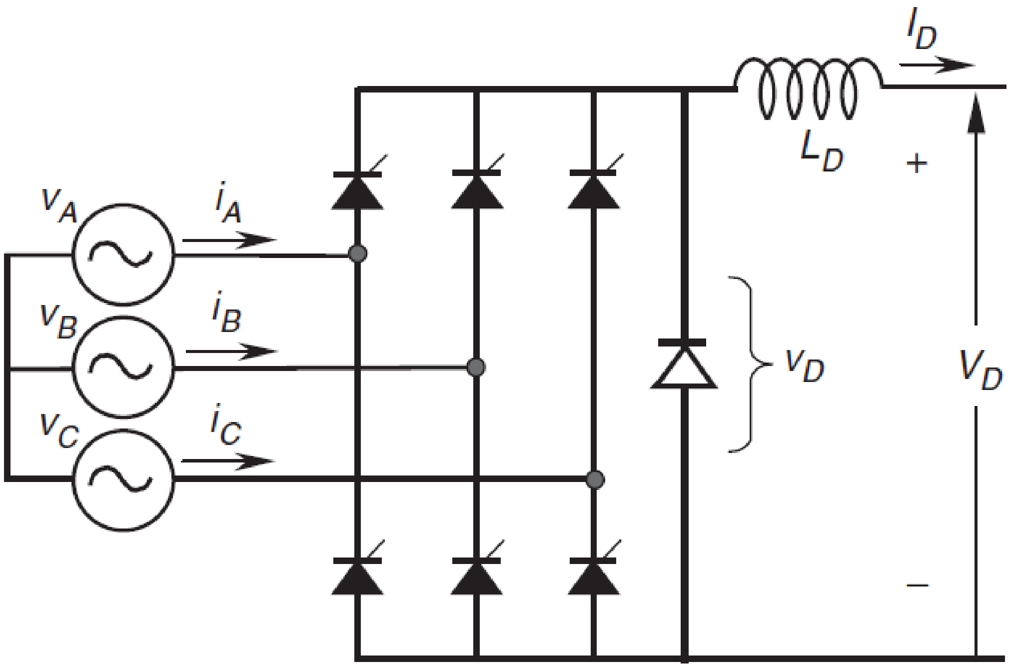


FIGURE (12) Free-Wheeling Diode bridge.

Inverters

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in Adjustable Speed Drives (ASDs), Uninterruptible Power Supplies (UPSs), static VAR compensators and active filters. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According to the type of ac output waveform, these topologies can be considered as Voltage-Source Inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as ASDs, which are the most popular application of inverters (Fig. (13)).

Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones. For instance, the ac output voltage produced by the VSI of a three-level ASD is a, Pulse Width Modulation (PWM) type of waveform. The VSI generates an ac output voltage waveform composed of discrete values (high dv/dt); therefore, the load should be inductive at the harmonic frequencies in order to produce a smooth current waveform.

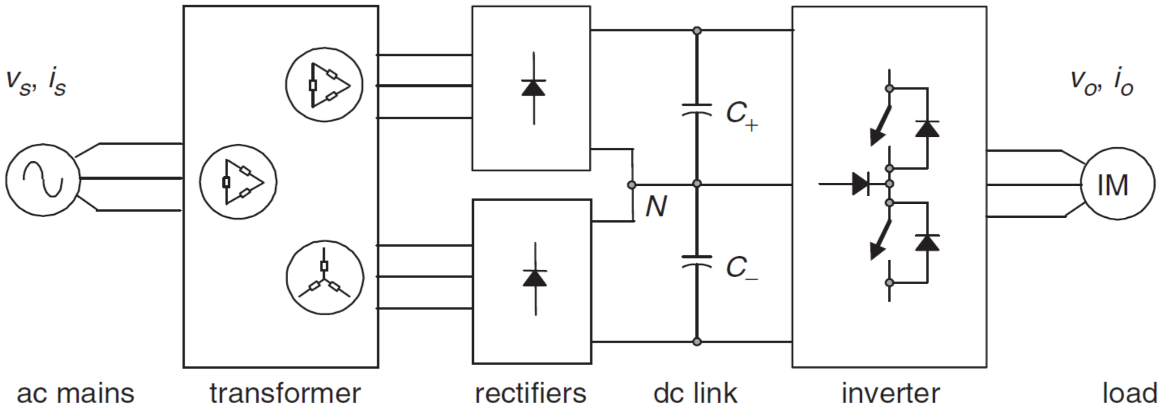


FIGURE (13) A three-level adjustable speed drive scheme

Single-phase Voltage Source Inverters (VSI)

Single-phase VSI can be found as half-bridge and full-bridge topologies. Although, the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form high-power static power topologies

Full-bridge VSI

Figure (14) shows the power topology of a full-bridge VSI. The existence of two legs provides the neutral point to the load. As expected, both switches S1+ and S1− (or S2+ and S2−) cannot be on simultaneously because a short circuit across the dc link voltage source v_i would be produced. There are four defined (states 1, 2, 3, and 4) and one undefined (state 5) switch state as shown in Table (1).

The undefined condition should be avoided so as to be always capable of defining the ac output voltage always. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value v_i.

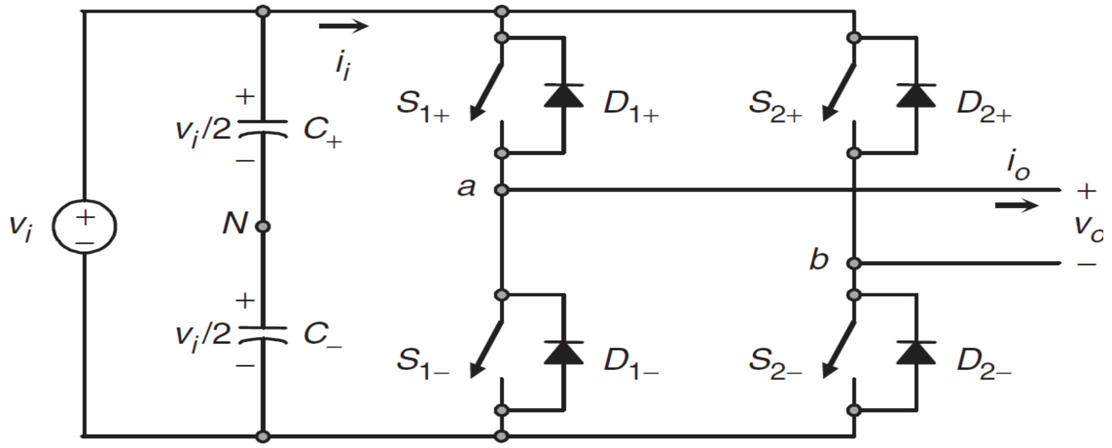
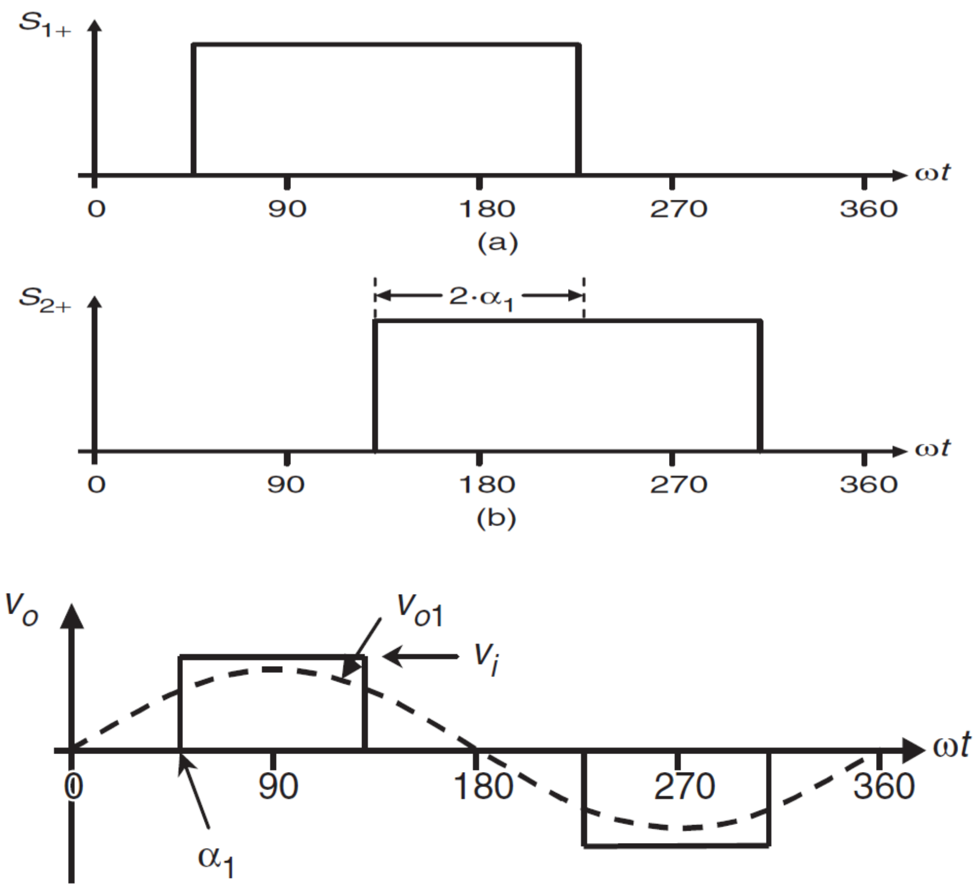


FIGURE (14) Single-phase full-bridge VSI.

TABLE (1) Switch states for a full-bridge single-phase VSI

State	State #	v_{aN}	v_{bN}	v_o	Components conducting	
S_{1+} and S_{2-} are on and S_{1-} and S_{2+} are off	1	$v_i/2$	$-v_i/2$	v_i	S_{1+} and S_{2-} D_{1+} and D_{2-}	if $i_o > 0$ if $i_o < 0$
S_{1-} and S_{2+} are on and S_{1+} and S_{2-} are off	2	$-v_i/2$	$v_i/2$	$-v_i$	D_{1-} and D_{2+} S_{1-} and S_{2+}	if $i_o > 0$ if $i_o < 0$
S_{1+} and S_{2+} are on and S_{1-} and S_{2-} are off	3	$v_i/2$	$v_i/2$	0	S_{1+} and D_{2+} D_{1+} and S_{2+}	if $i_o > 0$ if $i_o < 0$
S_{1-} and S_{2-} are on and S_{1+} and S_{2+} are off	4	$-v_i/2$	$-v_i/2$	0	D_{1-} and S_{2-} S_{1-} and D_{2-}	if $i_o > 0$ if $i_o < 0$
S_{1-}, S_{2-}, S_{1+}, and S_{2+} are all off	5	$-v_i/2$ $v_i/2$	$v_i/2$ $-v_i/2$	v_i $-v_i$	D_{1-} and D_{2+} D_{1+} and D_{2-}	if $i_o > 0$ if $i_o < 0$

Several modulating techniques have been developed that are applicable to full-bridge VSIs. They mainly differ in the sequence and duration of Devices' switching. FIGURE (15) shows the voltage waveforms resulting from the harmonic cancellation technique.



(c)

FIGURE (15) The full-bridge VSI.
Ideal waveforms for the output control by harmonic cancellation: (a) switch *S*1+ state; (b) switch *S*2+ state; (c) ac output voltage

Three-phase Voltage Source Inverters

Single-phase VSI's cover low-range power applications and three-phase VSIs cover medium- to high-power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. Although most of the applications require sinusoidal voltage waveforms (e.g. ASDs, UPSs, FACTS, VAR compensators), arbitrary voltages are also required in some emerging applications (e.g. active filters, voltage compensators). The standard three-phase VSI topology is shown in Fig. (16) and the eight valid switch states are given in Table (1).

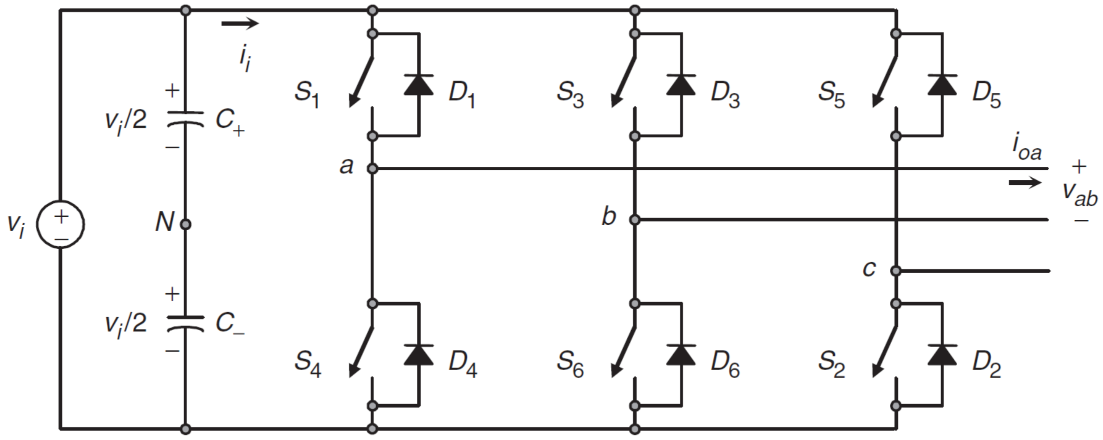


FIGURE (16) Three-phase VSI topology.

As in single-phase VSIs, the switches of any leg of the inverter (*S*1 and *S*4, *S*3 and *S*6, or *S*5 and *S*2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity.

Of the eight valid states, two of them (7 and 8 in Table (2)) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states (1 to 6 in Table (2)) produce non-zero ac output voltages. In order to generate a given voltage waveform, the inverter moves from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages that are v_i, 0, and $-v_i$ for the topology shown in Fig. (16). The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states.

TABLE (2) Valid switch states for a three-phase VSI

State	State #	v_{ab}	v_{bc}	v_{ca}	Space vector
S_1, S_2, and S_6 are on and S_4, S_5, and S_3 are off	1	v_i	0	$-v_i$	$\vec{\mathbf{v}}_1 = 1 + j0.577$
S_2, S_3, and S_1 are on and S_5, S_6, and S_4 are off	2	0	v_i	$-v_i$	$\vec{\mathbf{v}}_2 = j1.155$
S_3, S_4, and S_2 are on and S_6, S_1, and S_5 are off	3	$-v_i$	v_i	0	$\vec{\mathbf{v}}_3 = -1 + j0.577$
S_4, S_5, and S_3 are on and S_1, S_2, and S_6 are off	4	$-v_i$	0	v_i	$\vec{\mathbf{v}}_4 = -1 - j0.577$
S_5, S_6, and S_4 are on and S_2, S_3, and S_1 are off	5	0	$-v_i$	v_i	$\vec{\mathbf{v}}_5 = -j1.155$
S_6, S_1, and S_5 are on and S_3, S_4, and S_2 are off	6	v_i	$-v_i$	0	$\vec{\mathbf{v}}_6 = 1 - j0.577$
S_1, S_3, and S_5 are on and S_4, S_6, and S_2 are off	7	0	0	0	$\vec{\mathbf{v}}_7 = 0$
S_4, S_6, and S_2 are on and S_1, S_3, and S_5 are off	8	0	0	0	$\vec{\mathbf{v}}_8 = 0$

Square-wave Operation of Three-phase VSI's

Similar to the single-phase inverter, several modulating techniques have been developed too. The square-wave operation is illustrated in Fig. (17), where the power valves are on for 180◦. Odd switches (S_1 - S_3 - S_5) are triggered by similar gate signals shifted 120°. The same rule applies for even switches (S_2 - S_4 - S_6) while each one of the six switches is always in compliment state with the his partner on the same leg. This sequence of triggering yields three symmetrical line voltages shifted by 120° (V_{ab} is shown in figure). Finally, filters could be used to obtain the fundamental sinusoidal component out of the resultant ac output voltage of the inverter.

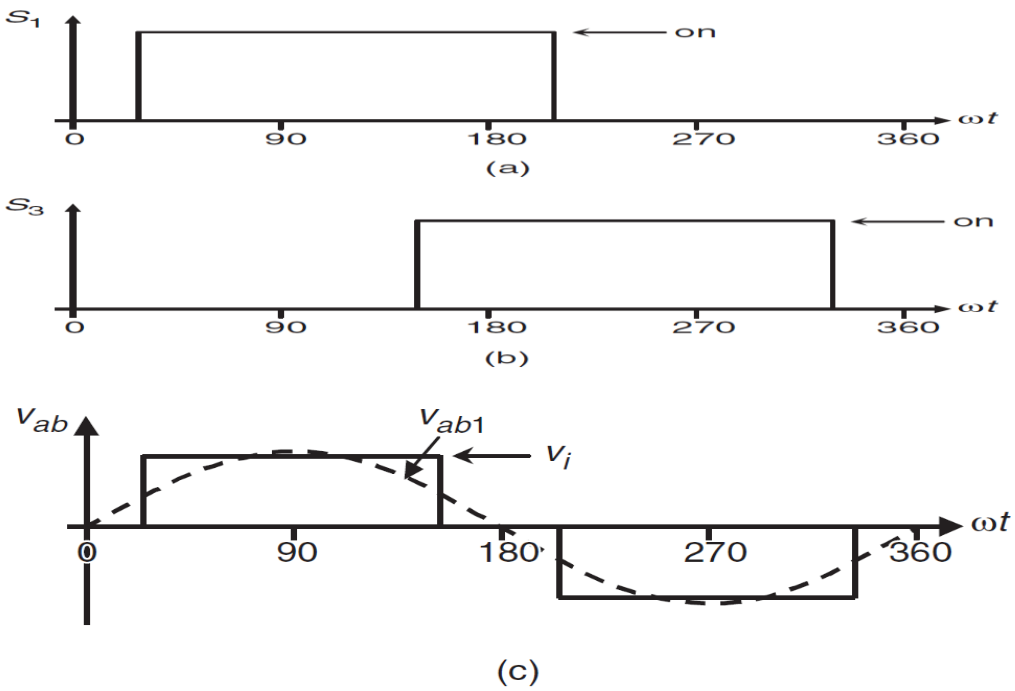


FIGURE (17) The three-phase VSI. Square-wave operation: (a) switch *S1* state (b) switch *S3* state (c) ac output voltage

Chapter 5

Fundamentals of DC motor control

Objective

- To understand the Induce torque principle of DC motor
- To study the methods of DC motor speed control.

The Induced Torque in the Rotating Loop

To understand the induced torque principle let us suppose that a battery is connected to the machine in Figure 1. The resulting configuration is shown in Figure 2. How much torque will be produced in the loop when the switch is closed and a current is allowed to flow into it ? To determine the torque, look at the close-up of the loop shown in Figure (2-b). The approach to take in determining the torque on the loop is to look at one segment of the loop at a time and then sum the effects of all the individual segments. The force on a segment of the loop is given by Equation (1):

$F = I\,(l \times B)$ (1)

And the torque on the segment is given by

$T = r * F * \sin(\theta)$ (2)

Where (θ) is the angle between r and F. The torque is essentially zero whenever the loop is beyond the pole edges. While the loop is under the pole faces, the torque is :

I. Segment ab: In segment ab, the current from the battery is directed out of the page. The magnetic field under the pole face is pointing radially out of the rotor.

So the force on the wire is given by

$F_{ab} = I\,(l \times B)$ (3)

$= I\,l\,B$ tangent to direction of motion

The torque on the rotor caused by this force is

$T_{ab} = r * F * \sin(\theta)$ (4)

$= r\,(I\,l\,B) * \sin 90$

$= r * I * l * B$ CCW (5)

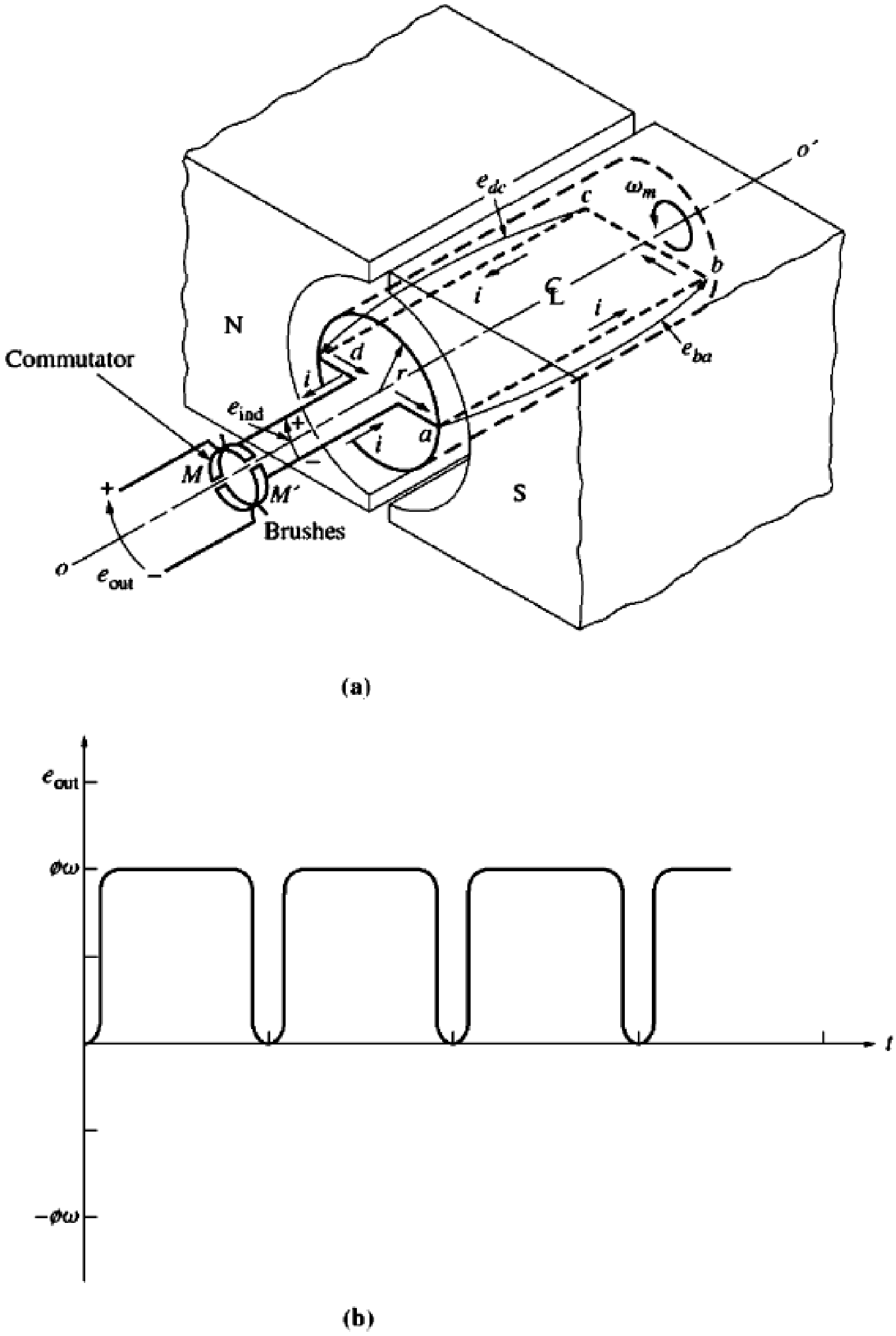


Fig. 1 DC output of the machine with a commutator and brushes

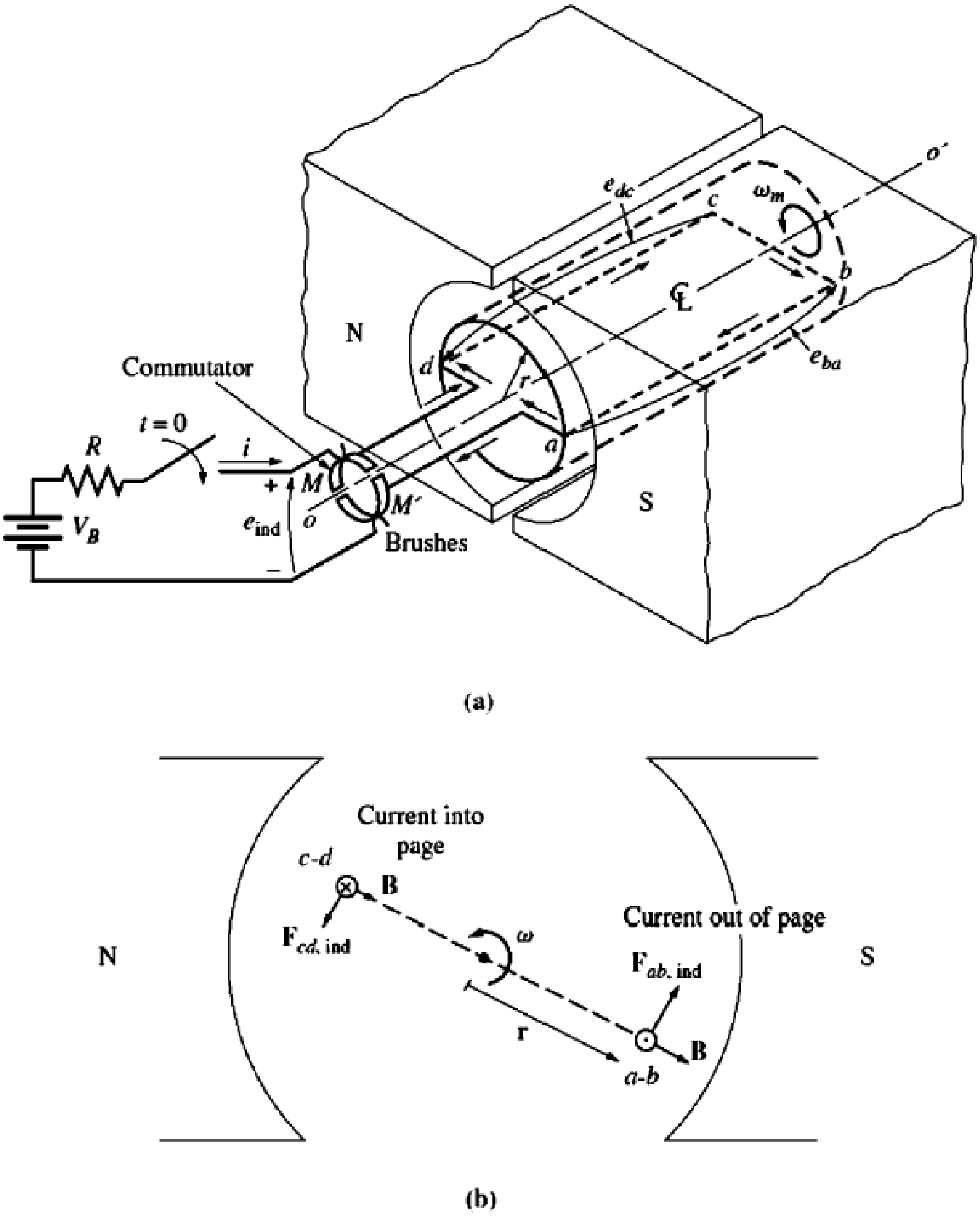


Fig. 2 Induced torque in the loop

2- Segment bc: In segment bc, the current from the battery is flowing from the upper left to the lower right in the picture. The force induced on the wire is given by

$F_{bc} = I\ (l \times B)$ (6)

$= 0$ since l is parallel to B

Therefore,

$T_{bc} = 0$ (7)

3. Segment cd: In segment cd, the current from the battery is directed into the page. The magnetic field under the pole face is pointing radially into the rotor, so the force on the wire is given by

$F_{cd} = I\ (l \times B)$ (8)

$= I\ l\ B$ tangent to direction of motion

The torque on the rotor caused by this force is

T_{cd} = r * F * sin (θ)

= r (I l B) sin 90

= r I l B CCW (9)

4- Segment da: In segment da, the current from the battery is flowing from the upper left to the lower right in the picture. The force induced on the wire is given by

F_{da} = I (I X B) (10)

= 0 since l is parallel to B

Therefore,

$T_{da} = 0$

The resulting total induced torque on the loop is given by

$T_{ind} = T_{ab} + T_{bc} + T_{cd} + T_{da}$

T_{ind} = 2 r I L B under the pole faces

= 0 beyond the pole edges (11)

By using the facts that $A_p = \pi r l$ and $\varphi i = A_p * B$, the torque expression can be reduced to :

$T_{ind} = 2\ \varphi_i\ /\ \pi$ under the pole faces

= 0 beyond the pole edges (12)

Thus, the torque produced in the machine is the product of the flux in the machine and the current in the machine, times some quantity representing the mechanical construction of the machine (the percentage of the rotor covered by pole faces). In general, the torque in any real machine will depend on the same three factors:

1- The flux in the machine
2- The current in the machine
3- A constant representing the construction of the machine

DC motor control

There are four major types of dc motors in general use:

I. The separately excited dc motor
2. The shunt dc motor
3. The series dc motor
4. The compounded dc motor

THE EQUIVALENT CIRCUIT of a DC MOTOR

The equivalent circuit of a dc motor is shown in Figure 3. In this figure, the armature circuit is represented by an ideal voltage source E_A, and a resistor R_A). This representation is really the Thevenin equivalent of the entire rotor structure, including rotor coils, inter-poles, and compensating windings, if present. The brush voltage drop is represented by a small battery V_{bruch} opposing the direction of current flow in the machine. 1lle field coils, which produce the magnetic flux in the generator, are represented by inductor L_F and resistor R_F. The separate resistor R_{adj} represents an external variable resistor used to control the amount of current in the field circuit. There are a few variations and simplifications of this basic equivalent circuit. The brush drop voltage is often only a very tiny fraction of the generated voltage in a machine. Therefore, in cases where it is not too critical, the brush drop voltage may be left out or approximately included in the value of R_A). Also, the internal resistance of the field coils is sometimes lumped together with the variable resistor, and the total is called R_F (see Figure 3b). A third variation is that some generators have more than one field coil, all of which will appear on the equivalent circuit. The internal generated voltage in this machine is given by the equation

$$E_A = K \varphi \omega \quad (13)$$

And the induced torque developed by the machine is given by

$$T_{ind} = K \varphi I_A \quad (14)$$

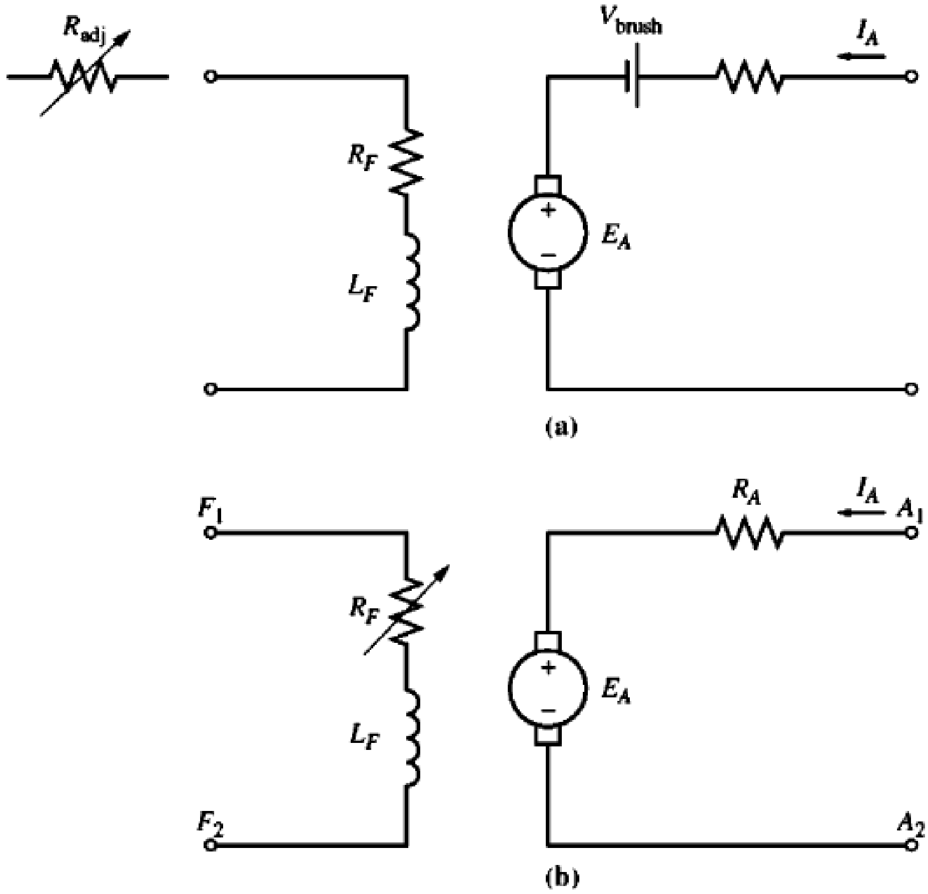


Fig. 3 (a) The equivalent circuit of DC motor (b) same as "a" but after eliminating of brush voltage drop and combining R_{adj} with field resistance

SEPARATELY EXCITED and SHUNT DC MOTORS

The equivalent circuit of a separately excited dc motor is shown in Figure 4-a and the equivalent circuit of a shunt dc motor is shown in Figure 4-b. A separately excited dc motor is a motor whose field circuit is supplied from a separate constant-voltage power supply, while a shunt dc motor is a motor whose field circuit gets its power directly across the armature terminals of the motor. When the supply voltage to a motor is assumed constant, there is no practical difference in behavior between these two machines. Unless otherwise specified, whenever the behavior of a shunt motor is described, the separately excited motor is included, too.

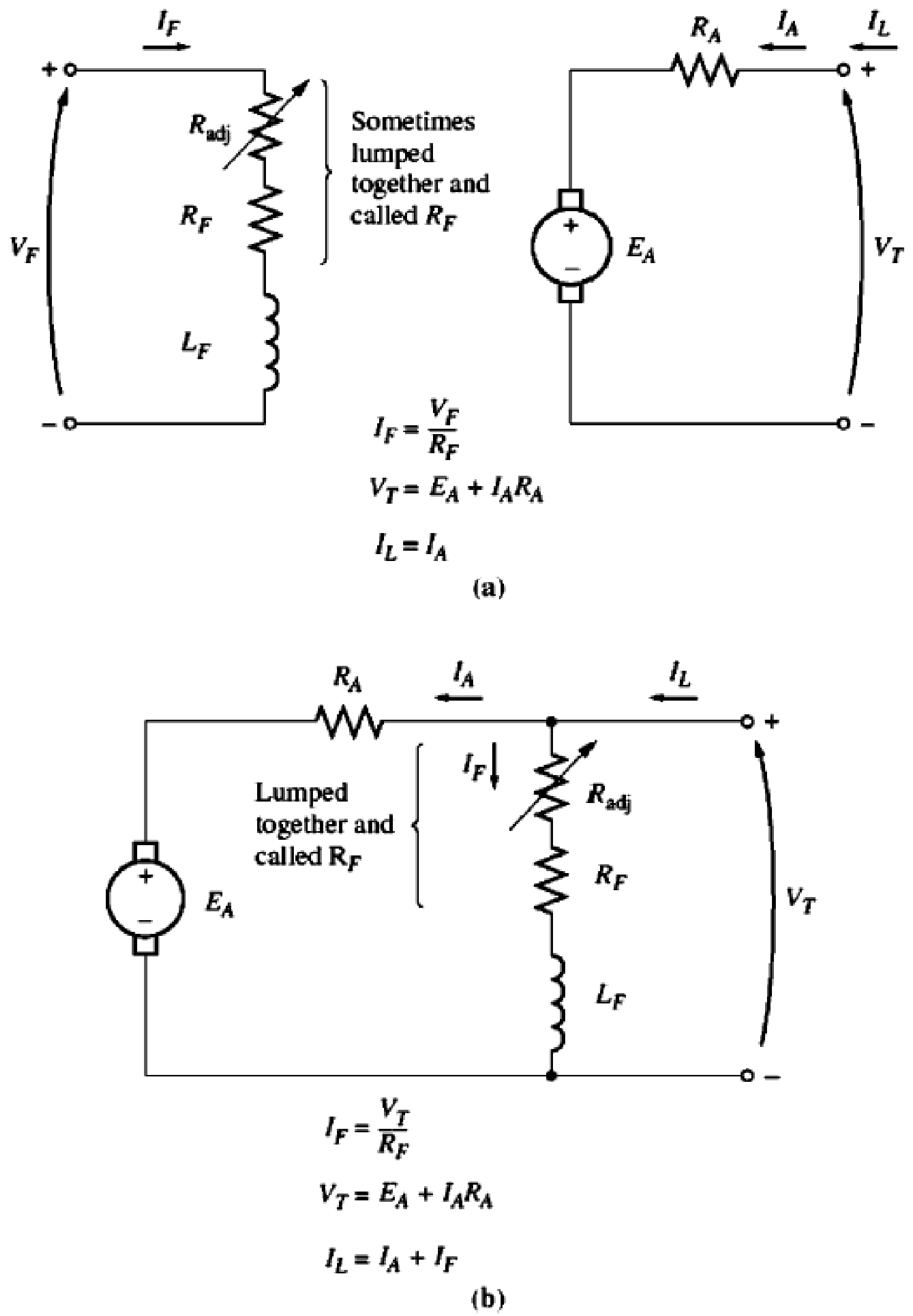


Fig. 4 (a) equivalent circuit of separately excited dc motor (b) equivalent circuit of a shunt dc motor

The Kirchhoff's voltage law (KVL) equation for the armature circuit of these motors is

$V_T = E_A + I_A R_A$ (15)

Sub from 6-12 and 6-13

$\omega = (V_T / K \varphi) - [(RA / (K \varphi)^2) T_{ind}]$ (16)

Speed Control of Shunt DC Motors

The two common ways in which the speed of a shunt dc machine can be controlled are by

1. Adjusting the field resistance RF (and thus the field flux)
2. Adjusting the terminal voltage applied to the armature.

The less common method of speed control is by

3. Inserting a resistor in series with the armature circuit.

Each of these methods is described in detail below.

CHANGING THE FIELD RESISTANCE:

To understand what happens when the field resistor of a dc motor is changed. Assume that the field resistor increases and observe the response. If the field resistance increases, then the field current decreases ($I_F = V_T/R_F$), and as the field current decreases, the flux decreases with it. A decrease in flux causes an instantaneous decrease in the internal generated voltage ($E_A = K\,\varphi\,\omega$) which causes a large increase in the machine's armature current, since

$I_A = (V_T - E_A) / R_A$ (17)

The induced torque in a motor is given by $T_{ind} = K\,\varphi\,I_A$ Since the flux in this machine decreases while the current I_A increases, which way does the induced torque change? 1lle easiest way to answer this question is to look at an example. Figure 5 shows a shunt dc motor with an internal resistance of 0.25 Ω. It is currently operating with a terminal voltage of 250 V and an internal generated voltage of 245 V. therefore, the armature current now is I_A = (250 V –245 V)/0.25 Ω = 20 A. What happens in this motor if there is a 1 percent decrease in flux? If the flux decreases by 1 percent, then E_A must decrease by 1 percent too, because EA = K φ ω. Therefore, E_A will drop to

$E_{A2} = 0.99\,E_{A1}$ = 0.99 (245 V) = 242.55 V (18)

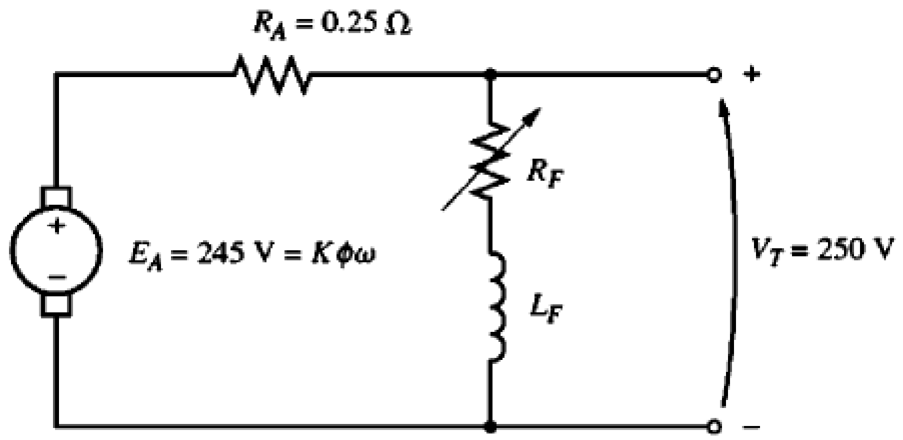


Fig. 5 A 250 V shunt dc motor

The armature current must then rise to I_A = (250 V - 242.55 V) / 0.25 Ω = 298 A Thus a 1 percent decrease in flux produced a 49 percent increase in armature current. So to get back to the original discussion, the increase in current predominates over the decrease in flux, and the induced torque rises: $T_{ind} = K\,\varphi\,I_A$. Since $T_{ind} > T_{load}$ the motor speeds up. However, as the motor speeds up, the internal generated voltage E_A rises, causing I_A to fall. As I_A falls, the induced torque T_{ind} falls too, and finally T_{ind} again equals T_{load} at a higher steady-state speed than originally.

CHANGING THE ARMATURE VOLTAGE.

The second form of speed control involves changing the voltage applied to the armature of the motor without changing the voltage applied to the field. A connection similar to that in Figure 6 is necessary for this type of control. In effect, the motor must be separately excited to use armature voltage control.

If the voltage V_T is increased, then the armature current in the motor must rise $I_A = (V_A - E_A) / R_A$. As I_A increases, the induced torque $T_{ind} = K\,\varphi\,I_A$ increases, making $T_{ind} > T_{load}$ and the speed ω of the motor increases.

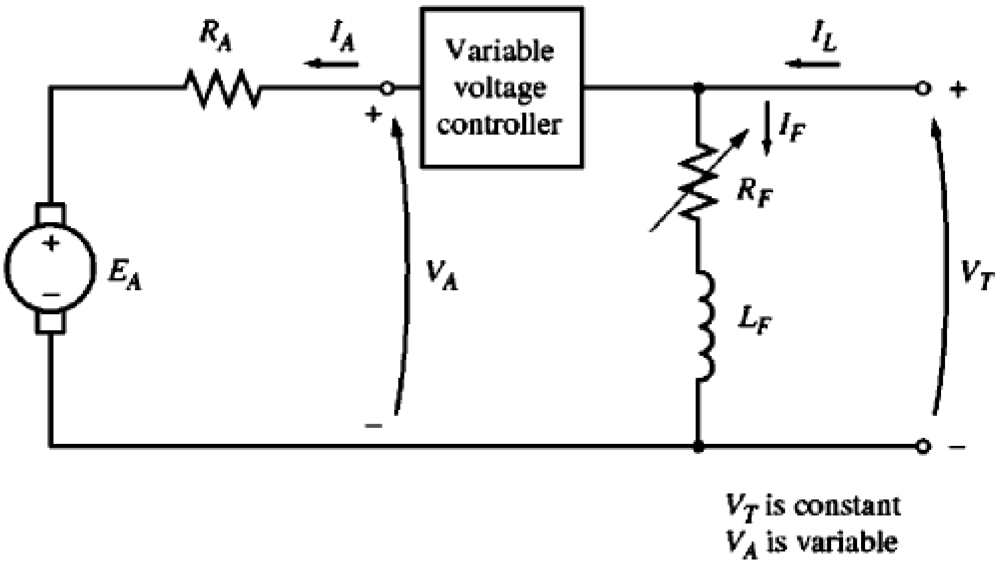


Fig. 6 Armature voltage control

But as the speed ω increases, the internal generated voltage E_A=K φ ω increases, causing the armature current to decrease. This decrease in I_A decreases the induced torque, causing T_{ind} to equal T_{load} at a higher rotational speed ω. The effect of an increase in V_A on the torque-speed characteristic of a separately excited motor is shown in Figure 7. Notice that the no-load speed of the motor is shifted by this method of speed control, but the slope of the curve remains constant.

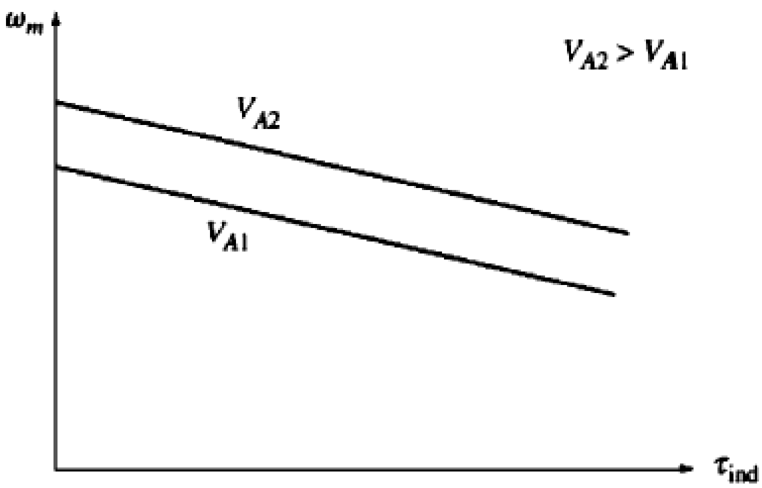


Fig. 7 Armature voltage control effect on the torque speed c/c's

INSERTING A RESISTOR IN SERIES WITH THE Armature circuit

If a resistor is inserted in series with the armature circuit, the effect is to drastically increase the slope of the motor's torque-speed characteristic, making it operate more slowly if loaded (Figure 8). The insertion of a resistor is a very wasteful method of speed control, since the losses in the inserted resistor are very large. For this reason, it is rarely used. It will be found only in applications in which the motor spends almost all its time operating at full speed or in applications too inexpensive to justify a better form of speed control.

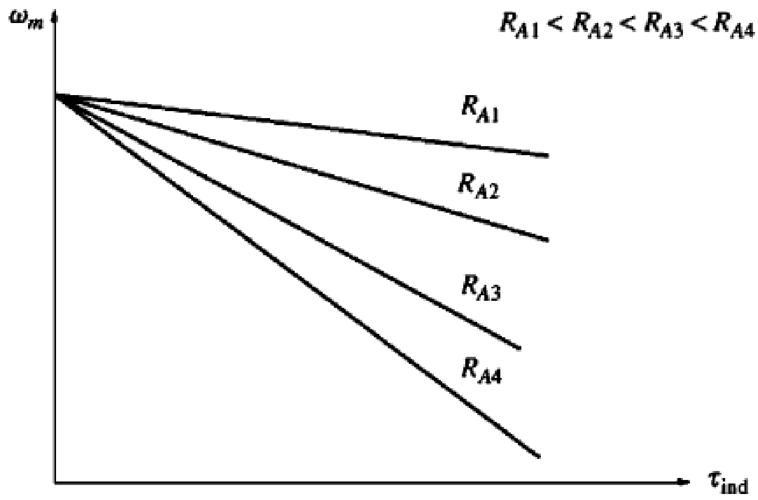


Fig. 8 the effect of armature resistance control on a torque speed c/c's

The two most common methods of shunt motor speed control - field resistance variation and armature voltage variation- have different safe ranges of operation.

In field resistance control, the lower the field current in a shunt (or separately excited) dc motor, the faster it turns: and the higher the field current, the slower it turns. Since an increase in field current causes a decrease in speed, there is always a minimum achievable speed by field circuit control. This minimum speed occurs when the motor's field circuit has the maximum permissible current flowing through it. If a motor is operating at its rated terminal voltage, power, and field current, then it will be running at rated speed, also known as base speed. Field resistance control can control the speed of the motor for speeds above base speed but not for speeds below base speed. To achieve a speed slower than base speed by field circuit control would require excessive field current, possibly burning up the field windings.

In armature voltage control, the lower the armature voltage on a separately excited dc motor, the slower it turns; and the higher the armature voltage, the faster it turns. Since an increase in armature voltage causes an increase in speed, there is always a maximum achievable speed by armature voltage control. This maximum speed occurs when the motor's armature voltage reaches its maximum permissible level. If the motor is operating at its rated voltage, field current, and power, it will be turning at base speed. Armature voltage control can control the speed of the motor for speeds below base speed but not for speeds above base speed. To achieve a speed faster than base speed by armature voltage control would require excessive armature voltage, possibly damaging the armature circuit.

These two techniques of speed control are obviously complementary. Armature voltage control works well for speeds below base speed, and field resistance or field current control works well for speeds above base speed. By combining the two speed-control techniques in the same motor, it is possible to get a range of speed variations of up to 40 to 1 or more. Shunt and separately excited dc motors have excellent speed control characteristics. These shunt dc motor power and torque limitations for safe operation as a function of speed are shown in Figure 9.

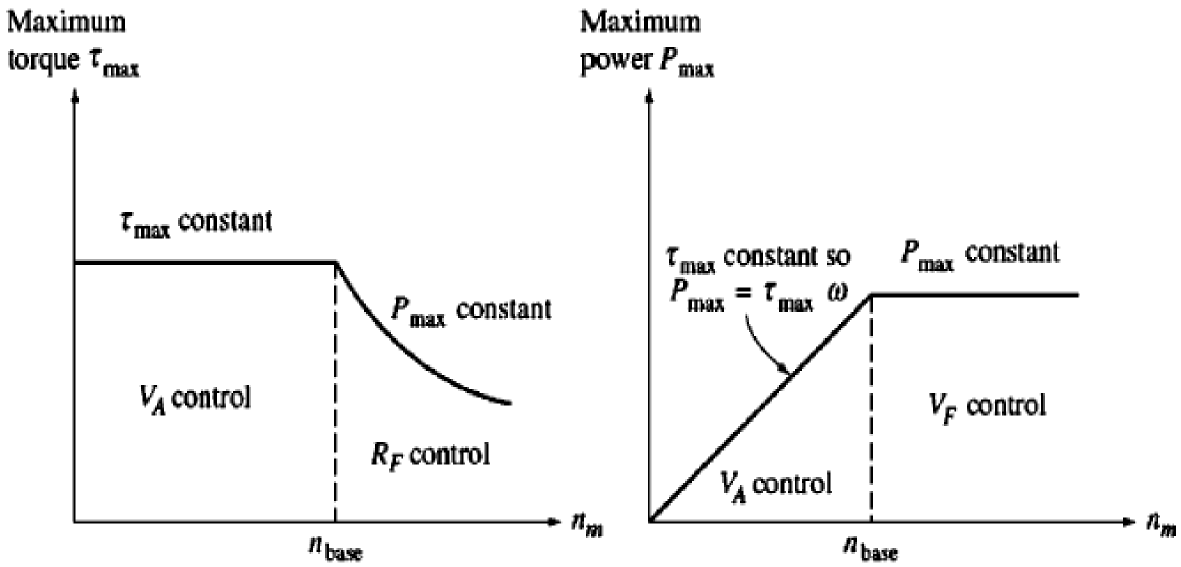


Fig. 9 power and torque limitations for safe operation as a function of speed

Chapter 6

Control of three-phase induction motors

Objective

- To understand induced torque principle of Induction motor.
- To study the methods of Induction motor speed control.

The development of induced torque in an induction motor

To understand the induced torque principle a three-phase set of voltages has been applied to the stator of cage rotor induction motor, and a three-phase set of stator currents is flowing. These currents produce a magnetic field B_s, which is rotating in a counterclockwise direction. The speed of the magnetic field's rotation is given by

$N_{sync} = 120\ f_e\ /\ p$ (1)

Where f_e is the system frequency in hertz and P is the number of poles in the machine. This rotating magnetic field B_s passes over the rotor bars and induces a voltage in them. The voltage induced in a given rotor bar is given by the equation

$e_{ind} = (v \times B) \bullet l$ (2)

Where v = velocity of the bar relative to the magnetic field

B = magnetic flux density vector

l = length of conductor in the magnetic field

It is the relative motion of the rotor compared to the stat or magnetic field that produces induced voltage in a rotor bar. The velocity of the upper rotor bars relative to the magnetic field is to the right, so the induced voltage in the upper bars is out of the page, while the induced voltage in the lower bars is into the page. This results in a current flow out of the upper bars and into the lower bars. However, since the rotor assembly is inductive, the peak rotor current lags behind the peak rotor voltage (see Figure 1-b). The rotor current flow produces a rotor magnetic field B_R. Finally, since the induced torque in the machine is given by

$T_{ind} = K\ B_R \times B_s$ (3)

The resulting torque is counterclockwise. Since the rotor induced torque is counterclockwise, the rotor accelerates in that direction.

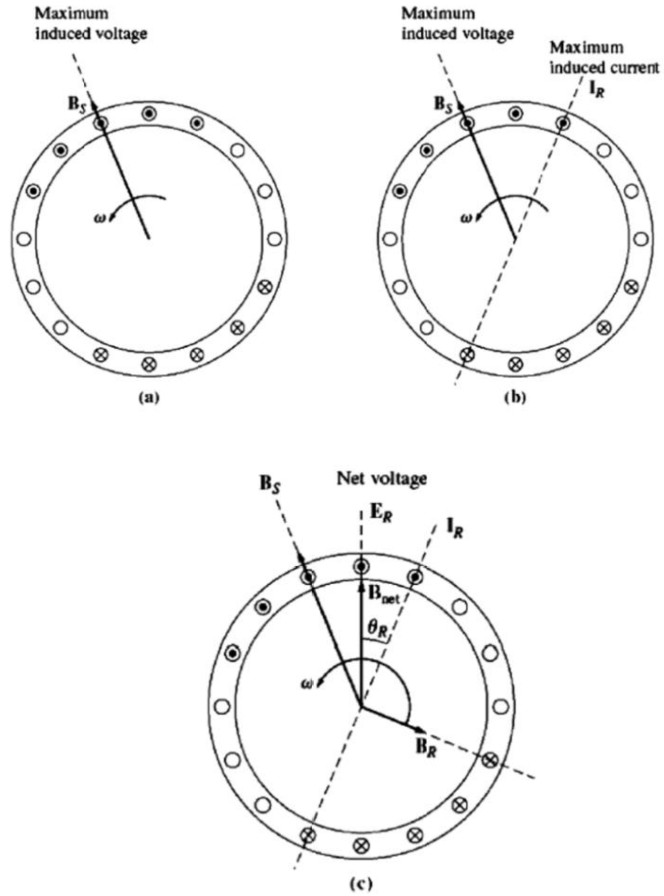


Fig 1 (a) stator rotating flux (b) rotor voltage (c) rotor current

There is a finite upper limit to the motor's speed, however. If the induction motor's rotor were turning at synchronous speed, then the rotor bars would be stationary relative to the magnetic field and there would be no induced voltage. If e_{ind} were equal to 0, then there would be no rotor current and no rotor magnetic field. With no rotor magnetic field, the induced torque would be zero, and the rotor would slow down as a result of friction losses. An induction motor can thus speed up to near-synchronous speed, but it can never exactly reach synchronous speed. Note that in normal operation both the rotor and stator magnetic fields B_R and B_s rotate together at synchronous speed n_{sync} while the rotor itself turns at a slower speed.

The voltage induced in a rotor bar of an induction motor depends on the speed of the rotor relative to the magnetic fields. Since the behavior of an induction motor depends on the rotor's voltage and current, it is often more logical to talk about this relative speed. Two terms are commonly used to define the relative motion of the rotor and the magnetic fields. One is slip speed, de fined as the difference between synchronous speed and rotor speed:

$n_{slip} = n_{sync} - n_m$ (4)

Where

n_{slip} = slip speed of the machine

n_{sync} = speed of the magnetic fields

n_m = mechanical shaft speed of motor

The other term used to describe the relative motion is slip, which is the relative speed, expressed on a per-unit or a percentage basis. That is, slip is defined as

$S = (n_{slip} / n_{sync}) \text{ X } 100\%$ (5)

$S = [(n_{sync} - n_m) / n_{sync}] \times 100\%$ (6)

Induced Torque from a Physical Standpoint

Figure 2 shows a cage rotor induction motor that is initially operating at no load and therefore very nearly at synchronous speed. The net magnetic field B_{net} in this machine is produced by the magnetization current i_M flowing in the motor's equivalent circuit (see Figure 3). The magnitude of the magnetization current and hence of B_{net} is directly proportional to the voltage E_1. If E_1 is constant, then the net magnetic field in the motor is constant. In an actual machine, E_1 varies as the load changes, because the stator impedances R_1 and X_1 cause varying voltage drops with varying load. However, these drops in the stator windings are relatively small, so E_1 (and hence i_M and B_{net}) is approximately constant with changes in load. Figure 2-a shows the induction motor at no load. At no load, the rotor slip is very small, and so the relative motion between the rotor and the magnetic fields is very small and the rotor frequency is also very small. Since the relative motion is small, the voltage E_R induced in the bars of the rotor is very small, and the resulting current flow I_R is small. Also, because the rotor frequency is so very small, the reactance of the rotor is nearly zero, and the maximum rotor current I_R is almost in phase with the rotor voltage E_R. The rotor current thus produces a small magnetic field B_R at an angle just slightly greater than 90° behind the net magnetic field B_{net} .

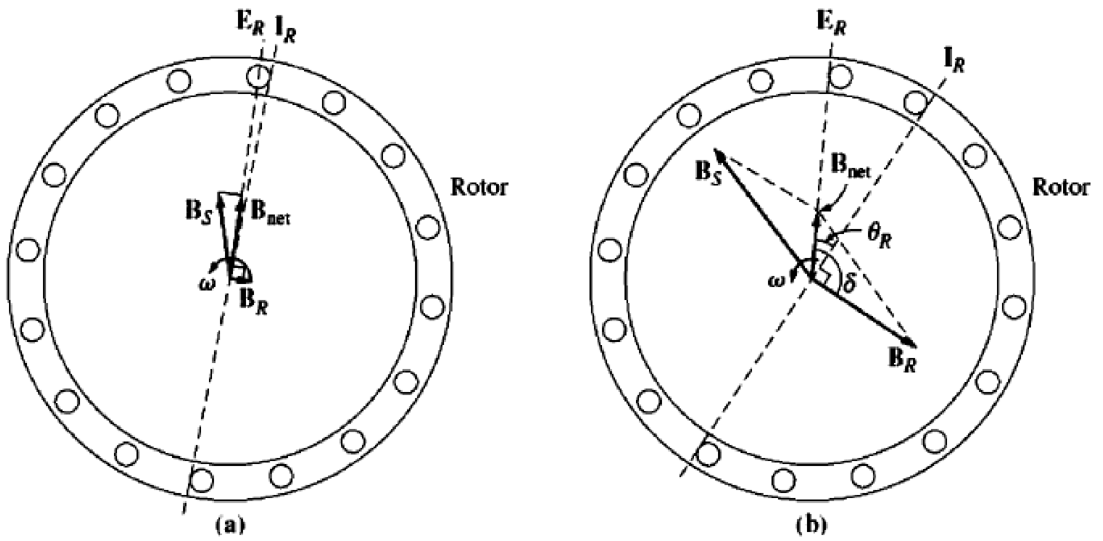


Fig. 2 magnetic field in an induction motor (a) under light loads (b) under heavy loads

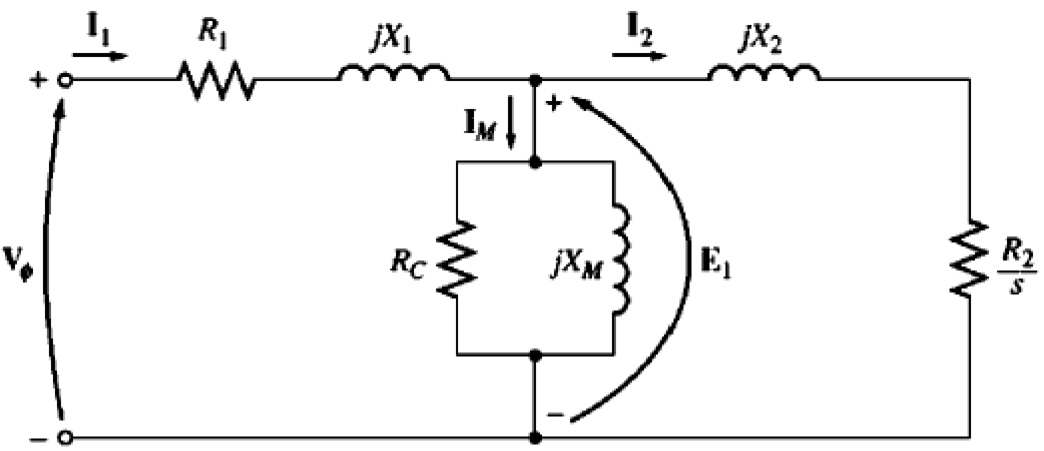


Fig. 3 per-phase equivalent circuit of an induction moto

Where

R_1 = Stator resistance

X_1 = Stator leakage reactance

R_c = Core losses resistance

X_m = Magnetizing reactance

R_2 = Referred rotor resistance

X_2 = Referred rotor leakage reactance

Notice that the stator current must be quite large even at no load, since it must supply most of B_{net},. (This is why induction motors have large no-load currents compared to other types of machines.) The induced torque, which keeps the rotor turning, is given by the equation

$T_{ind} = K\ B_R\ X\ B_{net}$ (7)

Then its magnitude is given by

$T_{ind} = K\ B_R\ B_{net} \sin \delta$ (8)

Where

B_R : The rotor magnetic field

B_{net}: The net magnetic field in the motor

δ : The angle between the net and rotor magnetic fields

The resulting torque-speed c/c's is shown in Figure 4.

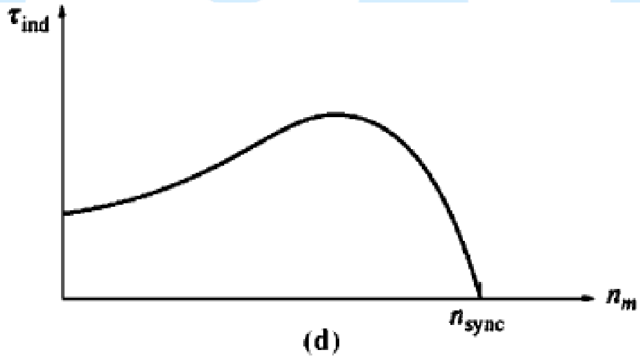


Fig. 4 the resulting torque-speed c/c's

General Notes

1-The induced torque of the motor is zero at synchronous speed.

2. The torque- speed curve is nearly linear between no load and full load. In this range, the rotor resistance is much larger than the rotor reactance, so the rotor current, the rotor magnetic field and the induced torque increase linearly with increasing slip.

3. There is a maximum possible torque that cannot be exceeded. This torque, called the pullout torque or breakdown torque is 2 to 3 times the rated full load torque of the motor. The next section of this chapter contains a method for calculating pullout torque.

4. The starting torque on the motor is slightly larger than its full -load torque, so this motor will start carrying any load that it can supply at full power.

5. Notice that the torque on the motor for a given slip varies as the square of the applied voltage.

6. If the rotor of the induction motor is driven faster than synchronous speed, then the direction of the induced torque in the machine reverses and the machine becomes a generator, converting mechanical power to electric power. The torque-speed c/c's which is

showing extended ranges is presented in Figure 5.

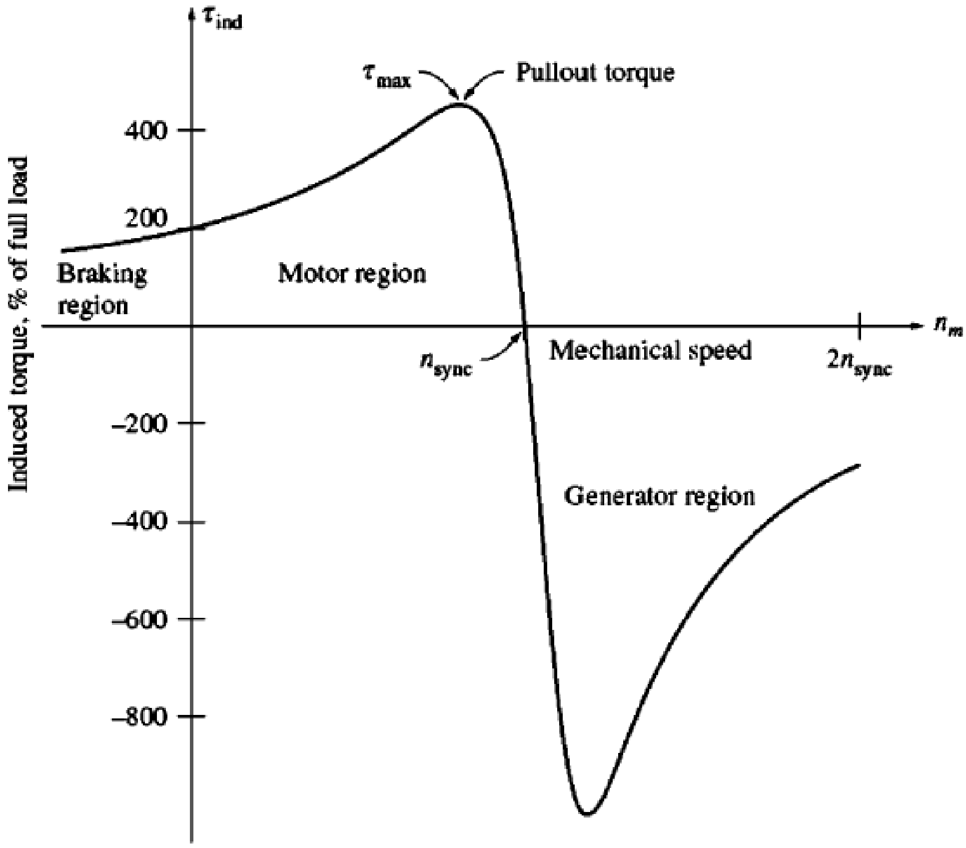


Fig. 5 the torque-speed c/c's showing extended ranges (braking and generator region)

Speed control of induction motor

There are really only two techniques by which the speed of an induction motor can be controlled. One is to vary the synchronous speed, which is the speed of the stator and rotor magnetic fields, since the rotor speed always remains near n_{sync} . The other technique is to vary the slip of the motor for a given load. Each of these approaches will be taken up in more detail. The synchronous speed of an induction on motor is given by

$n_{sync} = 120\, f_e\, /p$ (9)

So the only ways in which the synchronous speed of the machine can be varied are

(I) By changing the electrical frequency

(2) By changing the number of poles on the machine.

Slip control may be accomplished by varying either the rotor resistance or the terminal voltage of the motor.

Induction Motor Speed Control by Pole Changing

There are two major approaches to changing the number of poles in an induction motor:

I. The method of consequent poles

2. Multiple stator windings

The method of consequent poles is quite an old method for speed control, having been originally developed in 1897. It relies on the fact that the number of poles in the stator windings of an induction motor can easily be changed by a factor of 2: I with only simple changes in coil connections. Figure 6 shows phase "a" of a simple two-pole induction motor stator suitable for pole changing. Notice that the individual coils are of very short pitch (60 to 90°). Figure 7-a shows the current now in phase “a” of the stator windings at an instant of time during normal operation. Note that the magnetic field leaves the stator in the upper phase group (a north pole) and enters the stator in the lower phase group (a south pole). This winding is thus producing two stator magnetic poles.

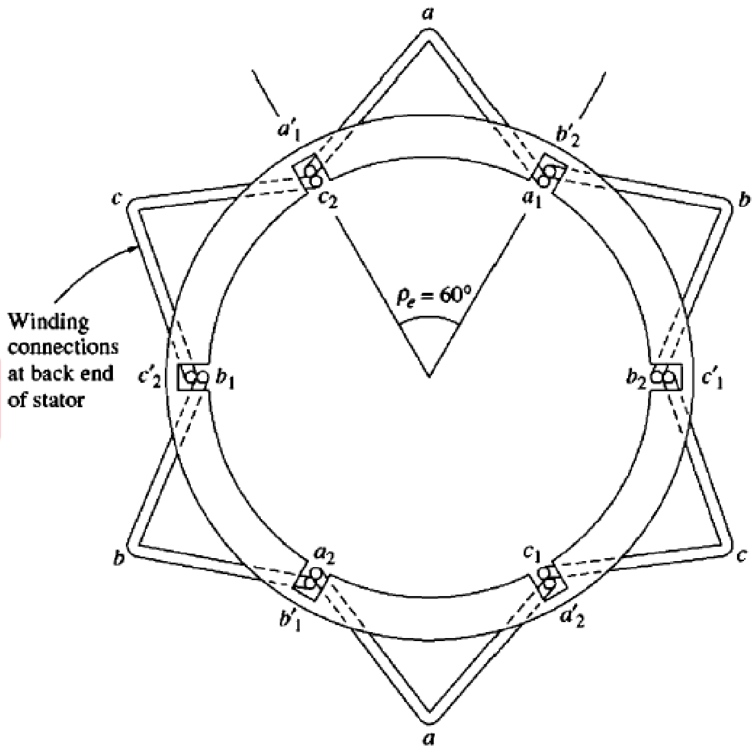


Fig. 6 A two pole stator winding for pole changing

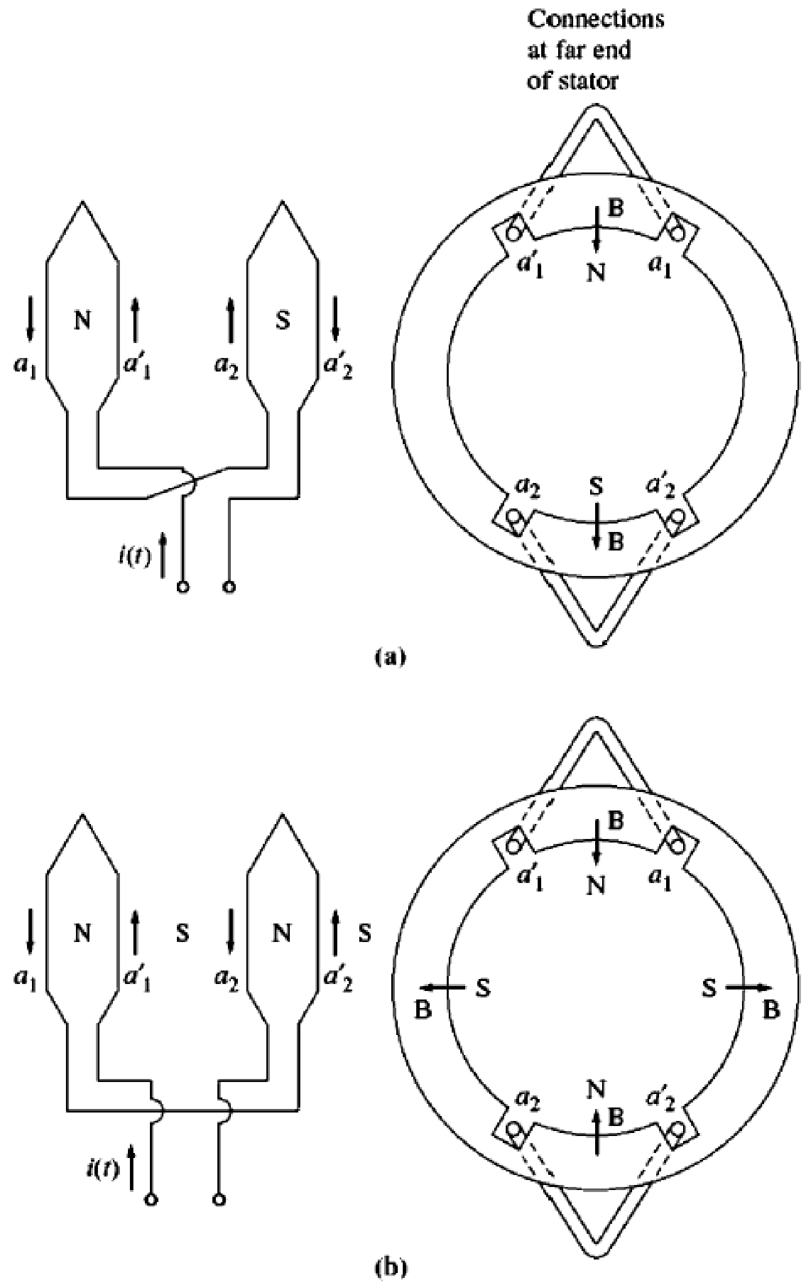
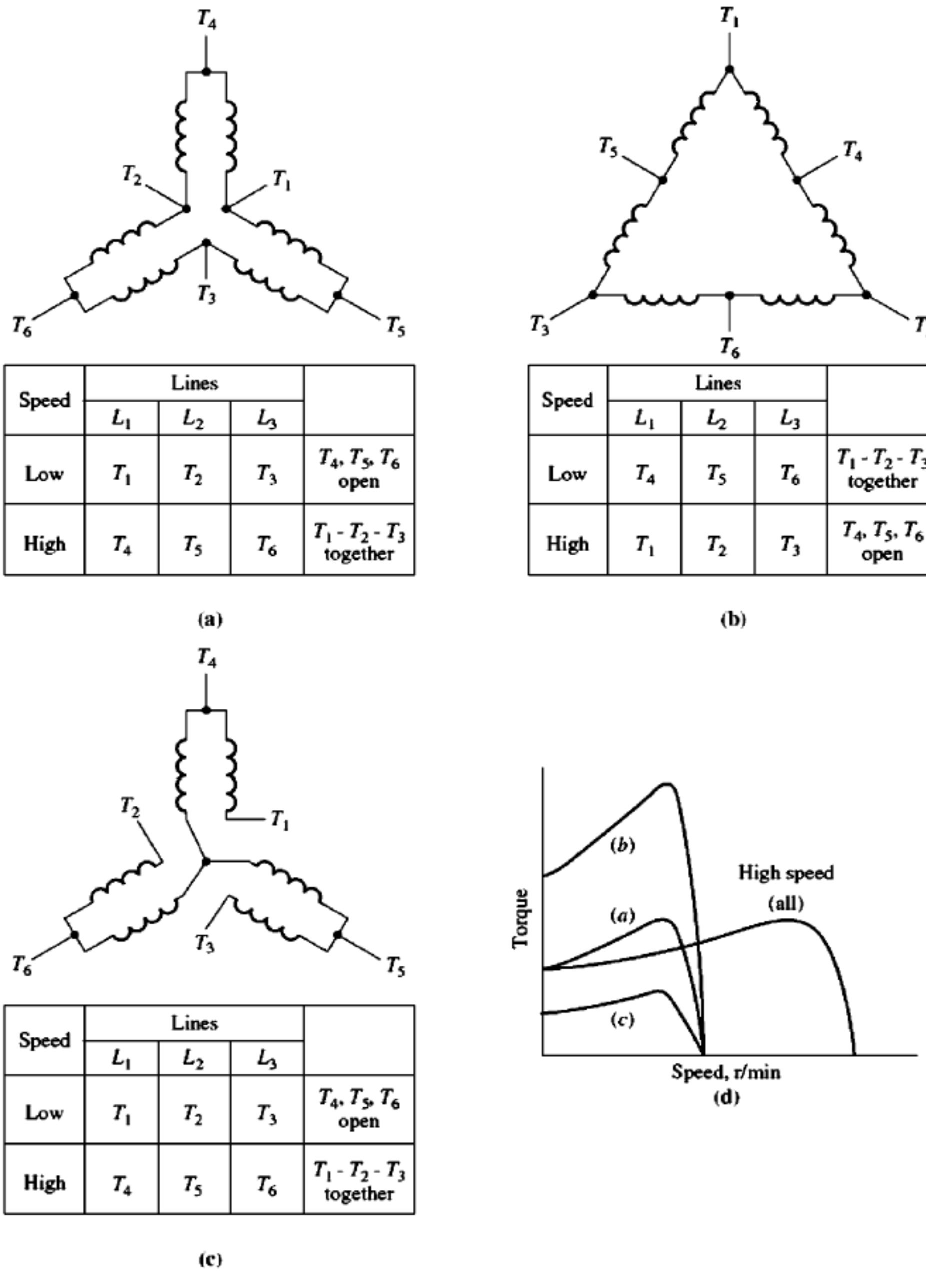


Fig. 7 one phase pole changing (a) one coil is a north pole and the other is a south (b) Both are north poles

Now suppose that the direction of current flow in the lower phase group on the stator is reversed (Figure 7-b). Then the magnetic field will leave the stator in both the upper phase group and the lower phase group-each one will be a north magnetic pole. The magnetic flux in this machine must return to the stator between the two phase groups, producing a pair of consequent south magnetic poles. Notice that now the stator has four magnetic poles-twice as many as before. The rotor in such a motor is of the cage design, since a cage rotor always has as many poles induced in it as there are in the stator and can thus adapt when the number of stator poles changes. When the motor is reconnected from two-pole to four-pole operation, the resulting maximum torque of the induction motor can be the same as before (constant-torque connection), half of its previous value (square-law-torque connection, used for fans, etc.), or twice its previous value (constant-output-power connection), depending on how the stator windings are rearranged. Figure 8 shows the possible stator connections and their effect on the torque-speed curve. The major disadvantage of the consequent-pole method of changing speed is that the speeds must be in a ratio of 2: I. the traditional approach to overcoming this limitation was to employ multiple stator windings with different numbers of poles and to energize only one set at a time. For example, a motor might be wound with a four-pole and a six-pole set of stator windings, and its synchronous speed on a 6O-Hz system could be switched from 1800 to 1200 r/min simply by supplying power to the other set of windings. Unfortunately, multiple stator windings increase the expense of the motor and are therefore used only when absolutely necessary. By combining the method of consequent poles with multiple stator windings, it is possible to build a four-speed induction motor. For example, with separate four- and six-pole windings, it is possible to produce a 6O-Hz motor capable of running at 600, 900, 1200, and 1800 r/min.



(a)

Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together

(b)

Speed	Lines			
	L_1	L_2	L_3	
Low	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together
High	T_1	T_2	T_3	T_4, T_5, T_6 open

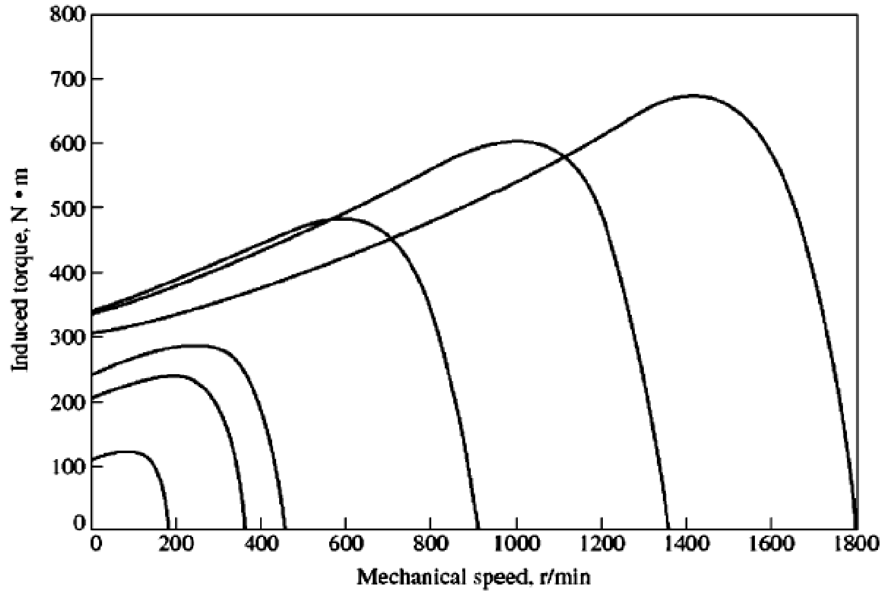
(c)

Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	$T_1 - T_2 - T_3$ together

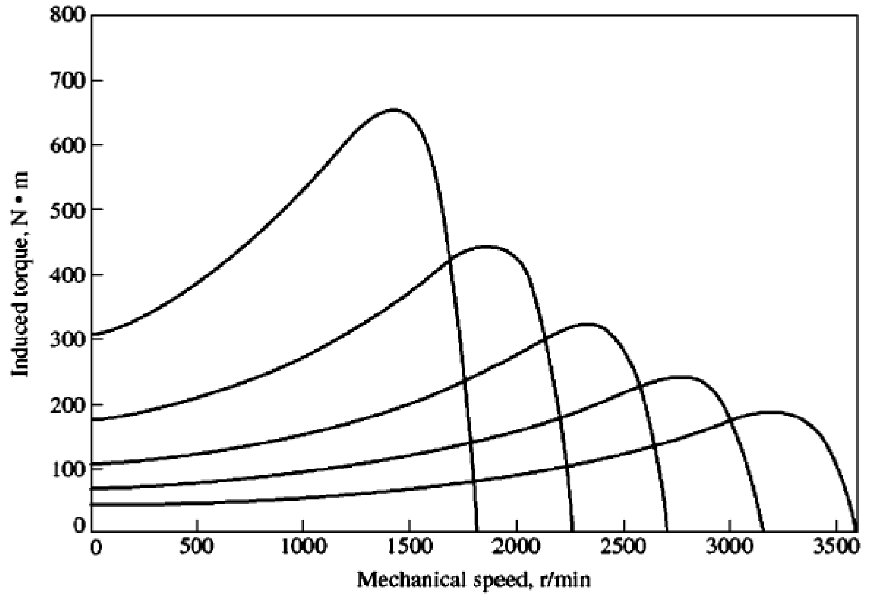
Fig. 8 possible connections of the stator in a pole changing motor with torque speed c/c's (a) constant torque (b) constant horse power (c) fan torque connection (torque change with speed as same manner of fan load

Speed Control by Changing the Line Frequency

If the electrical frequency applied to the stator of an induction motor is changed, the rate of rotation of its magnetic fields n_{sync} will change in direct proportion to the change in electrical frequency, and the no-load point on the torque-speed characteristic curve will change with it (see Figure 9). The synchronous speed of the motor at rated conditions is known as the base speed. By using variable frequency control, it is possible to adjust the speed of the motor either above or below base speed. A properly designed variable-frequency induction motor drive can be very flexible. It can control the speed of an induction motor over a range from as little as 5 percent of base speed up to about twice base speed. However, it is important to maintain certain voltage and torque limits on the motor as the frequency is varied, to ensure safe operation. When running at speeds below the base speed of the motor, it is necessary to reduce the terminal voltage applied to the stator for proper operation. The terminal voltage applied to the stator should be decreased linearly with decreasing stator frequency. This process is called derating. If it is not done, the steel in the core of the induction motor will saturate and excessive magnetization currents will flow in the machine. When the electrical frequency applied to the motor exceeds the rated frequency of the motor, the stator voltage is held constant at the rated value. Although saturation considerations would prevent the voltage to be raised above the rated value under these circumstances, it is limited to the rated voltage to protect the winding insulation of the motor. Thus the resulting flux in the machine decreases and the maximum torque decreases with it. Figure 9-b shows a family of induction motor torque- speed characteristic curves for speeds above base speed, assuming that the stator voltage is held constant. If the stator voltage is varied linearly with frequency below base speed and is held constant at rated value above base speed, then the resulting family of torque-speed characteristics is as shown in Figure 9-c. The rated speed for the motor shown in Figure 9 is 1800 r/min.

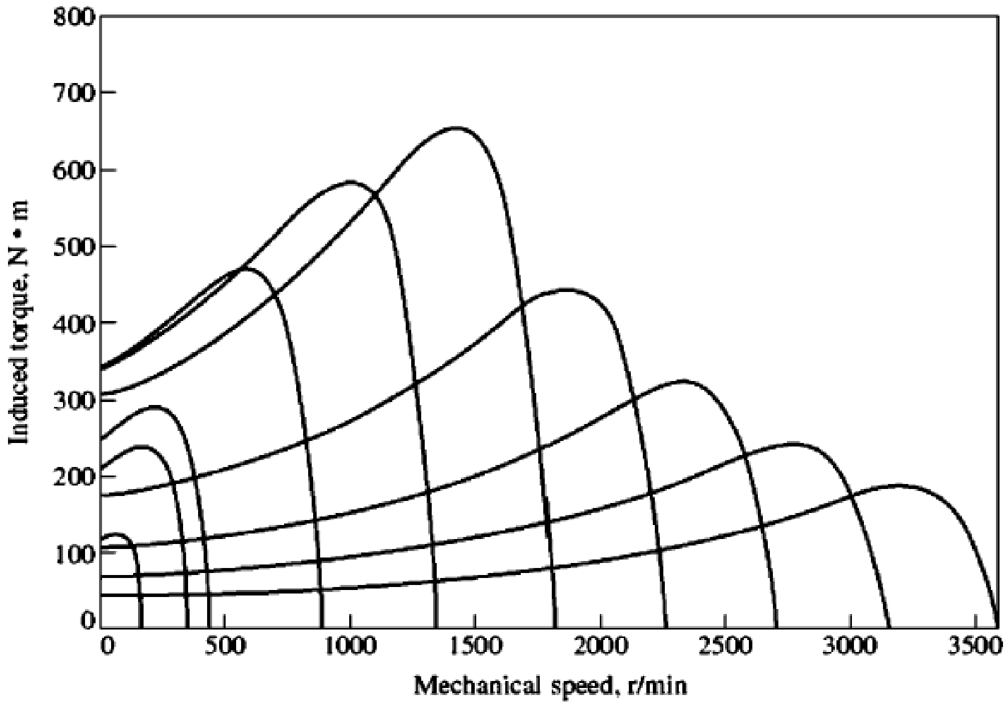


(a)



(b)

Fig. 9 the family of torque-speed c/c's in the variable frequency speed control (a) for speeds below base speed (b) for speeds above base speed with assuming the line voltage is held constant



(c)

Fig. 9 (c) The torque-speed characteristic curves for all frequencies

In the past, the principal disadvantage of electrical frequency control as a method of speed changing was that a dedicated generator or mechanical frequency changer was required to make it operate. This problem has disappeared with the development of modern solid-state variable- frequency motor drives. The drive is very flexible: its input power can be either single-phase or three-phase, either 50 or 60 Hz, and anywhere from 208 to 230 V. The output from this drive is a three-phase set of voltages whose frequency can be varied from 0 up to 120 Hz and whose voltage can be varied from 0 V up to the rated voltage of the motor. The output voltage and frequency control is achieved by using the pulse width modulation (PWM) techniques. Example is shown in Figure 10.

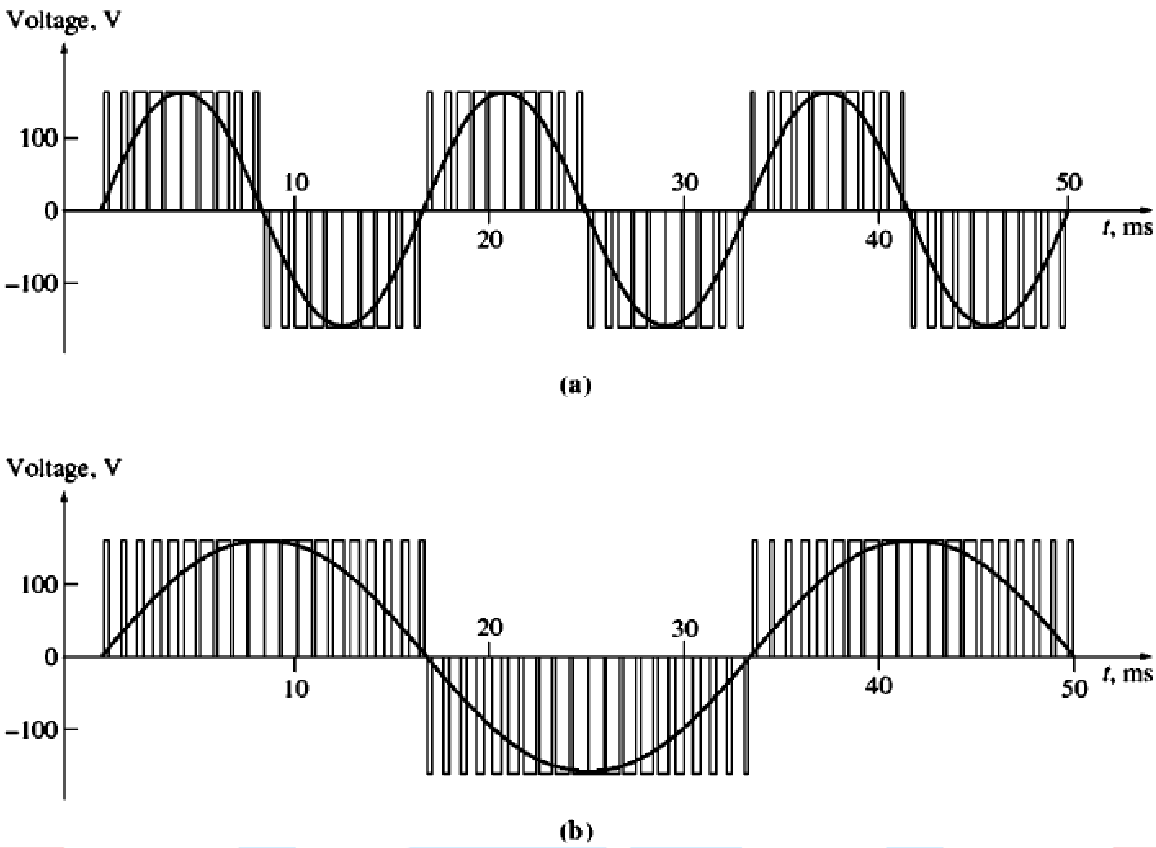


Fig. 10 Variable frequency control with PWM (a) 60 HZ, 120 V PWM waveform (b) 30 HZ, 120 V PWM waveform

Speed Control by Changing the Line Voltage

The torque developed by an induction motor is proportional to the square of the applied voltage. If a load has a torque-speed characteristic such as the one shown in Figure 11, then the speed of the motor may be controlled over a limited range by varying the line voltage. This method of speed control is sometimes used on small motors driving fans.

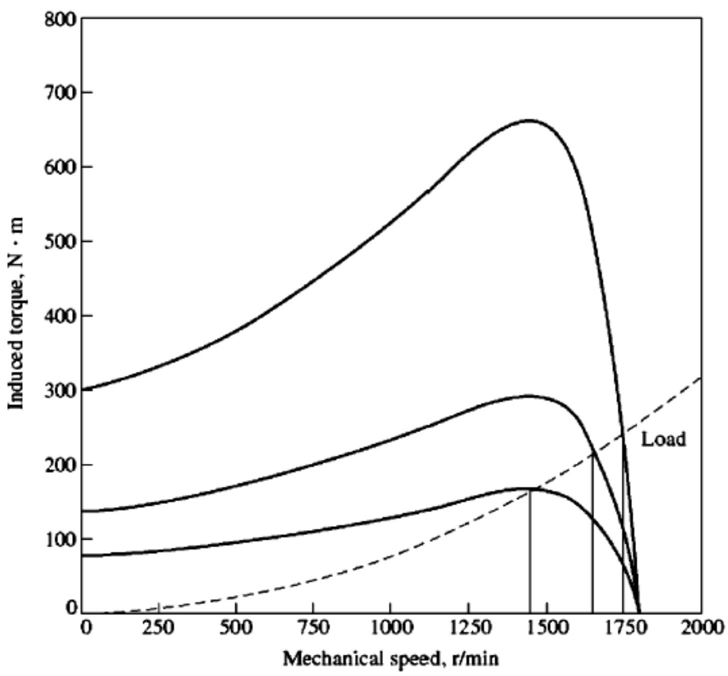


Fig. 11 Variable line voltage speed control

Speed Control by Changing the Rotor Resistance

In wound-rotor induction motors, it is possible to change the shape of the torque- speed curve by inserting extra resistances into the rotor circuit of the machine. The resulting torque-speed characteristic curves are shown in Figure 12.

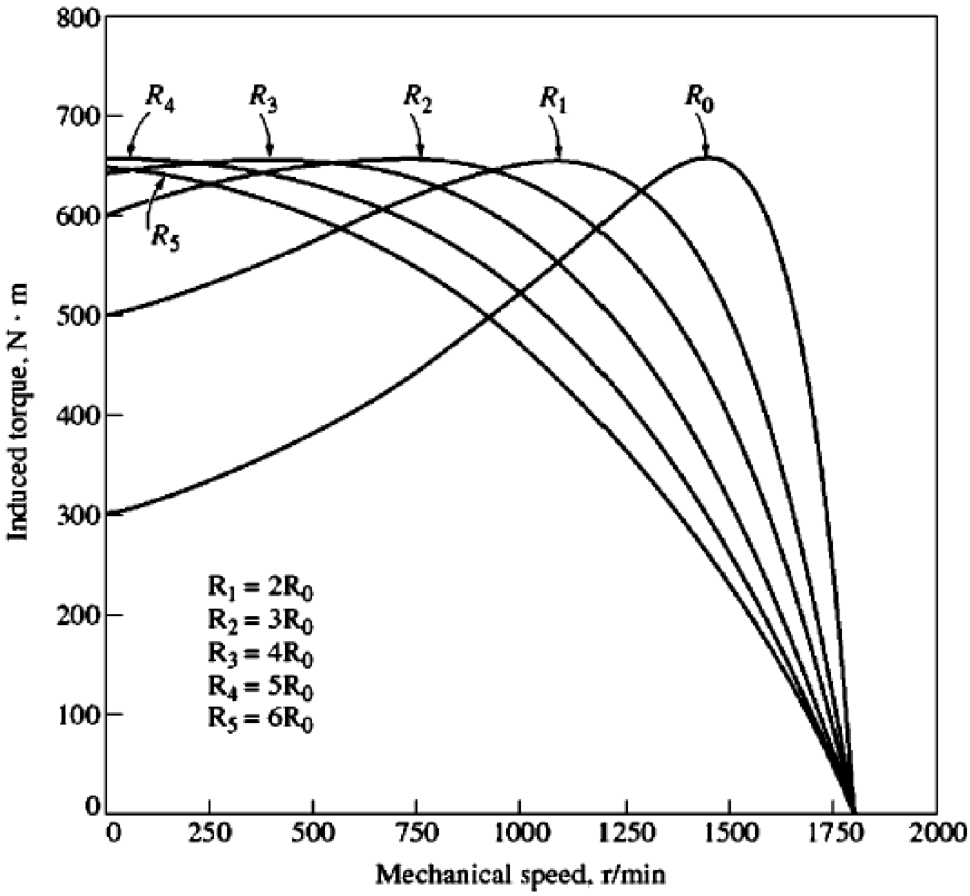


Fig. 12 Speed control by varying the rotor resistance of a wound rotor induction machine

If the torque-speed curve of the load is as shown in the figure, then changing the rotor resistance will change the operating speed of the motor. However, inserting extra resistances into the rotor circuit of an induction motor seriously reduces the efficiency of the machine. Such a method of speed control is normally used only for short periods because of this efficiency problem.

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