Brush Assembly

Thebrushassemblyconsistsofthebrushesandtheirholders.The brushes are usually small blocks of graphitic carbon, sincethis materialhasalongservicelifeandalsocausesminimumwearto the commutator. The holders permit some play in the brushes so they can follow any irregularities in the surface of the commutator and make good contact. Springs hold the brushes firmly against the commutator. A commutator and two pairs of brushes are shown in figure12.34.

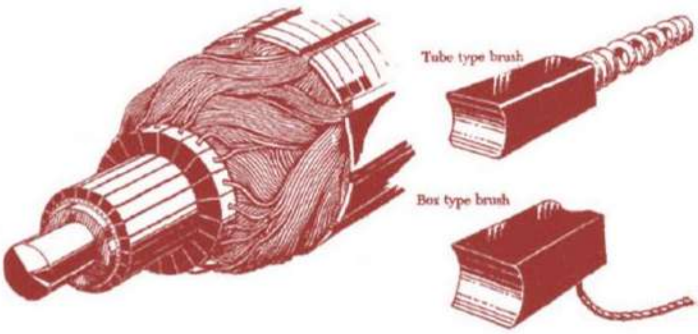


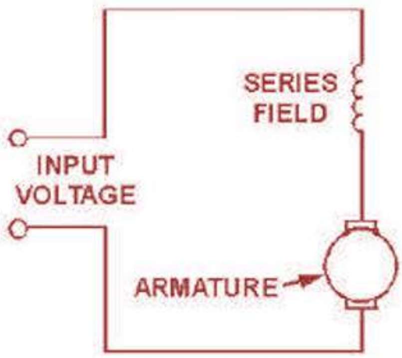

Fig. 12.34

End Frame

The end frame is the part of the motor opposite the commutator usually the end frame is designed so that it can be connected to the unit to be driven. The bearing for the drive end is also located in the end frame. Sometimes the end frame is made a part of the unit driven by the motor. When this is done, the bearing on the drive end may be located in any one of a number of places.

TYPES OF DC MOTORS

There are three basic types of dc motors: (1) Series motors (2) shunt motors, and (3) compound motors. They differ largely in the method in which their field and armature coils are connected.




Series DC Motor

Fig. 12.35

In the series motor, the field windings, consisting of a relatively few turns of heavy wire, are connected in series with the armature winding. Both a diagrammatic and a schematic illustration of a series motor

is shown in figure12.35. The same current flowing through the field winding also flows through the armature winding. Any increase in current, therefore, strengthens the magnetism of both the field and thearmature.
advantage.

The speed of a series motor is dependent upon the load. Any change in load is accompanied by a substantial change in speed. A series motor will run at high speed when it has a light load and at low speed with a heavy load. If the load is removed entirely, the

motor may operate at such a high speed that the armature will fly apart. If high starting torque is needed under heavy load
conditions, series motors have many applications. Seriesmotors areoftenusedinaircraftasenginestartersandforraisingand
lowering landing gears, cowl flaps, and wing flaps.

Shunt DC Motor

Intheshuntmotorthefieldwindingisconnectedinparallelorin shunt with the armature winding. (See figure12.35)Theresistance inthefieldwindingishigh.Sincethefieldwindingisconnected
directly across the power supply, the current through the field is constant. The field current does not vary with motor speed, as in the series motor and, therefore, the torque of the shunt motor will vary only with the current through the armature. The torque developedatstartingislessthanthatdevelopedbyaseriesmotor
of equal size.

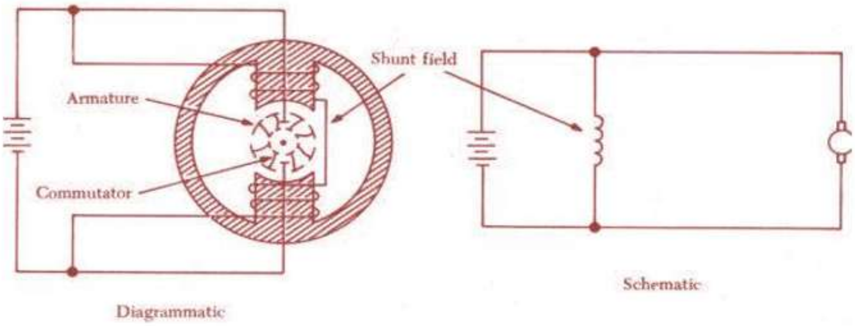
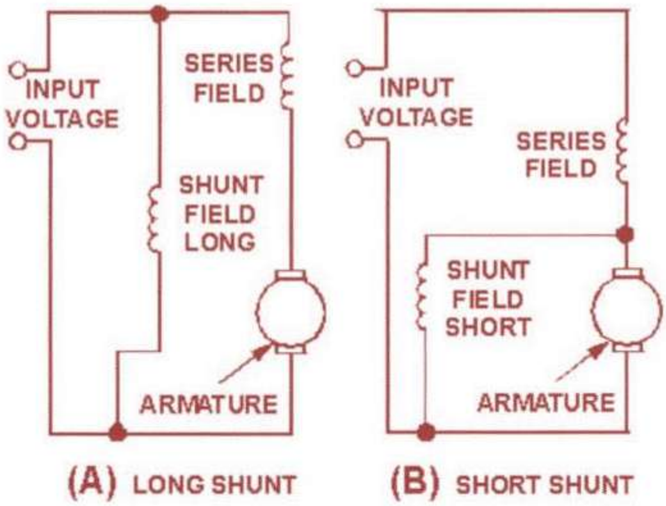



Fig. 12.36

The speed of the shunt motor varies very little with changes in load. When all load is removed, it assumes a speed slightly higher than the loaded speed. This motor is particularly suitable for use when constant speed is desired and when high starting torque is not needed.

Compound DC Motor

The compound motor is a combination of the series and shunt motors. There are two windings in the field: a shunt winding and a series winding. A schematic of a compound motor is shown infigure. The shunt winding is composed of many turns of fine wire and is connected in parallel with the armature winding. The series winding consists of a few turns of large wire and is connected in series with the armature winding. The starting torque is higher than in the shunt motor but lower than in the series motor. Variation of speed with load is less than in a series wound motor but greater than in a shunt motor. The compound motor is used whenever the combined characteristics of the series and shunt




motors aredesired.

Fig. 12.37Compound-wound DC motor.

Like the compound generator, the compound motor has both series and shunt field windings. The series winding may either aid the shunt wind (cumulative compound) or oppose the shunt winding (differentialcompound).

Thestartingandloadcharacteristicsofthecumulativecompound motoraresomewherebetweenthoseoftheseriesandthoseofthe shunt motor.

Because of the series field, the cumulative compound motor has a higher starting torque than a shunt motor. Cumulative compound motors are used in driving machines which are subject to sudden changes in load. They are also used where a high starting torque is desired, but a series motor cannot be used easily.
In the differential compound motor, an increase in load creates an increase in current and a decrease in total flux in this type of motor. These two tend to offset each other and the result is a practically constant speed. However, since an increase in load tends to decrease the field strength, the speed characteristic becomes unstable. Rarely is this type of motor used in aircraft systems.

A graph of the variation in speed with changes of load of the various types of dc motors is shown in figure 9-78.

voltage is induced in its windings. This voltage is called the back or counter e.m.f. (electromotive force) and is opposite in direction to the voltage applied to the motor from the external source.

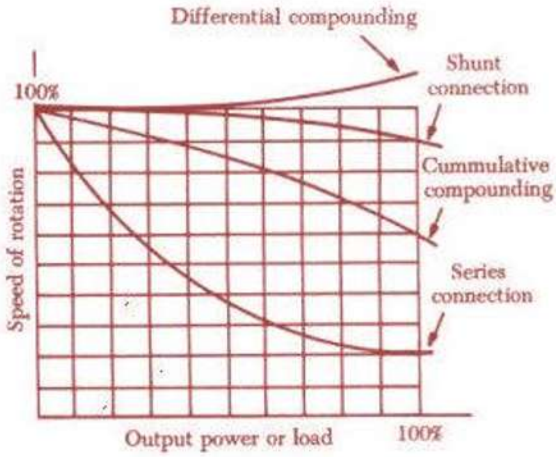



Fig. 12.38Load Characteristics Of Dc Motor Counter E. M. F.

The armature resistance of a small, 28 volt dc motor is extremely low, about 0.1 ohm. When the armature is connected across the 28 volt source, current through the armature will apparently be

This high valve of current flow is not only impracticable but also unreasonable, especially when the current drain, during normal operation of a motor, is found to be about 4 amperes. This is because the current through a motor armature during operation is determined by more factors than ohmic resistance.

When the armature in a motor rotates in a magnetic field, a

Counter e.m.f. opposes the current which causes the armature to rotate. The current flowing through the armature, therefore, decreases as the counter e.m.f. increases. The faster the armature rotates, the greater the counter e.m.f. For this reason, a motor connected to a battery may draw a fairly high current on starting, but as the armature speed increases, the current flowing through the armature decreases. At rated speed, the counter e.m.f. may be only a few volts less than the battery voltage. Then, if the load on the motor is increased, the motor will slow down, less counter e.m.f. will be generated, and the current drawn from the external source will increase. In a shunt motor, the counter e.m.f. affects only the current in the armature, since the field is connected in parallel across the power source. As the motor slows down and the counter e.m.f. decreases, more current flows through the armature, but the magnetism in the field is unchanged. When the series motor slows down, the counter e.m.f. decreases and more current flows through the field and the armature, thereby strengthening their magnetic fields. Because of these characteristics, it is more difficult to stall a series motor than a shuntmotor.

Types of Duty

Electric motors are called upon to operate under various conditions. Some motors are used for intermittent operation; others operate continuously. Motors built for intermittent duty can be operated for short periods only and, then, must be allowed to cool before being operated again. If such a motor is operated for long periods under full load, the motor will be overheated.Motors

built for continuous duty may be operated at rated power for long periods.

Reversing Motor Direction

By reversing the direction of current flow in either the armature or the field windings, the direction of a motor's rotation may be reversed. This will reverse the magnetism of either the armature or the magnetic field in which the armature rotates. If the wires connecting the motor to an external source are interchanged, the direction of rotation will not be reversed, since changing these wires reverses the magnetism of both field and armature and leaves the torque in the same direction asbefore.

One method for reversing direction of rotation employs two field windings wound in opposite directions on the same pole. This type of motor is called a split field motor. Figure shows a series motor with a split field winding. The single pole, double throw switch makes it possible to direct current through either of the two windings. When the switch is placed in the lower position, current flows through the lower field winding, creating a north pole at the lower field winding and at the lower pole piece, and a south pole at the upper pole piece. When the switch is placed in the upper position, current flows through the upper field winding, the magnetism of the field is reversed, and the armature rotates in the opposite direction. Some split field motors are built with two separate field windings wound on alternate poles. The armature in such a motor, a four pole reversible motor, rotates in one direction when current flows through the windings of one set of opposite pole pieces, and in the opposite direction when current flows through the other set of windings.

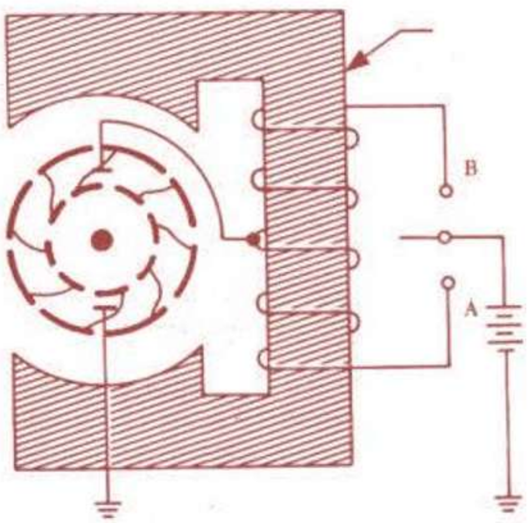



Fig. 12.39 SPLIT FIELD SERIES MOTOR

Another method of direction reversal, called the switch method, employs a double pole, double throw switch which changes thedirection of current flow in either the armature or the field. In the illustration of the switch method shown in figure, current direction may be reversed through the field but not through the armature. When the switch is thrown to the "up" position, current flows through the field winding to establish a north pole at the right side of the motor and a south pole at the left side of the motor. When the switch is thrown to the "down" position, this polarity is reversed and the armature rotates in the opposite direction.

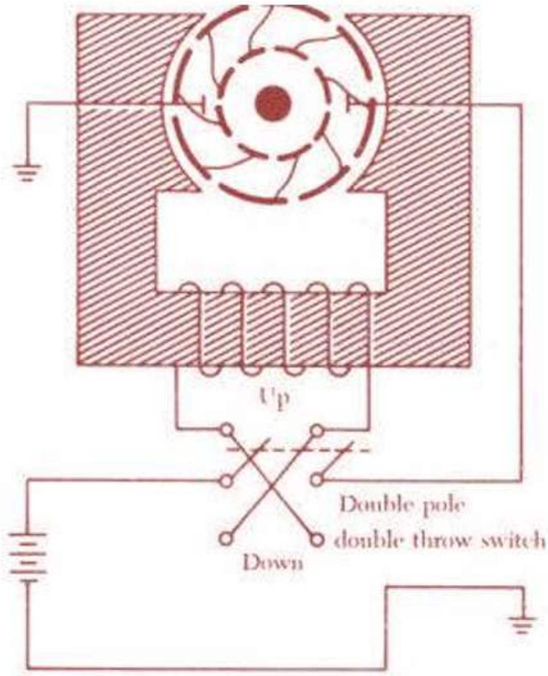



Fig. 12.40 SWITCH METHOD

Motor Speed

Motor speed can be controlled by varying the current in the field windings. When the amount of current flowing through the field windings is increased, the field strength increases, but the motor slows down since a greater amount of counter e.m.f. is generated in the armature windings. When the field current is decreased, the field strength decreases, and the motor speeds up because the counter e.m.f. is reduced. A motor in which speed can be controlled is called a variable speed motor. It may be either a shunt or seriesmotor.

In the shunt motor, speed is controlled by a rheostat in series with the field windings (figure). The speed depends on the amount of current which flows through the rheostat to the field windings. To increase the motor speed, the resistance in the rheostat is increased, which decreases the field current. As a result, there is a decreaseinthestrengthofthemagneticfieldandinthecounter e.m.f. This momentarily increases the armature current and the torque. The motor will then automatically speed up until the counter e.m.f. increases and causes the armature current to decrease to its former value. When this occurs, the motor will operate at a higher fixed speed than before.

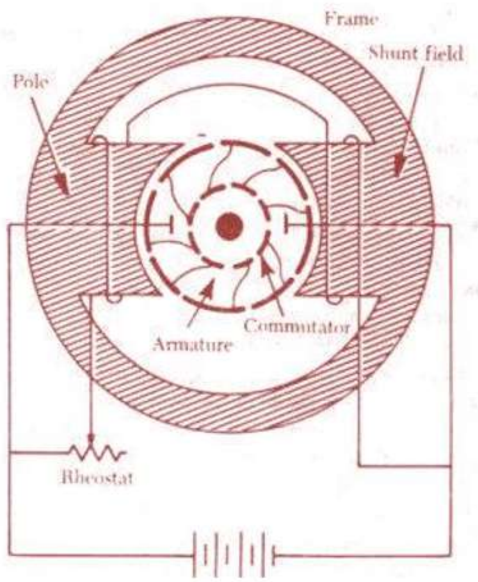



Fig. 12.41SHUNT MOTOR WITH VARIABLE SPEED CONTROL

To decrease the motor speed, the resistance of the rheostat is decreased. More current flows through the field windings and increases the strength of the field; then, the counter e.m.f. increases momentarily and decreases the armature current. As a result, the torque decreases and the motor slow down until the counter e.m.f. decreases to its former value; then the motor operates at a lower fixed speed than before.

In the series motor (figure), the rheostat speed control is connected either in parallel or in series with the motor field, or in parallel with the armature. When the rheostat is set for maximum resistance, the motor speed is increased in the parallel armature connection by a decrease in current. When the rheostat resistance is maximum in the series connection, motor speed is reduced by a reduction in voltage across the motor. For above normal speed operation, the rheostat is in parallel with the series field. Part of the series field current is bypassed and the motor speedsup.

Energy Losses in DC Motors

Losses occur when electrical energy is converted to mechanical energy (in the motor), or mechanical energy is converted to electrical energy (in the generator). For the machine to be efficient, these losses must be kept to a minimum. Some losses are electrical, others are mechanical. Electrical losses are classified as copper losses and iron losses; mechanical losses occurin overcoming the friction of various parts of the machine.

Copper losses occur when electrons are forced through the copper windings of the armature and the field. These losses are proportional to the square of the current. They are sometimes called I2R losses, since they are due to the power dissipated in the form of heat in the resistance of the field and armature windings.

Iron losses are subdivided in hysteresis and eddy current losses.

Hysteresis losses are caused by the armature revolving in an alternating magnetic field. It, therefore, becomes magnetized first in one direction and then in the other. The residual magnetism of the iron or steel of which the armature is made causes these losses. Since the field magnets are always magnetized in one direction (dc field), they have no hysteresislosses.

Eddy current losses occur because the iron core of the armature is a conductor revolving in a magnetic field. This sets up an e.m.f. across portions of the core, causing currents to flow within the core. These currents heat the core and, if they become excessive, may damage the windings. As far as the output is concerned, the power consumed by eddy currents is a loss. To reduce eddy currents to a minimum, a laminated core usually is used. A laminated core is made of thin sheets of iron electrically insulated from each other. The insulation between laminations reduces eddy currents, because it is "transverse" to the direction in which these currents tendto flow. However, it has no effect on the magnetic circuit. The thinner the laminations, the more effectively this method reduces eddy current losses.

Inspection and Maintenance of DC Motors

Use the following procedures to make inspection and maintenance checks:

1. Check the operation of the unit driven by the motor in accordance with the instructions covering the specific installation.

2. Check all wiring, connections, terminals, fuses, and switches for general condition andsecurity.

3. Keep motors clean and mounting boltstight.

4. Check brushes for condition, length, and spring tension. Minimum brush lengths, correct spring tension, and procedures for replacing brushes are given in the applicable manufacturer'sinstructions.

5. Inspect commutator for cleanness, pitting, scoring, roughness, corrosion or burning. Check for high mica (if the copper wears down below the mica, the mica will insulate the brushes from the commutator). Clean dirty commutators with a cloth moistened with the recommended cleaning solvent. Polish rough or corroded commutators with fine sandpaper (000 or finer) and blow out with compressed air. Never use emery paper since it contains metallic particles which may cause shorts. Replace the motor if the commutator is burned, badly pitted, grooved, or worn to the extent that the mica insulation is flush with the commutatorsurface.

6. Inspect all exposed wiring for evidence of overheating. Replace the motor if the insulation on leads or windings is burned, cracked, orbrittle.

7. Lubricate only if called for by the manufacturer's instructions covering the motor. Most motors used in today's airplanes require no lubrication betweenoverhauls.

8. Adjust and lubricate the gearbox, or unit which the motor drives, in accordance with the applicable manufacturer's instructions covering theunit.

When trouble develops in a dc motor system, check first to determine the source of the trouble. Replace the motor only when

the trouble is due to a defect in the motor itself. In most cases, the failure of a motor to operate is caused by a defect in the external electrical circuit, or by mechanical failure in the mechanism driven by themotor.

Check the external electrical circuit for loose or dirty connections and for improper connection of wiring. Look for open circuits, grounds, and shorts by following the applicable manufacturer's circuit testing procedure. If the fuse is not blown, failure of the motor to operate is usually due to an open circuit. A blown fuse usually indicates an accidental ground or short circuit. The chattering of the relay switch which controls the motor is usually caused by a low battery. When the battery is low, the open circuit voltage of the battery is sufficient to close the relay, but with the heavy current draw of the motor, the voltage drops below the level required to hold the relay closed. When the relay opens, the voltage in the battery increases enough to close the relay again. This cycle repeats and causes chattering, which is very harmful to the relay switch, due to the heavy current causing an arc which will burn thecontacts.

Check the unit driven by the motor for failure of the unit or drive mechanism. If the motor has failed as a result of a failure in the driven unit, the fault must be corrected before installing a new motor.

If it has been determined that the fault is in the motor itself (by checking for correct voltage at the motor terminals and for failure of the driven unit), inspect the commutator and brushes. A dirty commutator or defective or binding brushes may result in poor contact between brushes and commutator. Clean the commutator, brushes, and brush holders with a cloth moistened with the recommended cleaning solvent. If brushes are damaged or worn to the specified minimum length, install new brushes in accordance

with the applicable manufacturer's instructions covering the motor. If the motor still fails to operate, replace it with a serviceablemotor.

## MANUAL AND AUTOMATIC STARTERS

Because the dc resistance of most motor armatures is low (0.05 to 0.5 ohm), and because the counter emf does not exist until thearmature begins to turn, it is necessary to use an external starting resistance in series with the armature of a dc motor to keep the initial armature current to a safe value. As the armature begins to turn, counter emf increases; and, since the counter emf opposes the applied voltage, the armature current is reduced. The external resistance in series with the armature is decreased or eliminated as the motor comes up to normal speed and full voltage is applied across the armature. Controlling the starting resistance in a dc motor is accomplished either, by an operator, or by any of several automatic devices. The automatic devices are usually just switches controlled by motor speedsensors.

## STARTER GENERATOR

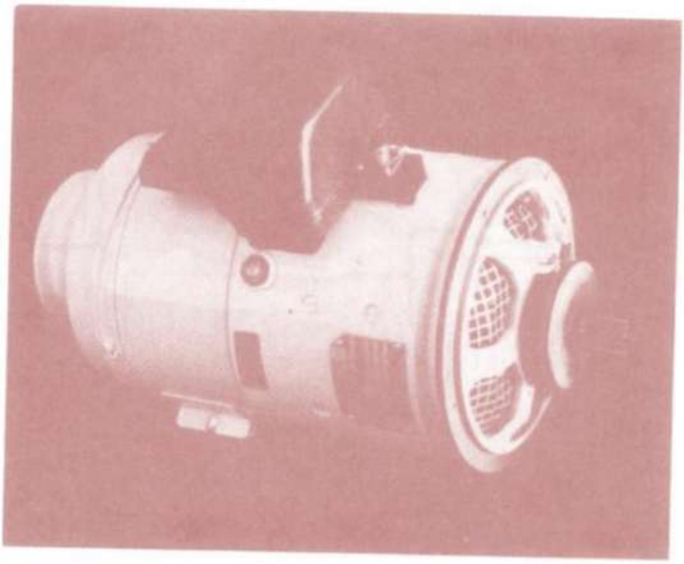
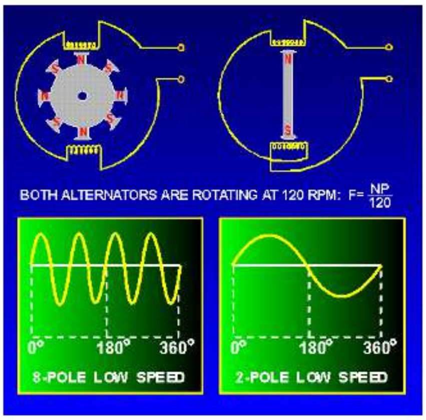


Fig. 12.42 A typical Starter-Generator (Lear Siegler, Inc, power Equipment Division)

Starter Generator are designed to provide torque for engine starting and generate dc electric power for the aircraft electrical's system. Starter Generator is a combination of dc generator and dc motor. The starter generator shown in above figure contains a self excited four pole generator. Four inter poles and compensating windings are used to help overcome armature reaction. An integral fan is used to draw air through the unit during rotation. The cooling air is required to maintain temperature limits during high power generation. A clutch damper may be used on some units to connect the armature to the starter generator's drive shaft.
Thisclutchprovidesfrictiondampingofanytorsionalloadsthat
may be applied to the armature during operation. Changes in torsional load occur whenever the aircraft's electric al equipment is turned on or off. If the armature is connected directly to the engine,withoutaclutch,thetorsionalloadsmayoverstressthe
drive shaft and cause generator failure. Some starter generator employ a drive shaft shear section, which is used to protect the engine's gear box in the event the generator mechanically fails and cannot rotate. In this situation the shear section breaks and disconnects the generator from the drive gear.

## FREQUENCY OF AC GENERATOR

The output frequency of alternator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency. The lower the speed, the lower the frequency. The more poles there are on the rotor, the higher the frequency is for a givenspeed same frequency of generated voltage. The frequency of any ac generator in hertz (Hz), which is the number of cycles per second, is related to the number of poles and the speed of rotation, as




## Module 3.13: AC Theory

## INTRODUCTION

Alternating current (AC) electricity is the type of electricity most commonly used in homes and businesses all over the world. It is said to "alternate" because it reverses direction in an electrical circuit at regular intervals, usually many times per second. Alternating current is created by an electric generator, which determines the frequency of these oscillations. In the United States, alternating current is generated at 60 hertz, meaning that the current alternates 60 times per second and some other countries use 50 Hz in householdutility.

There are a number of reasons why most electrical power plants produce AC rather than DC or direct current, where electrons flow constantly in one direction. First, large generators produce AC naturally, so conversion to DC would require an extra step and therefore an added cost. Secondly, and perhaps most importantly, electrical transformersmust have alternating current to operate. Transformers are a crucial part of a power grid, because they perform the task of stepping up electrical voltage for long-range transmission, as well as bringing voltage down to a safe level for use in homes and businesses

An AC waveform can be sinusoidal, square, or saw tooth-shaped.Some AC waveforms are irregular or complicated. An example of sine-wave AC is common household utility current (in the ideal case). Square or saw tooth waves are produced by certain types of electronic oscillators.

HOW AC DIFFERS FROM DC

Most students of electricity begin their study with what is known as direct current (DC), which is electricity flowing in a constant direction, and/or possessing a voltage with constant polarity. DC is the kind of electricity made by a battery (with definite positive and negative terminals), or the kind of charge generated by rubbing certain types of materials against eachother.
As useful and as easy to understand as DC is, it is not the only "kind" of electricity in use. Certain sources of electricity (most notably, rotary electro-mechanical generators) naturally produce voltages alternating in polarity, reversing positive and negative over time. Either as a voltage switching polarity or as a currentswitching direction back and forth, this "kind" of electricity isknown as Alternating Current (AC): Figure 13.1

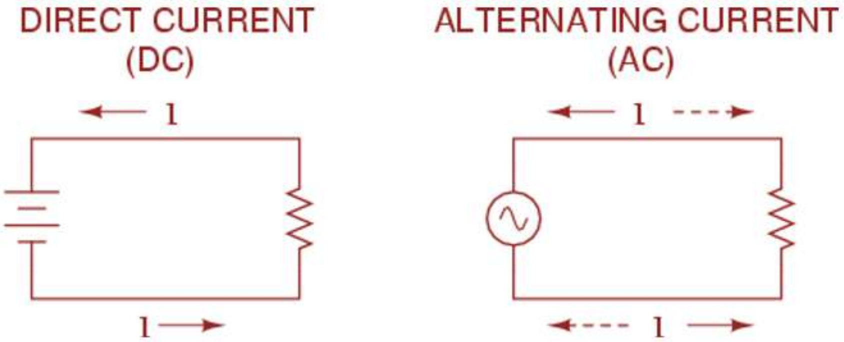



Fig. 13.1Direct vs alternating current

Whereas the familiar battery symbol is used as a generic symbol for any DC voltage source, the circle with the wavy line inside is the generic symbol for any AC voltage source.

Comparison chart

AlternatingCurrent   Direct Current

Electricity flows in two ways: either in an alternating current (AC) or in a direct current (DC). Electricity or "current" is nothing but the movement of electrons through a conductor,like a wire. The difference between AC and DC lies in the direction in which the electrons flow. In DC, the electrons flow steadily in a single direction, or "forward." In AC, electrons keep switching directions, sometimes going "forward" and then going "backward." Alternating current is the best way to transmit electricity over largedistances.

Amount of energy that can be carried

Cause of the direction of flow of electrons

Safe to transfer over longer city distances and can provide more power.
Rotating magnet along the wire.

The frequency of alternating current is 50Hz or 60Hz depending upon the country.

Voltage of DC cannot travel very far until it begins to lose energy.
Steady magnetism along thewire.

The frequency of direct current is zero.

Direction

It reverses its direction while flowing in a circuit.

It flows in one direction in the circuit.

Current

Flow of Electrons

Obtained from
Passive Parameters Power Factor
Types

It is the current of magnitude varying with time
Electrons keep switching directions - forward and backward.
A.C Generator and mains.
Impedance.
Lies between 0 & 1. Sinusoidal,Trapezoidal, Triangular,Square.

It is the current of constantmagnitude.

Electrons move steadily in one direction or'forward'.
Cell or Battery.

Resistance only it is always 1.
Pure and pulsating.

AC WAVEFORMS (SINUSOIDAL AND OTHER WAVES)

When an alternator produces AC voltage, the voltage switchespolarity over time, but does so in a very particular manner. Whengraphed over time, the "wave" traced by this voltage of alternatingpolarity from an alternator takes on a distinct shape, known as asine wave: Figure below

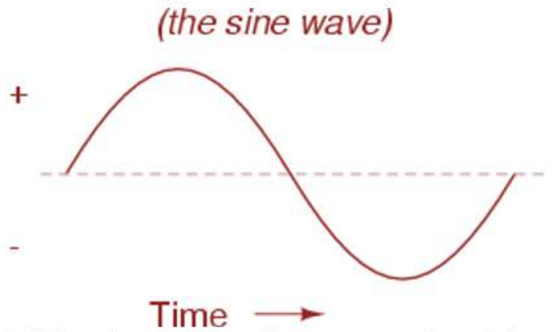



Fig. 13.2Graph of AC voltage over time (the sine wave)

In the voltage plot from an electromechanical alternator, the change from one polarity to the other is a smooth one, the voltage level changing most rapidly at the zero ("crossover") point and most slowly at its peak. If we were to graph the trigonometric function of "sine" over a horizontal range of 0 to 360 degrees, we would find the exact same pattern as in Table below.
Trigonometric "sine" function.

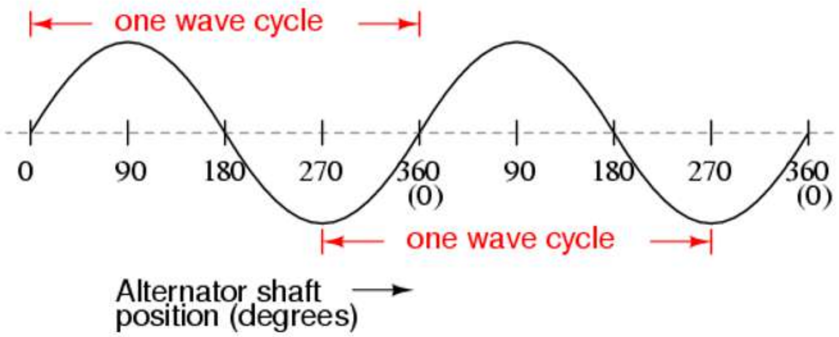
Table no. 13.1

| Angle (o) | sin(angle) | wave | Angle (o) | sin(angle) | wave |
|---|---|---|---|---|---|
| 0 | 0.0000 | zero | 180 | 0.0000 | zero |
| 15 | 0.2588 | + | 195 | -0.2588 | - |
| 30 | 0.5000 | + | 210 | -0.5000 | - |
| 45 | 0.7071 | + | 225 | -0.7071 | - |
| 60 | 0.8660 | + | 240 | -0.8660 | - |
| 75 | 0.9659 | + | 255 | -0.9659 | - |
| 90 | 1.0000 | +peak | 270 | -1.0000 | -peak |
| 105 | 0.9659 | + | 285 | -0.9659 | - |
| 120 | 0.8660 | + | 300 | -0.8660 | - |
| 135 | 0.7071 | + | 315 | -0.7071 | - |
| 150 | 0.5000 | + | 330 | -0.5000 | - |

| | | | | | |
|---|---|---|---|---|---|
| 165 | 0.2588 | + | 345 | -0.2588 | - |
| 180 | 0.0000 | zero | 360 | 0.0000 | zero |

The reason why an electromechanical alternator outputs sine-wave AC is due to the physics of its operation. The voltage produced by the stationary coils by the motion of the rotating magnet is proportional to the rate at which the magnetic flux is changing perpendicular to the coils (Faraday's Law of Electromagnetic Induction). That rate is greatest when the magnet poles are closest to the coils, and least when the magnet poles are furthest away from the coils. Mathematically, the rate of magnetic flux change due to a rotating magnet follows that of a sine function, so the voltage produced by the coils follows that same function.

If we were to follow the changing voltage produced by a coil in an alternator from any point on the sine wave graph to that point when the wave shape begins to repeat itself, we would have marked exactly one cycle of that wave. This is most easily shown by spanning the distance between identical peaks, but may be measured between any corresponding points on the graph. The degree marks on the horizontal axis of the graph represent the domain of the trigonometric sine function, and also the angular position




of our simple two-pole alternator shaft as it rotates: Figure below 13.3

Fig. 13.3Alternator voltage as function of shaft position (time).

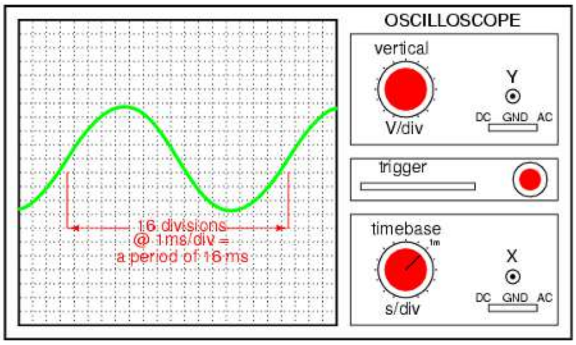
Since the horizontal axis of this graph can mark the passage of time as well as shaft position in degrees, the dimension marked for one cycle is often measured in a unit of time, most often seconds or fractions of a second. When expressed as a measurement, this is often called the period of a wave. The periodof a wave in degrees is always 360, but the amount of time oneperiod occupies depends on the rate voltage oscillates back andforth.

A more popular measure for describing the alternating rate of anAC voltage or current wave than period is the rate of that back-

Prior to the canonization of the Hertz unit, frequency was simply expressed as "cycles per second." Period and frequency are mathematical reciprocals of one another. That is to say, if a wave has a period of 10 seconds, its frequency will be 0.1 Hz, or 1/10 of a cycle per second:

Frequency inHertz= 1 Periodinseconds

An instrument called an oscilloscope, Figure13.4, is used to display a changing voltage over time on a graphical screen. You may be familiar with the appearance of an ECG or EKG (electrocardiograph) machine, used by physicians to graph the oscillations of a patient's heart over time. The ECG is a special- purpose oscilloscope expressly designed for medical use. General- purpose oscilloscopes have the ability to display voltagefrom virtually any voltage source, plotted as a graph with time as the independent variable. The relationship between period and frequency is very useful to know when displaying an AC voltage or current waveform on an oscilloscope screen. By measuring the period of the wave on the horizontal axis of the oscilloscope screen and reciprocating that time value (in seconds), you can determine the frequency in Hertz.




$$\text{Frequency} = \frac{1}{\text{period}} = \frac{1}{16\ \text{ms}} = 62.5\ \text{Hz}$$

Fig. 13.4 Time period of sinewave is shown on oscilloscope.

Voltage and current are by no means the only physical variables subject to variation over time. Much more common to our everyday experience is sound, which is nothing more than the alternating compression and decompression (pressure waves) of air molecules, interpreted by our ears as a physical sensation. Because alternating current is a wave phenomenon, it shares many of the properties of other wave phenomena, like sound. For this reason, sound (especially structured music) provides an excellent analogy for relating ACconcepts.

While electromechanical alternators and many other physical phenomena naturally produce sine waves, this is not the only kind of alternating wave in existence. Other “waveforms” of AC arecommonly produced within electronic circuitry. Here are but afew sample waveforms and their common designations in figure below13.5

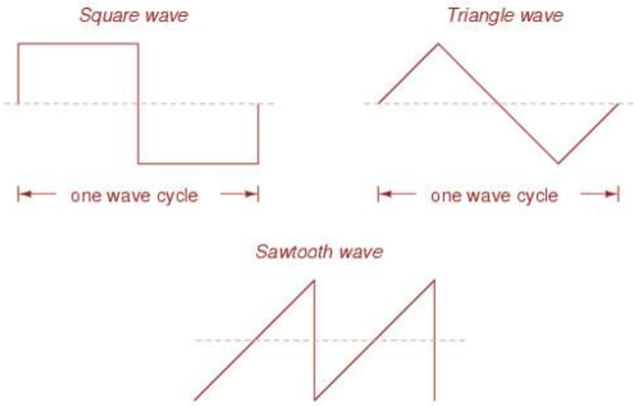



Fig. 13.5 Some common waveshapes (waveforms).

These waveforms are by no means the only kinds of waveforms in existence. They're simply a few that are common enough to have been given distinct names. Even in circuits that are supposed to manifest "pure" sine, square, triangle, or saw tooth voltage/current waveforms, the real-life result is often a distorted version of the intended waveshape. Some waveforms are so complex that they defy classification as a particular "type" (including waveforms associated with many kinds of musical instruments). Generallyspeaking, any waveshape bearing close resemblance to a perfectsine wave is termed sinusoidal,anything different being labeled asnon-sinusoidal. Being that the waveform of an AC voltage orcurrent is crucial to its impact in a circuit, we need to be aware ofthe fact that AC waves come in a variety of shape

CHARACTERISTICS OF AC WAVEFORM

The main characteristics of an AC Waveform are defined as:
AC Waveform Characteristics

- The Period, (T)is the length of time in seconds that the waveform takes to repeat itself from start to finish. This can also be called the Periodic Time of the waveform for sine waves, or the Pulse Width for squarewaves.
- The Frequency, ($f$) is the number of times the waveform repeats itself within a one second time period.Frequencyisthereciprocalofthetimeperiod,

(Hz).

• The Amplitude (A) is the magnitude or intensity ofthe signal waveform measured in volts oramps.
"Waveforms are basically a visual representation of the variation
of a voltage or current plotted to a base of time". Generally, for AC waveforms this horizontal base line represents a zero condition of either voltage or current. Any part of an AC type waveform which lies above the horizontal zero axis represents a voltage or current flowing in onedirection.
Likewise, any part of the waveform which lies below the horizontal zero axis represents a voltage or current flowing in the opposite direction to the first. Generally for sinusoidal AC waveforms the shape of the waveform above the zero axis is the same as the shape below it. However, for most non-power AC signals including audio waveforms this is not always the case.
The most common periodic signal waveforms that are used inElectrical and Electronic Engineering are the SinusoidalWaveforms. However, an alternating AC waveform may not always take the shape of a smooth shape based around the

Triangular Waves and these are shown below in fig 13.6.
Periodic Time,(T)= 1
Frequency

AC Waveform Example No1

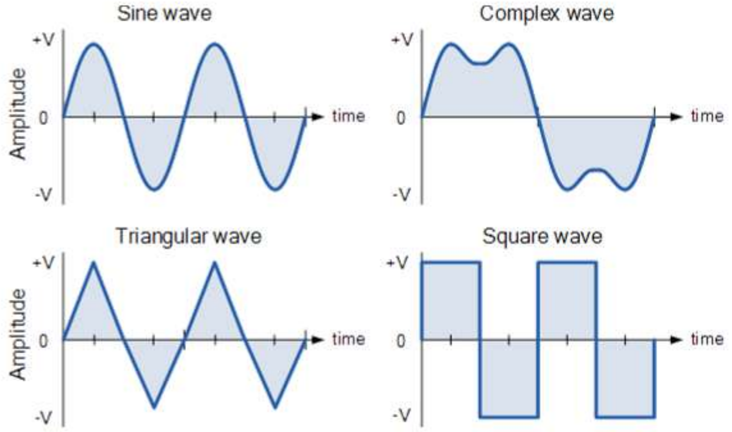


Fig. 13.6

1. What will be the periodic time of a 50Hz waveforma
2. what is the frequency of an AC waveform that hasa periodic time of10mS.

The time taken for an AC Waveform to complete one full pattern from its positive half to its negative half and back to its zero baseline again is called a Cycle and one complete cycle contains

1. periodic Time,(T)= 1
ƒ

= 150

= 0.02Secs or 20mS

both a positive half-cycle and a negative half-cycle. The time taken by the waveform to complete one full cycle is called the Periodic Time of the waveform, and is given the symbol"T".
The number of complete cycles that are produced within one

2. Frequency, ( F ƒ )= 1
T

= 1
10 X10−3

= 100HZ

second (cycles/second) is called the Frequency, symbol *f* of the alternating waveform. Frequency is measured in Hertz, ( Hz ) named after the German physicist Heinrich Hertz.
Then we can see that a relationship exists between cycles (oscillations), periodic time and frequency (cycles per second), so if there are *f* number of cycles in one second, each individual cycle must take $1/f$ seconds tocomplete.
Frequency used to be expressed in "cycles per second" abbreviated to "cps", but today it is more commonly specified in units called "Hertz". For a domestic mains supply the frequency will be either 50Hz or 60Hz depending upon the country and is fixed by the speed of rotation of the generator. But one hertz is a very small unit so prefixes are used that denote the order of magnitude of the waveform at higher frequencies such as kHz, MHz and evenGHz.

| Prefix | Definition | Written as | Periodic Time |
|---|---|---|---|
| Kilo | Thousand | kHz | 1mS |
| Mega | Million | MHz | 1uS |
| Giga | Billion | GHz | 1nS |
| Terra | Trillion | THz | 1pS |

Table 13.7

Amplitude of an AC Waveform

As well as knowing either the periodic time or the frequency of the alternating quantity, another important parameter of the ACwaveform is Amplitude, better known as its Maximum or Peak value represented by the terms, Vmax for voltage or Imax for current.

The peak value is the greatest value of either voltage or current that the waveform reaches during each half cycle measured from the zero baseline. Unlike a DC voltage or current which has a steady state that can be measured or calculated using Ohm's Law, an alternating quantity is constantly changing its value over time.

For pure sinusoidal waveforms this peak value will always be the same for both half cycles ( +Vm = -Vm ) but for non-sinusoidal or

complex waveforms the maximum peak value can be very different for each half cycle. Sometimes, alternating waveforms are given a peak-to-peak, Vp-p value and this is simply the distance or the sum in voltage between the maximum peak value,

+Vmax and the minimum peak value, -Vmax during one complete cycle.

The Average Value of an AC Waveform

The average or mean value of a continuous DC voltage will always be equal to its maximum peak value as a DC voltage is constant. This average value will only change if the duty cycle of the DC voltage changes. In a pure sine wave if the average value is calculated over the full cycle, the average value would be equal to zero as the positive and negative halves will cancel each other out. So the average or mean value of an ACwaveform is calculated or measured over a half cycle only and this is shown FIG 13.8.

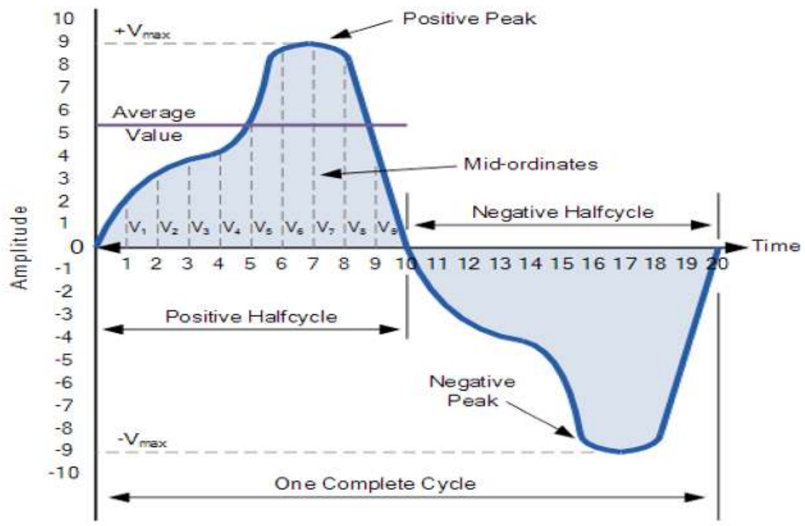



Fig. 13.8 Average Value of a Non-sinusoidal Waveform

To find the average value of the waveform we need to calculate the area underneath the waveform using the mid-ordinate rule, trapezoidal rule or the Simpson's rule found commonly in mathematics. The approximate area under any irregular waveform can easily be found by simply using the mid-ordinaterule.

The zero axis base line is divided up into any number of equal parts and in our simple example above this value was nine, (V1 to V9 ). The more ordinate lines that are drawn the more accurate will be the final average or mean value. The average value will be the addition of all the instantaneous values

added together and then divided by the total number. This is givenas.
Average Value of an AC Waveform

This effective power in an alternating current system is therefore equal to: ( $I^2$.R.Average ). Aspower is proportional to current squared, the effective current, I will be equal to √ I squared Ave.Therefore, the effective current in an AC system is called the Root Mean Squared or R.M.S. value and RMS values are the DC equivalent values that provide the same power to the load.
The effective or RMS value of an alternating current is measured in terms of the direct current value that produces the same heating effect in the same value resistance. The RMS value for any ACwaveform can be found from the following modified average value formula. Effective value is less than maximum instantaneousvalue.

RMS Value of an AC Waveform

$$V_{RMS} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}{n}}$$

Vaverage

= V 1+V 2+V 3+V 4 +Vn
n

Where: n equals the actual number of mid-ordinates used.
For a pure sinusoidal waveform this average or mean value will always be equal to 0.637 x Vmax and this relationship also holds true for average values of current.

The RMS Value of an AC Waveform

The average value of an AC waveform is NOT the same value as that for a DC waveforms average value. This is because the ACwaveform is constantly changing with time and the heating effect given by the formula ( $P = I^2.R$ ), will also be changing producing a positive power consumption.The equivalent average value for an alternating current system that provides the same power to the load as a DC equivalent circuit is called the "effectivevalue".

Where: n equals the number of mid-ordinates.
For a pure sinusoidal waveform this effective or R.M.S. value will always be equal to 1/√2 x Vmax which is equal to 0.707 x Vmax and this relationship holds true for RMS values of current. The RMS value for a sinusoidal waveform is always greater than the average value except for a rectangular waveform. In this case the heating effect remains constant so the average and the RMS values will be the same.
One final comment about R.M.S. values. Most multimeters, either digital or analogue unless otherwise stated only measure the
R.M.S. values of voltage and current and not the average. Therefore when using a multimeter on a direct current system the reading will be equal to I = V/R and for an alternating current system the reading will be equal to Irms =Vrms/R.

Also, except for average power calculations, when calculating RMS or peak voltages, only use VRMS to find IRMS values, or peak voltage, Vp to find peak current, Ip values. Do not mix the two together average, RMS or peak values as they are completely different and your results will be incorrect. Unless otherwise specified, any value for current or voltage are assumed to be rms/effective value.

Form Factor and Crest Factor

Although little used these days, both Form Factor and Crest Factor can be used to give information about the actual shape of the ACwaveform. Form Factor is the ratio between the rms value and the average value and is given as.

$$\text{Form Factor} = \frac{\text{R.M.S value}}{\text{Average value}} = \frac{0.707 \times \text{Vmax}}{0.637 \times \text{Vmax}}$$

The R.M.S. Voltage value is calculated as:

$$V_{RMS} = I \times R = 6 \times 40 = 240V$$

The Average Voltage value is calculated as:

For a pure sinusoidal waveform the Form Factor will always be equal to 1.11. Crest Factor is the ratio between the. peak value and the R.M.S value of the waveform and is given as.

For a pure sinusoidal waveform the Crest Factor will always be equal to 1.414.

AC Waveform Example No2

A sinusoidal alternating current of 6 amps is flowing through a resistance of 40Ω. Calculate the average voltage and the peak voltage of the supply.

The use and calculation of Average, R.M.S, Form factor and Crest Factor can also be use with any type of periodic waveform including Triangular, Square, Saw-toothed or any other irregular or complex voltage/current waveform shape. Conversion between the various sinusoidal values can sometimes be confusing so the following table gives a convenient way of converting one sine wave value toanother.

| Convert From | Multiply By | Or By | To Get Value |
|---|---|---|---|
| Peak | 2 | (√2)2 | Peak-to-Peak |
| Peak-to-Peak | 0.5 | 1/2 | Peak |
| Peak | 0.7071 | 1/(√2) | RMS |
| Peak | 0.637 | 2/π | Average |

| | | | |
|---|---|---|---|
| Average | 1.570 | $\pi/2$ | Peak |
| Average | 1.111 | $\pi/(2\sqrt{2})$ | RMS |
| RMS | 1.414 | $\sqrt{2}$ | Peak |
| RMS | 0.901 | $(2\sqrt{2})/\pi$ | Average |

Table No. 13.9 Sinusoidal Waveform Conversion Table MARK TO SPACE RATIO

The high time of the pulse waveform is called the mark, while the low time is called as space. The mark and space do not need to be of equal duration .(fig 13.20 and fig 13.21)

MARK RATIO = High Time/Low Time

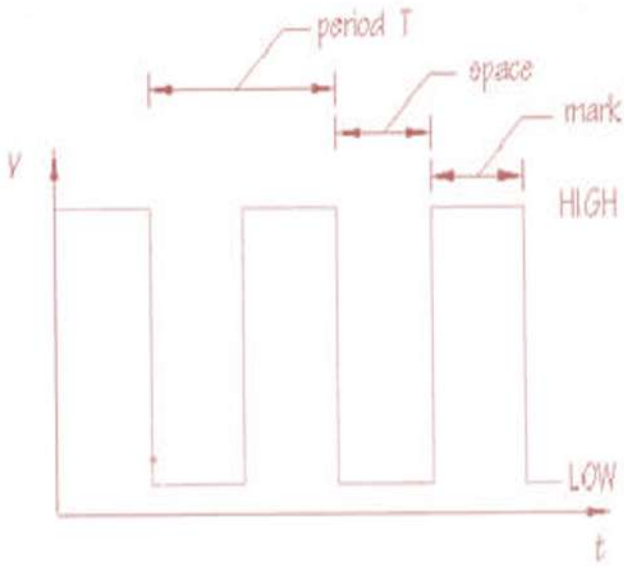



Fig. 13.20 Rectangular waveform's mark and Space

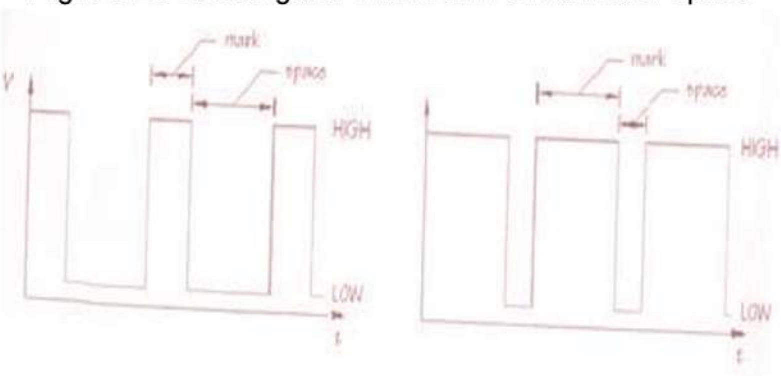



Fig. 13.21 Examples of different Mark- to – Space ratios

A mark to space ratio = 1.0 means that the high and low times are equal, while a mark to space ratio of 1.5 indicates that the high time is half as long as the low time.
A mark to space ratio of 3.0 corresponds to a longer high time,three times as that of space.

DUTY CYCLE

For clock signals, the percentage of the waveform period that thewaveform is at logic high level.
DUTY CYCLE = High TIME/period x 100%
The figure 13.22 shows the difference between two waveforms with different duty cycles. Notice that the 30% duty-cycle waveform is at logic high level for less time than the 50% duty cycle waveform.

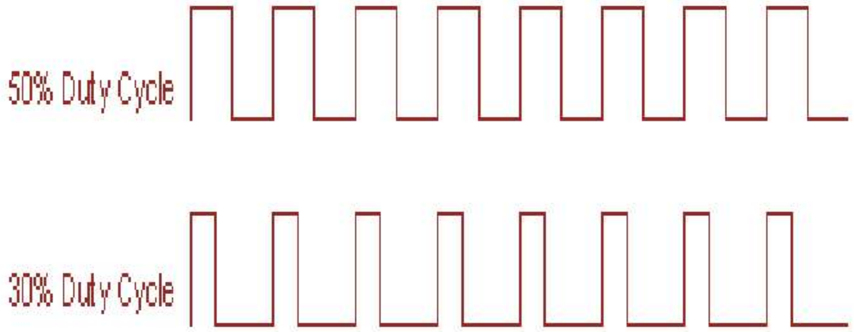



Fig. 13.22

MEASUREMENT OF AC VALUES

A wave form is a graph showing the variation, usually of voltage or current, against time. The horizontal axis shows the passing of time, progressing from left to right. The vertical axis shows the quantity measured (this is voltage in Fig 13.23).

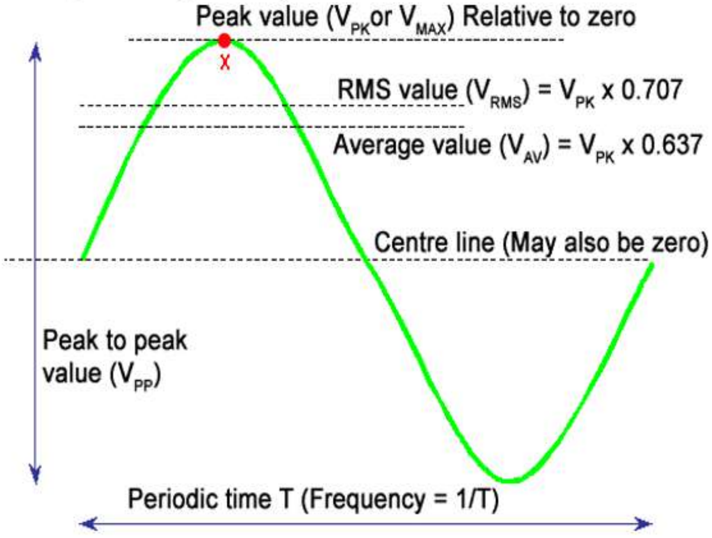



Fig. 13.23

through the cycle will be equal to the peak value. See point X inFig 13.29

Six of the most important characteristics of a sine wave are;

- PEAK TO PEAKvalue.
- INSTANTANEOUS value.
- AMPLITUDE.
- PEAKvalue.
- PERIODICTIME.
- AVERAGEvalue.
- RMSvalue.

Peak to Peak value

The PEAK TO PEAK value is the vertical distance between thetop and bottom of the wave. It will be measured in volts on a used to represent current. (fig 13.27)

Instantaneous Value

This is the value (voltage or current) of a wave at any particularinstant.often chosen to coincide with some other event. E.g. The instantaneous value of a sine wave one quarter of the way

Amplitude

The AMPLITUDE of a sine wave is the maximum verticaldistance reached, in either direction from the centre line of thewave. Asa sine wave is symmetrical about its centre line, theamplitude of the wave is half the peak to peak value, as shown in Fig .13.24

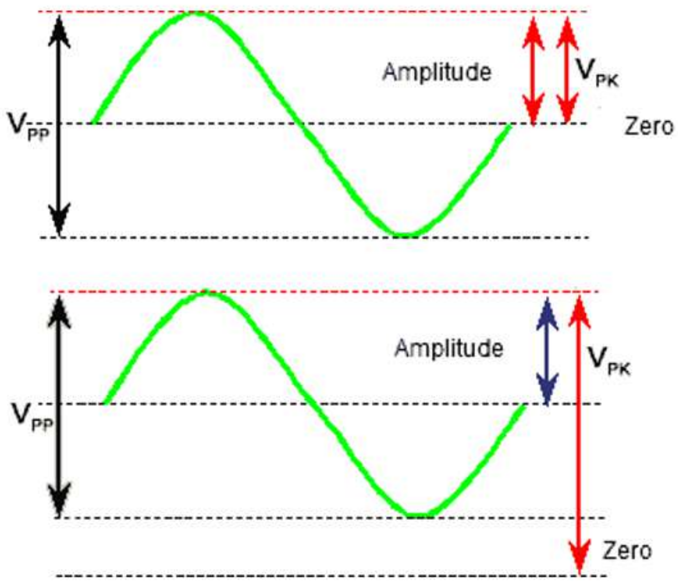



Fig. 13.24 Defining the Peak value VPK

Peak value

The PEAK value of the wave is the highest value the wavereaches above a reference value.The reference value normallyused is zero. In a voltage waveform the peak value may belabelled VPK or VMAX (IPK or IMAX in a current waveform).
If the sine wave being measured is symmetrical either side ofzero volts (or zero amperes), meaning that the dc level or dccomponent of the wave is zero volts, then the peak value must bethe same as the amplitude, that is half of the peak to peak value.
However this is not always the case, if a dc component otherthan zero volts is also present, the sine wave will be symmetricalabout this level rather than zero. The waveform in Fig 13.26 shows that the peak value can now be even larger than the peak to peak value, (the amplitude of the wave however, remains the same, and is the difference between the peak value and the "centre line" of thewaveform).

Periodic Time & Frequency

The PERIODIC TIME (given the symbol T) is the time, in
wave. It can be used to find the FREQUENCY of the wave $f$ using the formula $T = 1/f$
Thus if the periodic time of a wave is 20ms (or 1/50th of asecond) then there must be 50 complete cycles of the wave inone second. A frequency of 50 Hz. Note that when you use thisformula, if the periodic time is in seconds then the frequencywill be in Hz.

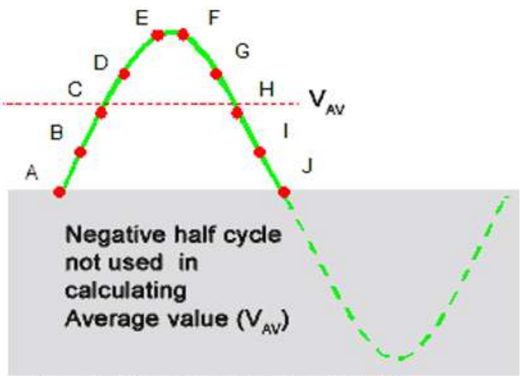



Fig. 13. 25 Determining the Average Value of a Sine Wave

The AVERAGE value. This is normally taken to mean the average value of only half a cycle of the wave (Fig 13.25). If the average of the full cycle was taken it would of course be zero, as inasinewavesymmetricalaboutzero,thereareequalexcursions

above and below the zero line. Using only half a cycle, the average value (voltage or current) is always 0.637 of the peak value of thewave.
VAV = VPK x 0.637

or
IAV = IPK X 0.637

The average value is the value that usually determines the voltage or current indicated on a test meter. There are however some meters that will read the RMS value, these are called "True RMS meters".
The RMS Value.

The RMS or ROOT MEAN SQUARE value is the value of the equivalent direct (non varying) voltage or current which would provide the same energy to a circuit as the sine wave measured. That is, if an AC sine wave has a RMS value of 240 volts, it will provide the same energy to a circuit as a DC supply of 240 volts.
It can be shown that the RMS value of a sine wave is 0.707 of the peak value.
VRMS = VPK x 0.707 and IRMS = IPK x 0.707
Also, the peak value of a sine wave is equal to 1.414 x the RMS value.

The Form Factor
If VAV (0.637) is multiplied by 1.11 the answer is 0.707, which is the RMS value. This difference is called the Form Factor of the

wave, and the relationship of 1.11 is only true for a perfect sine wave. If the wave is some other shape, either the RMS or the average value (or both) will change, and so will the relationship between them. This is important when measuring AC voltages with a meter as it is the average value that most meters actually measure. However they display the RMS value simply by multiplying the voltage by 1.11. Therefore if the AC wave being measured is not a perfect sine wave the reading will be slightly wrong. If you pay enough money however, you can buy a true RMS meter that actually calculates the RMS value of non-sine waves.

The Mains (Line) Supply

To demonstrate some of these characteristics in use, consider a very common sine wave, the mains supply or line waveform, which in many parts of the world is a nominal 230V.Electrical equipment that connects to the mains supply always carries a label giving information about what supply the equipment can be connected to. These labels are quite variable in appearance, but often there is a picture of a sine wave showing that an a.c. supply must be used. The voltage quoted will be 230V (or 120V in the USA) or range of voltages including these values. These voltages actually refer to the RMS value of the mains sine wave. The label also states that the frequency of the supply, which is 50Hz in Europe or 60Hz in the USA.

From this small amount of information other values can be workedout:

a. The peak voltage of the waveform, as VPK = VRMS x1.414

b. The AVERAGE value of the waveform, asVA

V =VP K x

d. 0.637

The PEAK TO PEAK value of the waveform. This is twicethe AMPLITUDE, which (because the mains waveform is symmetrical about zero volts) is the same value as

VPK. Because VPK is already known from a. it follows thatVPP = VPK x 2

The PERIODIC TIME which is given by $T = 1/f$

One way to express the intensity, or magnitude (also called

the amplitude), of an AC quantity is to measure its peak height on a waveform graph. This is known as the peak or crest value of an AC waveform: Figure13.26

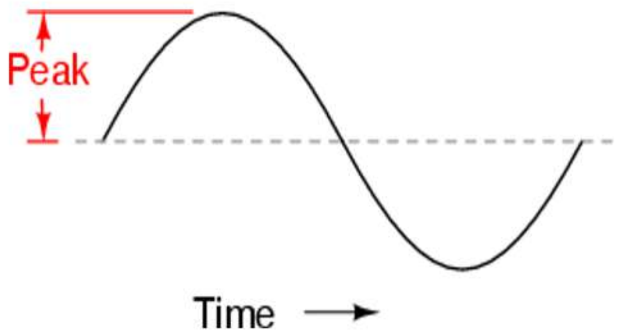



Fig. 13.26 Peak voltage of a waveform.

Another way is to measure the total height between opposite peaks. This is known as the peak-to-peak (P-P) value of an AC waveform: Figure 13.27

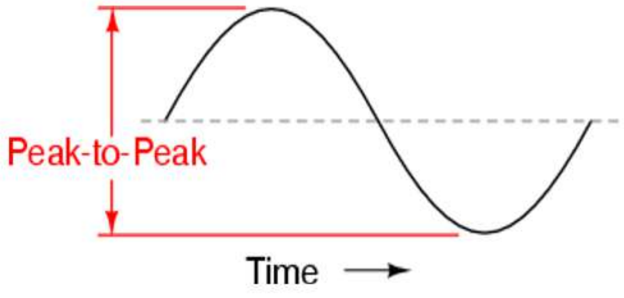



Fig. 13.27 Peak-to-peak voltage of a waveform.

Unfortunately, either one of these expressions of waveform amplitude can be misleading when comparing two different types of waves. For example, a square wave peaking at 10 volts is obviously a greater amount of voltage for a greater amount of time than a triangle wave peaking at 10 volts. The effects of these two AC voltages powering a load would be quite different: Figure fig 13.28

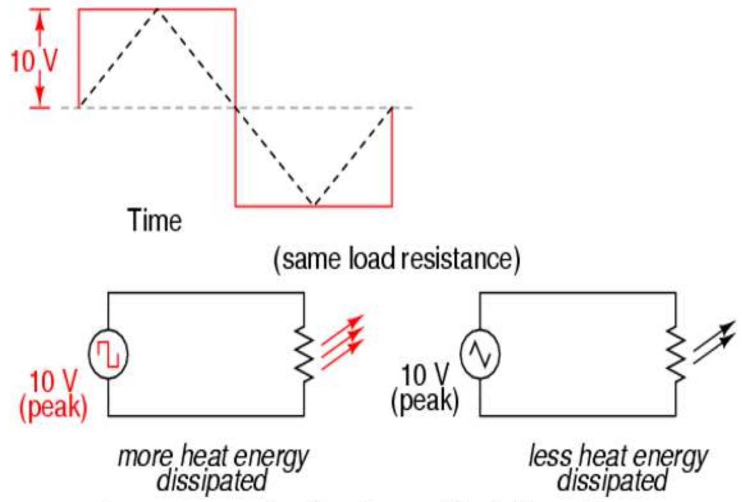



Fig. 13.28A square wave produces a greater heating effect than the same peak voltage triangle wave.

One way of expressing the amplitude of differentwave shapes in a more equivalent fashion is to

mathematically average the values of all the points on a waveform's graph to a single, aggregate number. This amplitude measure is known simply as the average value of the waveform. If we average all the points on the waveform algebraically (that is, to consider their sign, either positive or negative), the average value for most waveforms is technically zero, because all the positive points cancel out all the negative points over a full cycle: Figure13.29

This, of course, will be true for any waveform having equal-area portions above and below the “zero” line of a plot. However, as apractical measure of a waveform's aggregate value, “average” is usually defined as the mathematical mean of all the points' absolute values over a cycle. In other words, we calculate the practical average value of the waveform by considering all points on the wave as positive quantities, as if the waveform looked likethis:
Figure13.30

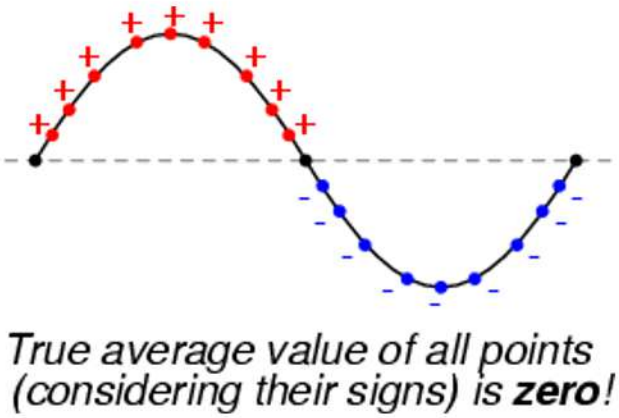



Fig. 13.29The average value of a sinewave is zero.

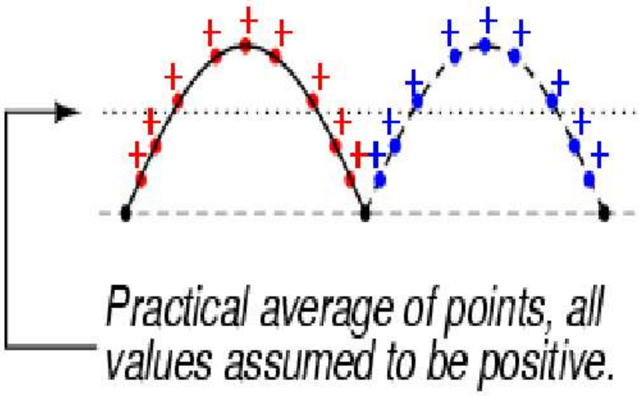



Fig. 13.30

For "pure" waveforms, simple conversion coefficients exist for equating Peak, Peak-to-Peak, Average (practical, not algebraic), and RMS measurements to one another: Figure 13.31

In addition to RMS, average, peak (crest), and peak-to- peak measures of an AC waveform, there are ratios expressing the proportionality between some of these fundamental measurements. The crest factor of an AC waveform, for instance, is the ratio of its peak (crest) value divided by its RMS value. The form factor of an AC waveform is the ratio of its RMS value divided by its average value. Square-shaped waveforms always have crest and form factors equal to 1, since the peak is the same as the RMS and average values. Sinusoidal waveforms have an RMS value of 0.707 (the reciprocal of the square root of 2) and a form factor of 1.11 (0.707/0.636). Triangle- andsawtooth-shaped

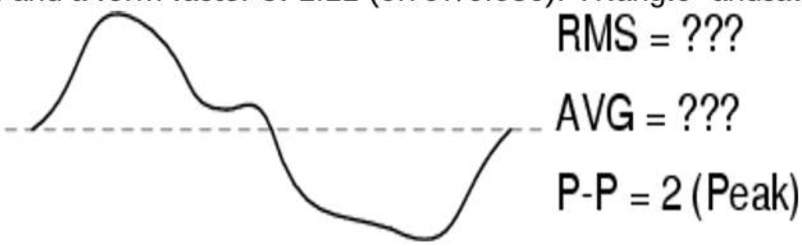



Fig. 13.32Arbitrary waveforms have no simple conversions.

This is a very important concept to understand when using an analog D'Arsonval meter movement to measure AC voltage or current. An analog D'Arsonval movement, calibrated to indicate sine-wave RMS amplitude, will only be accurate when measuring pure sine waves. If the waveform of the voltage or current being measured is anything but a pure sine wave, the indication given by the meter will not be the true RMS value of the waveform, because the degree of needle deflection in an analog D'Arsonval meter movement is

proportional to the average value of the waveform, not the RMS. RMS meter calibration is obtained by "skewing" the span of the meter so that it displays a small multiple of the average value, which will be equal to be the RMS value for a particular waveshape and a particular waveshapeonly.
Since the sine-wave shape is most common in electrical measurements, it is the waveshape assumed for analog meter calibration, and the small multiple usedinthecalibrationofthemeteris1.1107(theform factor: 0.707/0.636: the ratio of RMS divided by average for a sinusoidal waveform). Any wave shape other than a pure sine wave will have a different ratio of RMS and average values, and thus a meter calibrated for sine-wave voltage or current will not indicatetrueRMSwhenreadinganon-sinusoidalwave. Bearinmindthatthislimitationappliesonlytosimple, analogAC metersnotemploying"True-RMS" technology.

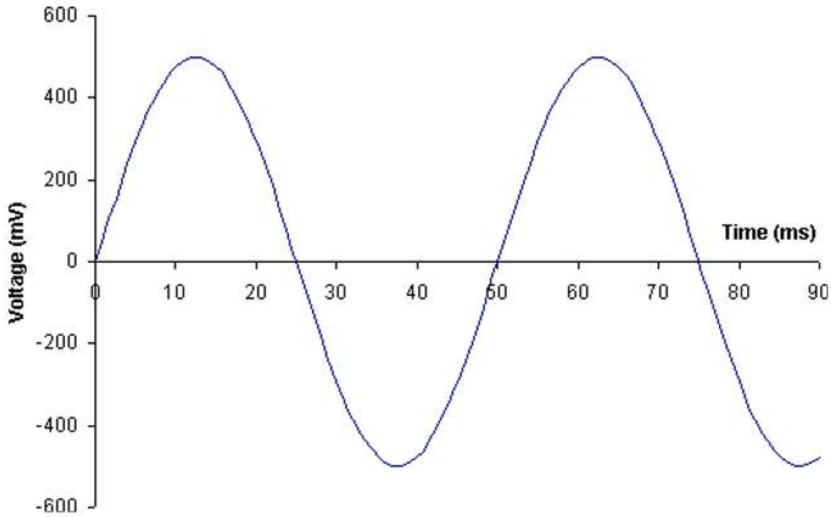



Fig. 13.33Determining ac values :

Cycle

- The plot of a periodic waveform shows a regularly repeating pattern of values, each of which is called acycle.

- Example: In the picture of the sine wave shown just13.33, we see a little less than two full cycles. Thefirst cycle extends from 0 ms to 50 ms, and the second (incomplete)cycleextendsfrom50mstotheedgeofthe chart, where it is cut off.

Period

- The time required for the values to rise and fall through one complete cycle is called the period of thewaveform.

- The symbol for period is T.

- Period is measured in units of seconds, abbreviateds.

- Example: The sine wave shown 13.33 has a period of 50 ms.

Frequency

- The frequency of a periodic waveform is the number of cycles that occur in 1second.
- The symbol for frequency is f.

Frequency is measured in units of cycles per second, or Hertz, abbreviatedHz.

Relationship Between Period and Frequency

- Period and frequency are the reciprocal of eachother:

$f = 1 \div T$

Example: The sine wave shownearlierhas a period of 50 ms. Therefore, its frequency is 20 Hz.

Peak Value

The maximum value reached by an ac waveform is called its peakvalue.

- If the waveform is a voltage waveform, then its peak value is also called its peak voltage, abbreviatedVp.

If the waveform is a current waveform, then its peak value is also called its peak current, abbreviatedIp.

- The peak value of a waveform is sometimes also called its amplitude, but the term "peak value" is more descriptive.

Peak-to-Peak Value

• The peak-to-peak value is the difference between a waveform's positive peak value and its negative peak value.

• If the waveform is a voltage waveform, then its peak-to- peak value is also called its peak-to-peak voltage, abbreviated Vpp.

• If the waveform is a current waveform, then its peak-to- peak value is also called its peak-to-peak current, abbreviated Ipp.

• If the waveform is symmetrical about the time axis, then the peak-to-peak value equals twice the peakvalue.

• Example: The sine wave shownearlierhas a peak-to-peak value of 1 Vpp. That's the difference between the maximum positive value (which is 500 mV) and the maximum negative value (which is -500 mV). Notice that I wrote a "pp" after the unit to show that I'm talking about a peak-to- peak value.

p and pp

- As mentioned in the two examples above, we write p as the subscript of a quantity or unit to show that we're talking about a peak value, and we write pp as the subscript of a quantity or unit when we're talking abouta peak-to-peak value.

## AC CIRCUIT CALCULATIONS

simple circuits (figure13.34) involving nothing more than an AC power source and resistance, the same laws and rules of DCapply simply and directly.

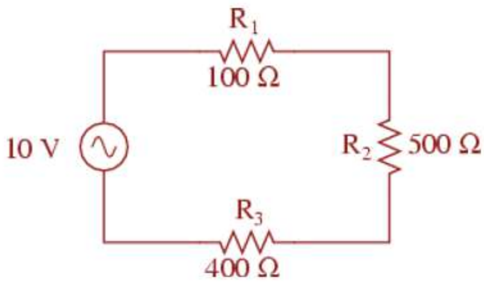



Fig. 13.34AC circuit calculations for resistive circuits are the same as for DC.

Series resistances still add, parallel resistances still diminish, and the Laws of Kirchhoff and Ohm still hold true. Actually, as we will discover later on, these rules and laws always hold true, its just that we have to express the quantities of voltage, current, and opposition to current in more advanced mathematical forms. With purely resistive circuits, however, these complexities of AC are of no practical consequence, and so we can treat the numbers as though we were dealing with simple DC quantities.
Because all these mathematical relationships still hold true, we can make use of our familiar "table" method of organizing circuit values just as with DC (fig13.35)

Power consumed,p= I2 R = 2.4 2 x 100 = 576W

| | $R_1$ | $R_2$ | $R_3$ | Total | |
|---|---|---|---|---|---|
| E | 1 | 5 | 4 | 10 | Volts |
| I | 10m | 10m | 10m | 10m | Amps |
| R | 100 | 500 | 400 | 1k | Ohms |

Table. 13.35

Unless otherwise stated, all values of voltage and current in ACcircuits are generally assumed to be RMS rather than peak, average, or peak-to-peak.
POWER CALCULATION FOR AC CIRCUIT P = V2/R ; P = VI ; P = I2R
A 1000W heating element is connected to a 250v AC supply
voltage. Calculate the impedance (AC resistance) of the element when it is hot and the amount of current taken from the supply.

AC PHASE

In addition to frequency and cycle characteristics, alternating voltage and current also have a

Current,I= P
V
V

= 1000W
250V
250

= 4 amps

relationship called “phase”.
When capacitors or inductors are involved in an AC circuit, the

Z= I =

4 = 62.5Ω

current and voltage do not peak at the same time. The fraction of a period difference between the peaks expressed in degrees is said

Resistors in AC Circuits Example No2
Calculate the power being consumed by a 100Ω resistive element connected across a 240v supply.
As there is only one component connected to the supply, the resistor, then VR = VS

to be the phase difference. The phase difference is <= 90 degrees. It is customary to use the angle by which the voltage leads the current. This leads to a positive phase for inductive circuits since current lags the voltage in an inductive circuit. The phase relation is often depicted graphically in a phasordiagram(fig 13.36)

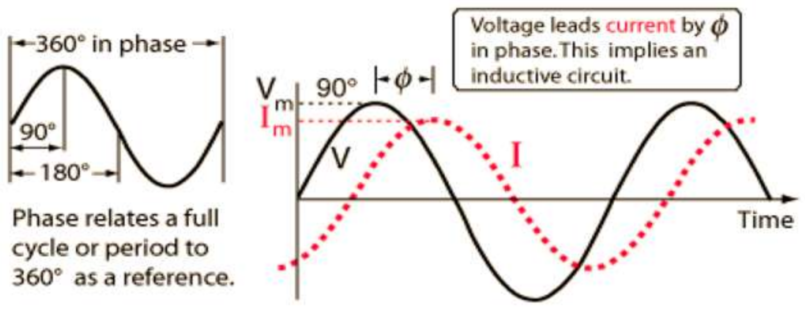



Fig. 13.36

Phase refers to the relationship of two sine waves (signals) to each other. If both signals are at their highest peak (+) at the same time they are in phase. If one signal is at its highest peak (+) while the other signal is at its lowest peak (-) they are 180 degrees out of phase. If the peaks and zero points of two ac waves do not match up at the same points in time. The graph in figure 13.37illustrates an example of this.

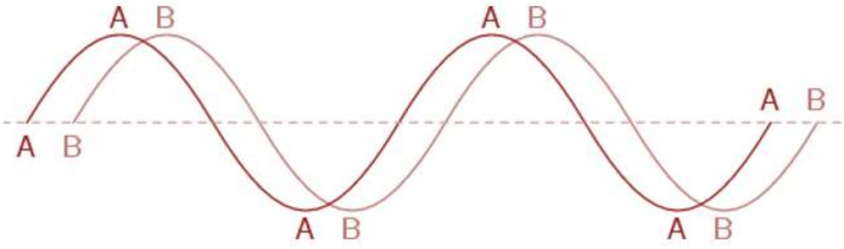



Fig. 13.37Out of phase waveforms

The two waves shown above (A versus B) are of the same amplitude and frequency, but they are out of step with each other. In technical terms, this is called a phase shift. Earlier we saw how we could plota "sine

wave" by calculating the trigonometric sine function for angles ranging from 0 to 360 degrees, a full circle. The starting point of a sine wave was zero amplitude at zero degrees, progressing to full positive amplitude at 90 degrees, zero at 180 degrees, full negative at 270 degrees, and back to the starting point of zeroat

360 degrees. We can use this angle scale along the horizontal axis of our waveform plot to express just how far out of step one wave is with another: Figure13.38

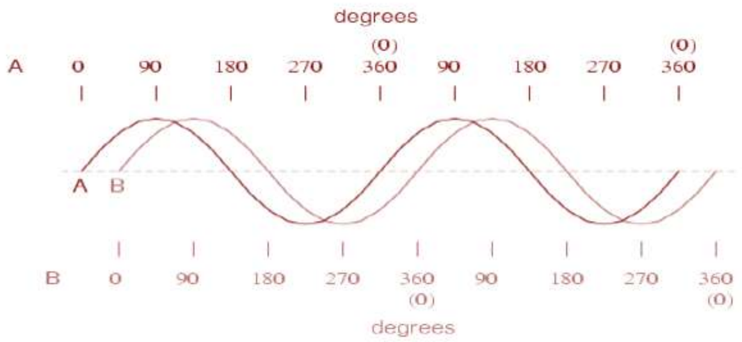



Fig.13.38WaveAleadswave B by 45o

The shift between these two waveforms is about 45 degrees, the "A" wave being ahead of the "B" wave. A sampling of different phase shifts is given in the following graphs to better illustrate this concept: Figure13.39

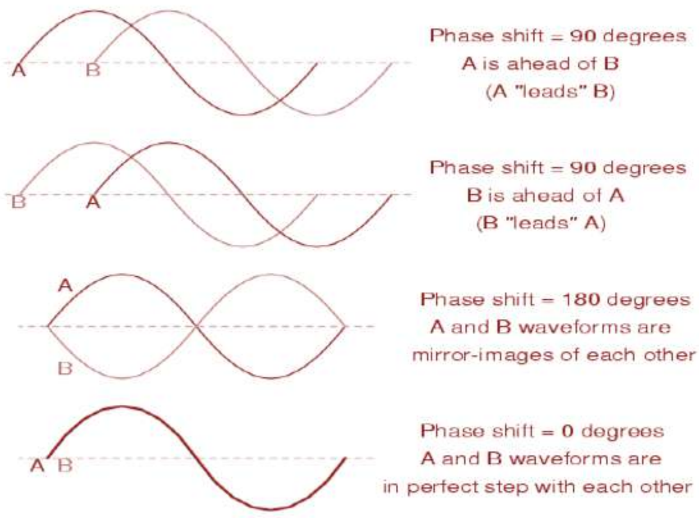



Fig. 13.39Examples of phase shifts

Because the waveforms in the above examples are at the same frequency, they will be out of step by the same angular amount at every point in time. For this reason, we can express phase shift for two or more waveforms of the same frequency as a constant quantity for the entire wave, and not just an expression of shift between any two particular points along the waves. That is, it is safe to say something like, "voltage 'A' is 45 degrees out of phase with voltage 'B'." Whichever waveform is ahead in its evolution is said to be leading and the one behind is said to be lagging.

Phase shift, like voltage, is always a measurement relative between two things. There's really no such thing as a waveform with anabsolute phase measurement because there's no known universal reference for phase. Typically in the analysis of AC circuits, the voltage waveform of the power supply is used as a reference for phase, that voltage stated as "xxx volts at 0degrees."

Any other AC voltage or current in that circuit will have its phase shift expressed in terms relative to that source voltage.

NOTE

- Phase shift is where two or more waveforms are out of step with eachother.
- The amount of phase shift between two waves can be expressed in terms of degrees, as defined by the degree units on the horizontal axis of the waveform graph used in plotting the trigonometric sinefunction.
- A leading waveform is defined as one waveform that is ahead of another in its evolution. A lagging waveformis one that is behindanother.

SINGLE AND THREE PHASEPRINCIPLES


Fig. 13.40

Depicted above (Figure 13.40) is a very simple AC circuit. If the load resistor's power dissipation were substantial, we might call this a "power circuit" or "power system" instead of regarding it as just a regular circuit. The distinction between a "power circuit"

and a “regular circuit” may seem arbitrary, but the practical concerns are definitely not.
One such concern is the size and cost of wiring necessary to deliver power from the AC source to the load. Normally, we do not give much thought to this type of concern if we're merely analyzing a circuit for the sake of learning about the laws of electricity. However, in the real world it can be a major concern.If we give the source in the above circuit a voltage value and also give power dissipation values to the two load resistors, we can determine the wiring needs for this particular circuit: (Figure 13.41)

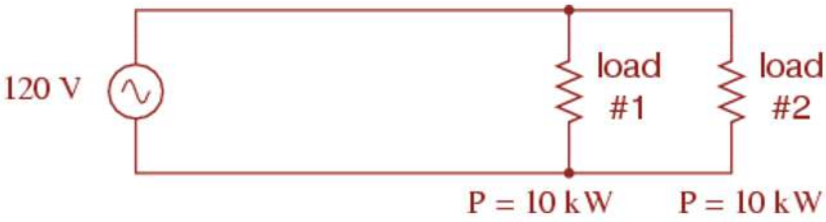



Fig. 13.41As a practical matter,the wiring for the 20 kW loads at 120 Vac is rather substantial (167A).
83.33 amps for each load resistor in Figure 13.41adds upto166.66ampstotalcircuitcurrent.Thisisnosmall amount of current, and would necessitate copper wire conductors of at least 1/0 gage. Such wire is well over 1/4 inch (6 mm) in diameter, weighing over 300 pounds per thousand feet. Bear in mind that copper is not cheap either! It would be in our best interest to find ways to minimize such costs if we were designing a power system with long conductorlengths.
One way to do this would be to increase the voltage of the power source and use loads built to dissipate 10 kW each at this higher voltage. The loads, of course, would have to have greater resistance values to dissipate the same power as before (10 kW each) at a greater voltage than before. The advantage would be

less current required, permitting the use of smaller, lighter, and cheaper wire: (Figure below)

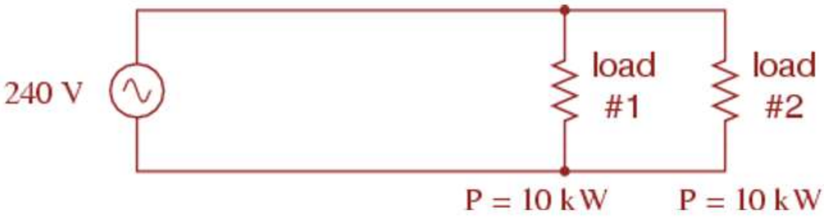



Fig. 13.42Same 10 kW loads at 240 Vac requires less substantial wiring than at 120 Vac (83 A).

Now our total circuit current is 83.33 amps, half of what it was before. We can now use number 4 gage wire,whichweighslessthanhalfofwhat1/0gagewire doesperunitlength.Thisisaconsiderablereductionin system cost with no degradation in performance. This is why power distribution system designers electto

transmit electric power using very high voltages(many thousands of volts): to capitalize on the savings realizedbytheuseofsmaller,lighter,cheaperwire.
However, this solution is not without disadvantages. Another practical concern with power circuits is the dangerofelectricshockfromhighvoltages.Again,this isnotusuallythesortofthingweconcentrateonwhile learning about the laws of electricity, but it is a very valid concern in the real world, especially when large amounts of power are being dealt with. The gain in efficiency realized by stepping up the circuit voltage presents us with increased danger of electric shock. Power distribution companies tackle this problem by stringing their power lines along high poles or towers,

andinsulatingthelinesfromthesupportingstructures with large, porcelaininsulators.
At the point of use (the electric power customer), there is still the issue of what voltage to use for powering loads. High voltage gives greater system efficiency by means of reduced conductor current, but it might not always be practical to keep power wiring out of reach at the point of use the way it can be elevated out of reach in distribution systems. This tradeoff between efficiency and danger is one that European power system designers have decided to risk, all their households and appliances operating at a nominal voltage of 240 volts instead of 120 volts as it isin

North America. That is why tourists from America visiting Europe must carry small step-down transformers for their portable appliances, to step the 240VAC (voltsAC)powerdowntoamoresuitable120 VAC.
Is there any way to realize the advantages of both increased efficiency and reduced safety hazard at the sametime?Onesolutionwouldbetoinstallstep-down transformersattheend-pointofpoweruse,justasthe American tourist must do while in Europe. However, this would be expensive and inconvenient foranything but very small loads (where the transformers can be built cheaply) or very large loads (where the expense of thick copper wires would exceed the expense of a transformer).
An alternative solution would be to use a higher voltage supply to provide power to two lower voltage loads in series. This approach combines the efficiency of a high-voltage system with the safety of a low- voltage system: (Figure13.43)

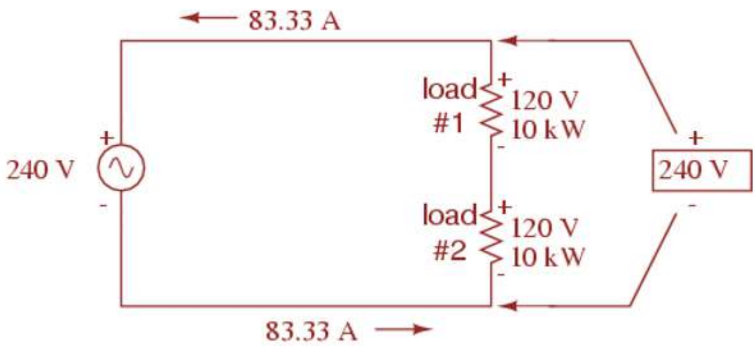


Fig. 13. 43Series connected 120 Vac loads, driven by 240 Vac source at 83.3 A total current.

Noticethepolaritymarkings(+and-)foreachvoltage shown, as well as the unidirectional arrows forcurrent. For the most part, I've avoided labeling "polarities" in the AC circuits we've been analyzing, even though the notation is valid to provide a frame of reference for phase. In later sections of this chapter,phase relationships will become very important, so I'm introducing this notation early on in the chapter for your familiarity.
The current through each load is the same as it was in the simple 120 volt circuit, but the currents are not additive because the loads are in series rather than parallel.Thevoltageacrosseachloadisonly120volts, not 240, so the safety factor is better. Mind you, we still have a full 240 volts across the power system wires, but each load is operating at a reduced voltage. If anyone is going to get shocked, the odds are thatit

willbefromcomingintocontactwiththeconductorsof a particular load rather than from contact across the main wires of a powersystem.

There's only one disadvantage to this design: the consequencesofoneloadfailingopen,orbeingturned off (assuming each load has a series on/off switch to interruptcurrent)arenotgood.Beingaseriescircuit,if either load were to open, current would stop in the other load as well. For this reason, we need to modify the design a bit:(Figure13.44)

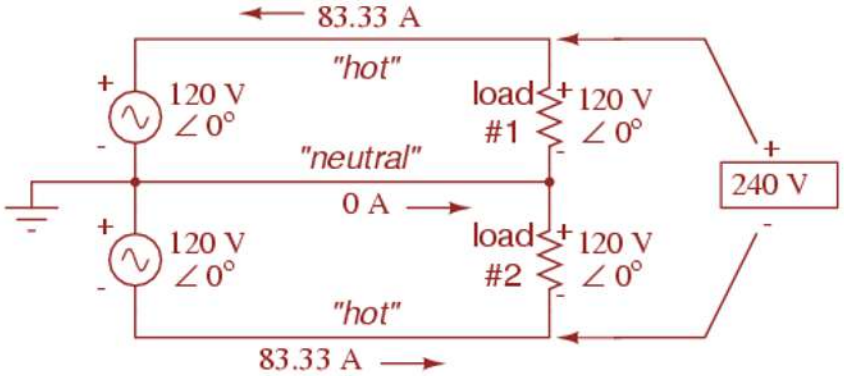



Fig. 13.44Addition of neutral conductor allows loads to be individually driven.

Instead of a single 240 volt power supply, we use two 120 volt supplies (in phase with each other!) in series to produce 240 volts, then run a third wire to the connection point between the loads to handle the eventuality of one load opening. This is called a split- phase power system. Three smaller wires are still cheaper than the two wires needed with the simple parallel design, so we're still ahead on efficiency. The astute observer will note that the neutral wire only has to carry the difference of current between the two loads back to the source. In the above case, with perfectly "balanced" loads consuming equal amounts of power, the neutral wire carries zero current.

Notice how the neutral wire is connected to earth ground at the power supply end. This is a common feature in power systems containing "neutral" wires,

since grounding the neutral wire ensures the least possible voltage at any given time between any "hot" wire and earthground.

Anessentialcomponenttoasplit-phasepowersystem is the dual AC voltage source. Fortunately, designing andbuildingoneisnotdifficult.SincemostACsystems receive their power from a step-down transformer anyway (stepping voltage down from high distribution levels to a user-level voltage like 120 or 240), that transformer can be built with a center-tapped secondary winding: (Figure13.45)

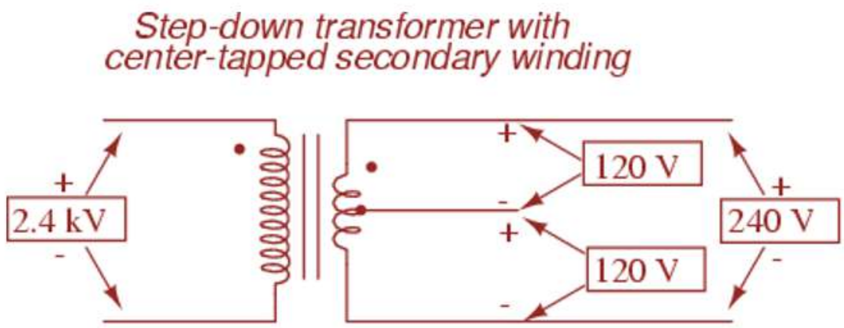



Fig. 13.45 American 120/240 Vac power is derived from a center tapped utility transformer.

If the AC power comes directly from a generator (alternator),thecoilscanbesimilarlycenter-tappedfor thesameeffect.Theextraexpensetoincludeacenter- tapconnectioninatransformeroralternatorwindingis minimal.

Here is where the (+) and (-) polarity markings really become important. This notation is often used to reference the phasings of multiple AC voltage sources, so it is clear whether they are aiding ("boosting") each other or opposing ("bucking") each other. If not for these polarity markings, phase relations between multipleACsourcesmightbeveryconfusing.Notethat thesplit-phasesourcesintheschematic(eachone120 volts∠0o),withpolaritymarks(+)to(-)justlikeseries- aiding batteries can alternatively be represented as such: (Figure13.46)

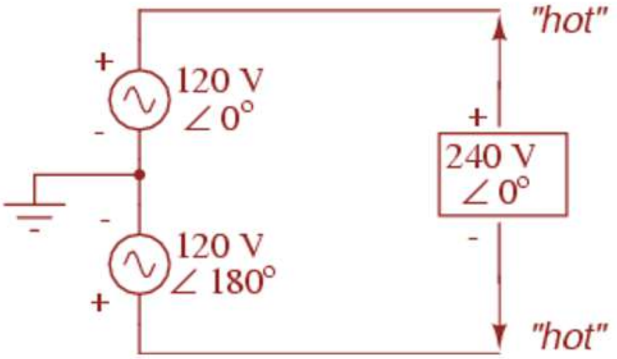



Fig. 13.46 Split phase 120/240 Vac source is equivalent to two series aiding 120 Vac sources.

To mathematically calculate voltage between "hot" wires, we must subtract voltages, because their polarity marks show them to be opposed to each other:

| *Polar* | *Rectangular* |
|---|---|
| $120 \angle 0^\circ$ | $120 + j0$ V |
| $- \ 120 \angle 180^\circ$ | $- \ (-120 + j0)$ V |
| $240 \angle 0^\circ$ | $240 + j0$ V |

If we mark the two sources' common connection point (the neutral wire) with the same polarity mark (-), we must express their relative phase shifts as being 180oapart. Otherwise, we'd bedenotingtwovoltage sources in direct opposition with each other, which would give 0 volts between the two "hot" conductors. Why am I taking the time to elaborate on polarity marks and phase angles? It will make more sense in the next section!

Power systems in American households and light industry are most often of the split-phase variety, providing so-called 120/240 VAC power. The term "split-phase"merelyreferstothesplit-voltagesupply in such a system. In a more general sense, this kind of AC power supply is called single phase because both voltage waveforms are in phase, or in step, with each other.

The term "single phase" is a counterpoint to another kind of power system called "polyphase" which we are about to investigate in detail. Apologies for the long introductionleadinguptothetitle-topicofthischapter. The advantages of polyphase power systems aremore obvious if one first has a good understanding of single phase system

NOTE

- Single phase power systems are defined by having anAC source with only one voltagewaveform.
- A split-phase power system is one with multiple (in-phase) AC voltage sources connected in series, delivering powerto loads at more than one voltage, with more than two wires. They are used primarily to achieve balance between system efficiency (low conductor currents) and safety (low load voltages).
- Split-phase AC sources can be easily created by center- tapping the coil windings of transformers oralternators.

THREE PHASE POWER SYSTEM

Three-phase electric power is a common method of alternating-current electric power generation, transmission, and distribution. It is a type of polyphase system and is the most common method used by electrical grids worldwide to transfer power. It is also used to power large motors and other heavy loads. A three-phase system is usually more economical than

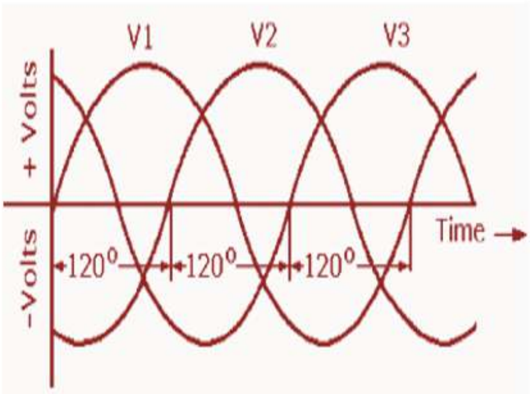



Fig. 13.47 Three-phase voltage waveforms are separated by 120 electrical degrees.

an equivalent single-phase or two-phase system at the same line to ground voltage because it uses less conductor material to transmit electrical power Both three-phase and single-phase devices can be powered from a three-phase supply. A three-phase circuit is a combination of three single-phase circuits. The current, voltage, and power relations of balanced three-phase AC circuits can be studied by applying the rules that apply to single-phase circuits.

phase transformer with four wire output for 208Y/120 voltservice: one wire for neutral, others for A, B and C phases

Principle of 3 Phase System

Fig. 13.49Three-phase electric powertransmission

In a balanced three-phase power supply system (by far, the most common type), three conductors each carry an alternatingcurrent of the same frequency and voltage relative to a common reference (Typically such a reference is connected to ground and often to a current-carrying conductor called the neutral) but with a phase difference of one third the period; hence the voltage on any conductor reaches

its peak at one third of a cycle after one of the other conductors and one third of a cycle before the third conductor. From any of the three conductors, the peak voltage on the other two conductors is delayed by one third and two thirds of one cycle respectively. This phase delay gives constant power transfer over each cycle. It also makes it possible to produce a rotating magnetic field in an electric motor and generate other phase arrangements usingtransformer.
With a perfectly balanced three phase supply the instantaneous voltage of any phase is exactly equal in magnitude but opposite to the sum of the other two phases. This means that if the load on the three phases is balanced as well, the return path for the current in any phase conductor is the other two phase conductors.
Hence, the sum of the currents in the three conductors is always zero and the current in each conductor is equal to and in the opposite direction as the sum of the currents in the other two. Thus, each conductor acts as the return path for the currents from the other two.
While a single phase AC power supply requires two conductors (Go and Return), a three phase supply can transmit three times the power by using only one extra conductor. This means that a 50%

increase in transmission cost yields a 200% increase in the power transmitted.
Three-phase systems may also utilise a fourth wire, particularly in low-voltage distribution. This is the neutral wire. The neutral allows three separate single-phase supplies to be provided at a constant voltage and is commonly used for supplying groups of domestic properties which are each single-phase loads. The connections are arranged so that, as far as possible in each group, equal power is drawn from each phase. Further up the supply chain in high-voltage distribution the currents are usually well balanced and it is therefore normal to omit the neutralconductor.
Three-phase supplies have properties that make them very desirable in electric power distribution systems:

- The phase currents tend to cancel out one another, summing to zero in the case of a linear balanced load. This makes it possible to reduce the size of the neutral conductor because it carries little or no current. With a balanced load, all the phase conductors carry the same current and so can be the same size.

- Power transfer into a linear balanced load is constant, which helps to reduce generator and motorvibrations.
- Three-phase systems can produce a rotating magneticfield with a specified direction and constant magnitude, which simplifies the design of electricmotors.

Most household loads are single-phase. In North American residences, three-phase power might feed a multiple-unit apartment block, but the household loads are connected only assingle phase. In lower-density areas, only a single phase might be used for distribution. Some large European appliances may be powered by three-phase power, such as electric stoves and clothes dryers.
Wiring for the three phases is typically identified by color codes which vary by country. Connection of the phases in the right order is required to ensure the intended direction of rotation of three- phase motors. For example, pumps and fans may not work in reverse. Maintaining the identity of phases is required if there is any possibility two sources can be connected at the same time; adirect interconnection between two different phases is a short-circuit.

Generation and Distribution

At the power station, an electrical generator converts mechanical power into a set of three AC electric currents, one from each coil (or winding) of the generator. The windings are arranged such that the currents vary sinusoid ally at the same frequency but with the peaks and troughs of their forms offset to

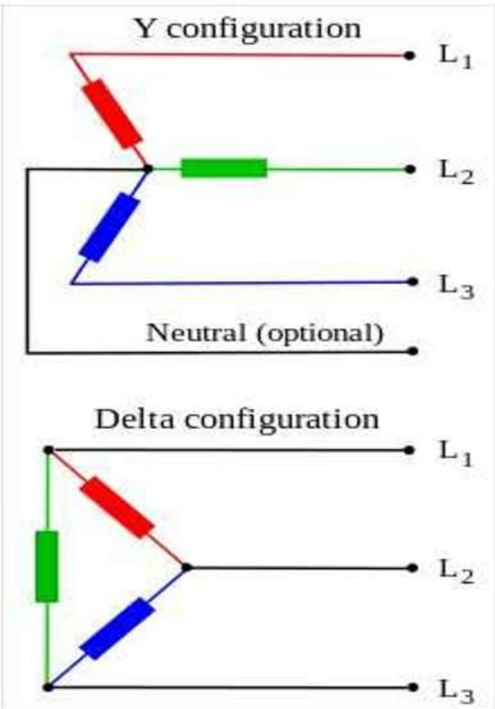
provide three complementary currents with a phase separation of one-third cycle (120° or $2\pi/3$radians). The generator frequency is typically 50 or 60 Hz, varying by country.
At the power station, transformers change the voltage from generators to a level suitable for transmission minimizing losses.

After further voltage conversions in the transmission network, the voltage is finally transformed to the standard utilization before power is supplied to customers.
Transformer connections
A "delta" connected transformer winding is connected betweenphases of a three-phase system. A "wye" ("star") transformerconnects each winding from a phase wire to a common neutralpoint.
In an "open delta" or "V" system, only two transformers are used. A closed delta system can operate as an open delta if one of thetransformers has failed or needs to be removed. In open delta,each transformer must carry current for its respective phases aswell as current for the third phase, therefore capacity is reduced to87%. With one of three transformers missing and the remainingtwo at 87% efficiency, the capacity is 58% ((2/3) ×87%).
Where a delta-fed system must be grounded for protection from surge voltages, a grounding transformer (usually a zigzagtransformer) may be connected to allow ground fault currents to return from any phase to ground. Another variation is a "cornergrounded" delta system, which is a closed delta that is grounded atone of the junctions of transformers.

Three-wire and four-wire circuits

There are two basic three-phase configurations: delta and wye (star). As shown in fig 13.51, a delta configuration requires only 3 wires for transmission but a wye (star) configuration may utilise a fourth wire. The fourth wire, if present, is provided as a Neutral and is normally Grounded. The '3-wire' and '4-wire' designations do not count the ground wire used above many transmission lines

which is solely for fault protection and does not carry current under non-fault conditions.
A four-wire system with symmetrical voltages between phase and neutral is obtained when the neutral is connected to the "common star point" of all supply windings. In such a system, all three phases will have the same magnitude of voltage relative to the Neutral. Other non-symmetrical systems have been



used.
The four-wire wye system is used when ground referenced voltages or the flexibility of more
Fig. 13. 51Wye (Y) and Delta (Δ) circuits
voltage selections are required. Faults on one phase to ground will cause a protection event (fuse or breaker open) locally and not involve other phases or other connected equipment. An example of application is local distribution in Europe (and elsewhere), where each customer may be only fed from one phase and the neutral (which is common to the three phases). When a group of customers sharing the neutral draw unequal phase currents, the common neutral wire carries the currents resulting from these imbalances. Electrical engineers try to design the system so the loads are balanced as much as possible within premises where 3-phase power is utilized. These same principles apply to the wide scale distribution of power to individual premises. Hence, every effort is made by supply authorities to distribute all three phases over a large number of premises so that, on average, as nearly as possible a balanced load is seen at the point of supply. In North America, a high-legdelta supply is sometimes used, where one winding of a delta connected transformer feeding the load is center-tapped and that centertapisgroundedandconnectedasaNeutral,asshownon

the right. This setup produces three different voltages. If thevoltage between the center tap (neutral) and each of the twoadjacent phases is 120 V (100%), the voltage across any twophases is 240 V (200%) and the Neutral to "high leg" voltage is ≈ 208 V (173%).[7]
The reason for providing the delta connected supply is usually to power large motors requiring a rotating field. However, the premises concerned will also require the "normal" North American 120 V supplies, two of which are derived (180 degrees "out of phase") between the "Neutral" and either of the center tapped phasepoints.

STAR AND DELTA CONNECTION

Three-phase power systems is developed by connecting three voltage sources together in what is commonly known as the "Y" (or "star") configuration. This configuration of voltage sources is characterized byacommonconnectionpointjoiningonesideofeach source. (Figure13.53)
Three-phase "Y" connection has three voltage sources connected to a common point.
If we draw a circuit showing each voltage source to be a coil of wire (alternator or transformer winding) and do some slight rearranging, the "Y" configuration becomes more obvious inFigure13.53.

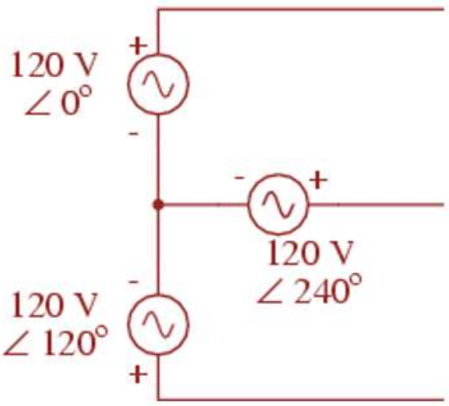



Fig. 13.53 Three-phase, four-wire "Y" connection usesa "common" fourthwire.

The three conductors leading away from the voltage sources (windings) toward a load are typically called lines, while the windings themselves are typically called phases. In a Y-connected system, there may or may not (Figure 13.54) be a neutral wire attached at the junction point in the middle, although it certainly helps alleviate potential problems should one element of a three- phase load fail open.

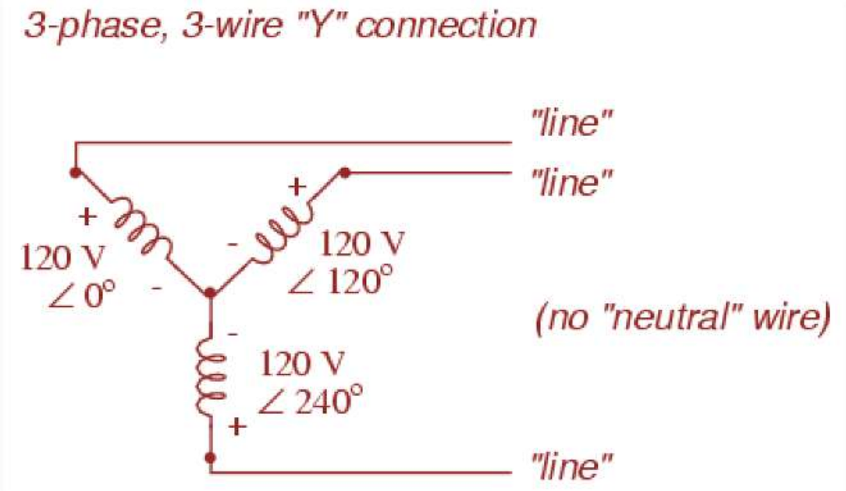



Fig. 13.54Three-phase, three-wire "Y" connection does notuse the neutralwire.

When we measure voltage and current in three-phasesystems, we need to be specific as to where we'remeasuring. Line voltage refers to the amount ofvoltage measured between any two line conductors ina balanced three-phase system. With the above circuit,the line voltage is roughly 208volts. Phase
voltage refers to the voltage measured across any onecomponent (source winding or load impedance) in abalanced three-phase source or load. For the circuitshown above, the phase voltage is 120 volts. Theterms line current and phase current follow the samelogic: the former referring to current through any oneline conductor, and the latter to current through anyone component.

Y-connected sources and loads always have line voltages greater than phase voltages, and line currents equal to phase currents. If the Y-connected source orload is balanced, the line voltage will be equal to thephase voltage times the square root of3:
However, the "Y" configuration is not the only valid one for connecting three-phase voltage source or load elements together. Another configuration is known as the "Delta," for its geometric resemblance to the Greek letter of the same name (Δ). Take close notice of the polarity for each winding in Figure13.55.

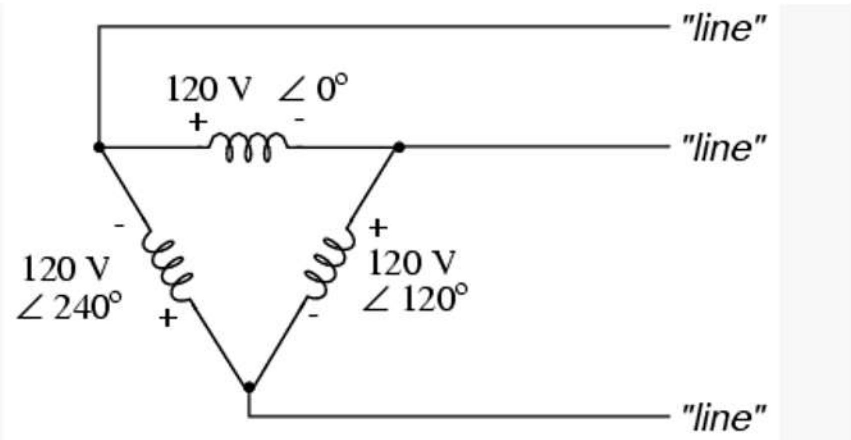



Fig. 13. 55Three-phase, three-wire Δ connection has no common.

At first glance it seems as though three voltage sources like this would create a short-circuit, electrons flowing around the triangle with nothing but the internal impedance of the windings to hold them back.

Due to the phase angles of these three voltage sources, however, this is not thecase.
One quick check of this is to use Kirchhoff's Voltage Lawtoseeifthethreevoltagesaroundtheloopaddup to zero. If they do, then there will be no voltage availabletopushcurrentaroundandaroundthatloop, and consequently there will be no circulating current. Startingwiththetopwindingandprogressingcounter-clockwise, our KVL expression looks something like this:

Indeed, if we add these three vector quantities together,theydoadduptozero.Anotherwaytoverify the fact that these three voltage sources can be connected together in a loop without resulting in circulating currents is to open up the loop atone

junction point and calculate voltage across the break: (Figure 13.56)

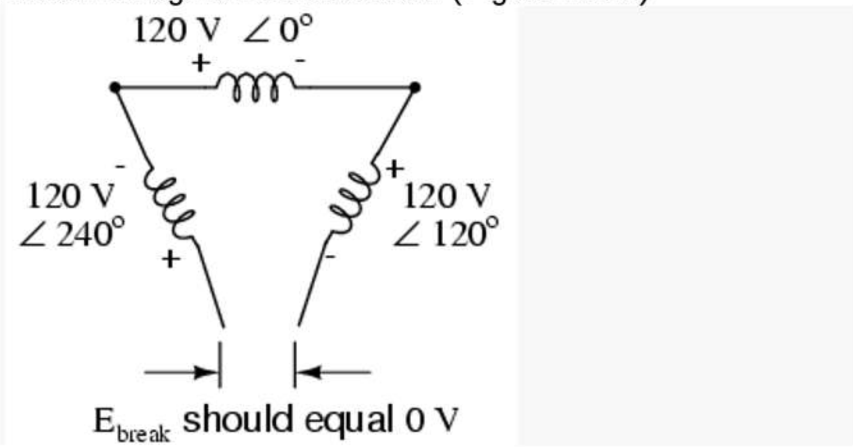



Fig. 13.56Voltage across open Δ should be zero.

Startingwiththe rightwinding(120 V∠120o)and progressing counter-clockwise, our KVL equation looks like this:

Sure enough, there will be zero voltage across the break,tellingusthatnocurrentwillcirculatewithinthe

triangular loop of windings when that connection is made complete.
Having established that a Δ-connected three-phase voltage source will not burn itself to a crisp due to circulating currents, we turn to its practical use as a source of power in three-phase circuits. Because each pair of line conductors is connected directly across a single winding in a Δ circuit, the line voltage will be equal to the phase voltage. Conversely, because each line conductor attaches at a node between two windings, the line current will be the vector sum ofthe two joining phase currents. Not surprisingly, the resultingequationsforaΔconfigurationareasfollows:

Let'sseehowthisworksinanexamplecircuit: (Figure13.57)

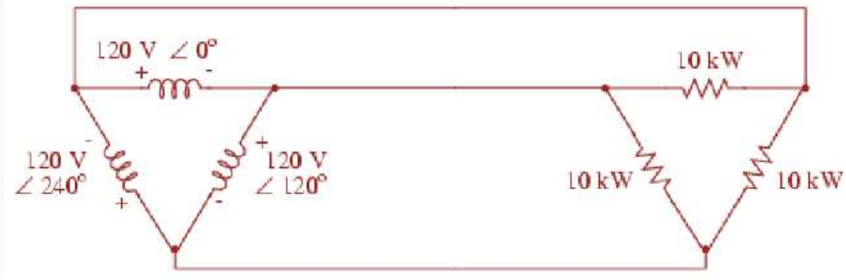



Fig. 13.57The load on the Δ source is wired in a Δ.

With each load resistance receiving 120 volts from its respective phase winding at the source, the current in each phase of this circuit will be 83.33 amps:

So each line current in this three-phase power system is equal to 144.34 amps, which is substantially more than the line currents in the Y-connected system we

lookedatearlier.Onemightwonderifwe'velostallthe advantages of three-phase power here, given the fact that we have such greater conductor currents, necessitating thicker, more costly wire. The answer is no. Although this circuit would require three number1 gage copper conductors (at 1000 feet of distance between source and load this equates to a little over 750 pounds of copper for the whole system), it is still less than the 1000+ pounds of copper required for a single-phase system delivering the same power (30 kW) at the same voltage (120 volts conductor-to- conductor).

One distinct advantage of a Δ-connected system is its lack of a neutral wire. With a Y-connected system, a neutral wire was needed in case one of the phase loads were to fail open (or be turned off), in order to keep the phase voltages at the load from changing. This is not necessary (or even possible!) in a Δ- connected circuit. With eachload phase element directly connected across a respective source phase winding, the phase voltage will be constant regardless of open failures in the loadelements.

Perhaps the greatest advantage of the Δ-connected source is its fault tolerance. It is possible for one of the windings in a Δ-connected three-phase source to fail open (Figure 13.58) without affecting load voltage or current!

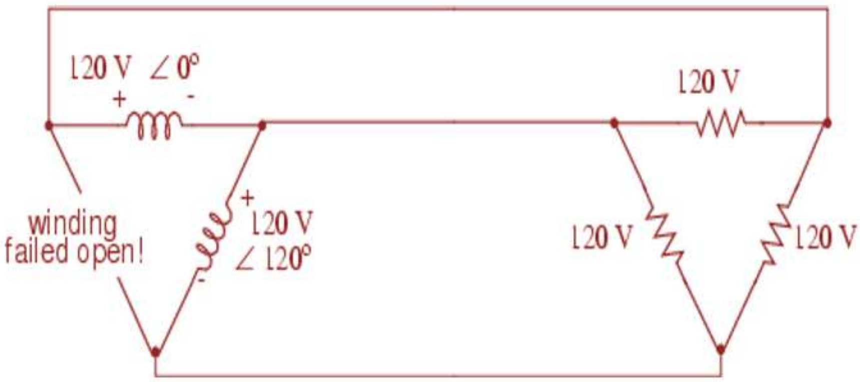



Fig. 13.58 Even with a source winding failure, the line voltage is still 120 V, and load phase voltage is still 120 V. The only difference is extra current in the remaining functional source windings.

The only consequence of a source winding failing open for a Δ- connected source is increased phase current in the remaining windings. Compare this fault tolerance with a Y-connected system suffering an open source winding in Figure 13.59.

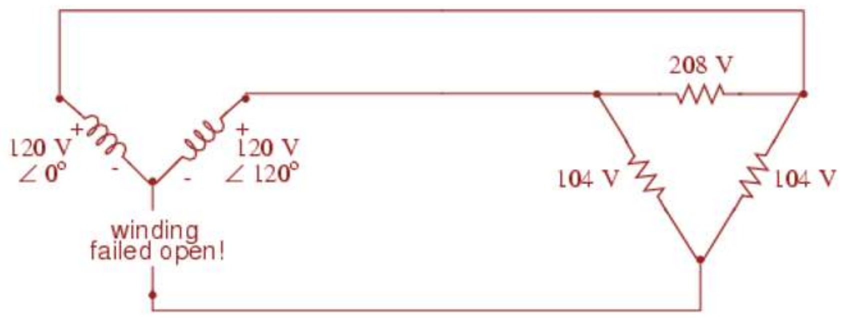



Fig. 13.59Open "Y" source winding halves the voltage on two loads of a Δ connected load.

With a Δ-connected load, two of the resistances suffer reduced voltage while one remains at the original line voltage, 208. A Y-connected load suffers an even worse fate (Figure 13.60) with the same winding failure in a Y- connected source


Fig. 13.60Open source winding of a "Y-Y" system halves the voltage on two loads, and looses one load entirely.

In this case, two load resistances suffer reduced voltage while the third loses supply voltage completely! For this reason, Δ-connected sources are preferred for reliability. However, if dual voltages are needed (e.g. 120/208) or preferred for lower line currents, Y-connected systems are the configuration of choice

NOTES

- The conductors connected to the three points of athree-phase source or load are calledlines.

- The three components comprising a three-phase source or load are called phases.
- Line voltage is the voltage measured between any twolines in a three-phasecircuit.
- Phase voltage is the voltage measured across a singlecomponent in a three-phase source orload.
- Line current is the current through any one line betweena three-phase source andload.
- Phase current is the current through any one componentcomprising a three-phase source orload.
- In balanced "Y" circuits, line voltage is equal to phasevoltage times the square root of 3, while line current isequal to phase current.
-
- In balanced Δ circuits, line voltage is equal to phase voltage, while line current is equal to phase current times the square rootof3.

Δ-connected three-phase voltage sources give greater reliability in the event of winding failure than Y-connected sources. However, Y-connected sources can deliver the same amount of power with less line current than Δ-connected.

Delta Star Transformation

To convert a delta network to an equivalent star networkweneedtoderiveatransformationformula for equating the various resistors to each other between the various terminals. Consider the circuit below.

Delta to Star Network. (fig 13.61)

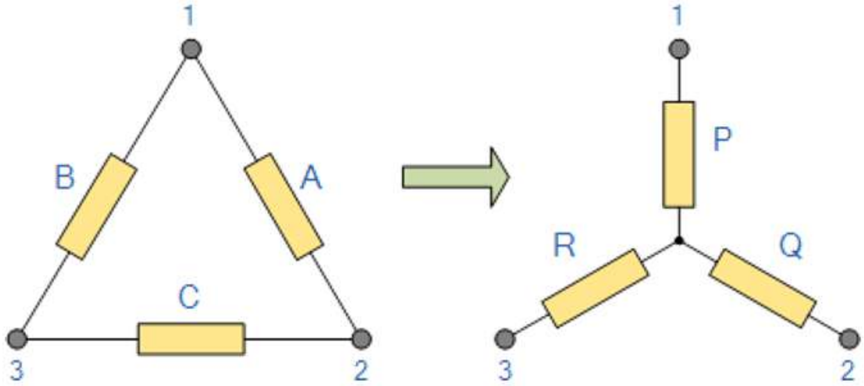



Fig. 13.61

Compare the resistances between terminals 1 and 2.

∴ P– Q BA+CB
A+B+C

∴ P-Q= BA−CA
A+B+C

- CA+CBA+B+C

P + Q = A in parallel with (B+C)

Then, re-writing Equation 1 will give us:

P+Q= A(B+C)
A+B+C

. . . EQI

P +Q=AB+AC
A+B+C

Resistance between the terminals 2 and 3.

Q+R = C in parallel with (A+B)

Adding together equation 1 and the result above of equation 3 minus equation 2 gives:

(P-Q)+(P+Q)

Q+R =C(A+B)

A+B+C
= EQ2

=BA−CA

+ AB+AC

Resistance between the terminals 1 and 3.

P + R = B in parallel with (A+C)

A+B+C

=2 P 2AB
A+B+C

A+B+C

P +R = B(A+C)
A+B+C

. . . . . EQ3

From which gives us the final equation for resistor P as:

This now gives us three equations and taking equation 3 from equation 2 gives:

EQ3 – EQ2 = (P+R) – (Q+R)

Then to summarize a little about the above maths, we cannow saythatresistorPinaStarnetworkcanbefoundasEquation1 plus (Equation 3 minus Equation 2) or Eq1 + (Eq3 –Eq2).
Similarly, to find resistor Q in a star network, is equation 2 plus

P+R = B(A+C)
A+B+C

- Q + R= C(A+B)
A+B+C

the result of equation 1 minus equation 3 or Eq2 + (Eq1 – Eq3) and this gives us the transformation of Qas:

Q= B(A+C)AC
A +B+ C
and again, to find resistor R in a Star network, is equation 3 plus the result of equation 2 minus equation 1 or Eq3 + (Eq2 –
Eq1) and this gives us the transformation of R as:

R= BA

A+B+C

Delta – Star Example No1
Convert the following Delta Resistive Network into an equivalent Star Network.(fig 13.62)

When converting a delta network into a star network the denominators of all of the transformation formulas are the same: A + B + C, and which is the sum of ALL the delta resistances. Then to convert any delta connected network to an equivalent star network we can summarized the above transformation equationsas:

Delta to Star Transformations Equations

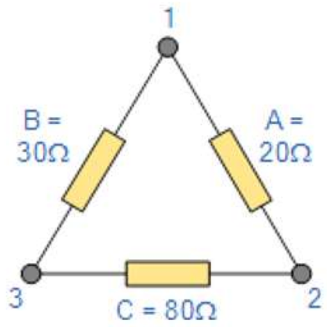



Fig 13.62

Q= AC = A+B+C

P= AB = A+B+C

R = BC = A+ B+C

20 X 80
130 =12.31Ω
20 X30 =4.61Ω
130

30X80=18.46Ω
130

P= AB
A+B+C
R= BC
A+B+C

Q= AC
A+B+C

Star Delta Transformation

Star Delta transformation is simply the reverse of above. We have seen that when converting from a delta network to an equivalent star network that the resistor connected to one terminal is the

If the three resistors in the delta network are all equal in value
then the resultant resistors in the equivalent star network will be equal to one third the value of the delta

resistors, giving each branchinthestar networkas:RSTAR= 1/3RDELTA

product of the two delta resistances connected to the same terminal, for example resistor P is the product of
resistors A and B connected to terminal 1.

By rewriting the previous formulas a little we can also find the transformation formulas for converting a resistive star network to an equivalent delta network giving us a way of producing a star delta transformation as shown 13.63.

Star to Delta Transformation

with respect to terminal 3 and resistor B is given as:

B = PQ +QR + RP
Q
with respect to terminal 2 with resistor C given as:

C = PQ +QR + RP
QP
with respect to terminal 1.

By dividing out each equation by the value of the denominator we end up with three separate transformation formulas that can be used to convert any Delta resistive network into an equivalent star network as given below.

Star Delta Transformation Equations

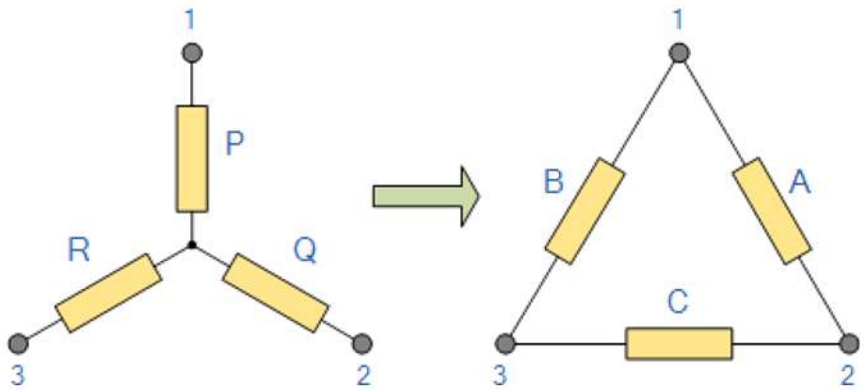



Fig 13.63

The value of the resistor on any one side of the delta, Δ network is the sum of all the two-product combinations of resistors in the star network divide by the star resistor located "directly opposite" the delta resistor being found. For example, resistor A is given as:

A= PQQR

C = PQQR

+ Q + PB= RP

Q

+ Q + R

+ P + R

A= PQ+QR+RP
R

RESONANT CIRCUITS

the magnetic field in the inductor. This process is repeatedcontinually. An analogy is a mechanical pendulum.

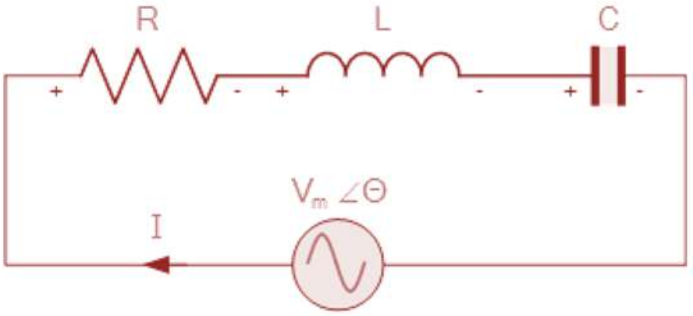
At resonance, the seriesimpedance of the two elements is at aminimum and the parallel impedance is at maximum. Resonanceis used fortuning and filtering, because it occurs at a t
particularfrequency for given values
of inductanceand capacitance. It can be detrimental to the operation of communicationscircuits by causing unwanted sustained and transient oscillations that may causenoise, signaldistortion, and damage to circuit elements.

Parallel resonance or near-to-resonance circuits can be used to prevent the waste of electrical energy, which would otherwise occur while the inductor built its field or the capacitor charged and discharged. As an example, asynchronous motors waste inductive current while synchronous ones waste capacitive current. The use of the two types in parallel makes the inductor feed the capacitor, and vice versa, maintaining the same resonant current in the circuit, and converting all the current into useful work.
Since the inductive reactanceand the capacitive reactance are of equal magnitude, $\omega L = 1/\omega C$, so:

where $\omega = 2\pi f$, in which f is the resonance frequency in hertz, L is the inductance in henries, and C is the capacitance in faradswhen standard SI unitsare used.

The Series Resonance Circuit

inradioand television tuning circuits producing a very selectivetuning circuit for the receiving of the different frequency.

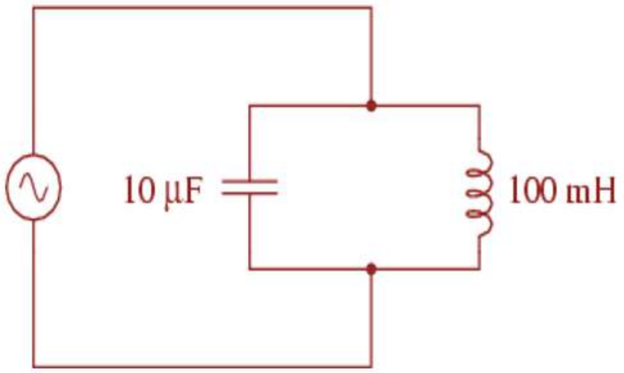



minimum so easily accepts the current whose frequency is equalto its resonantfrequency.

PARALLEL RESONANT CIRCUIT

A condition of resonance will be experienced in a tank circuit(Figure 14.47) when the reactances of the capacitor and inductorare equal to each other. Because inductive reactance increaseswith increasing frequency and capacitive reactance decreases withincreasing frequency, there will only be one frequency wherethese two reactances will be equal.

Simple parallel resonant circuit (tank circuit).




Module 3.14: Resistive (R), Capacitive (C) and Inductive (L) Circuits

Inductance and Alternating Current

We know ,that inductors are basically coils or loops of wire that

DC voltage is applied across the terminals of an inductor.

The growth of the current flowing through the inductor is not instant but is determined by the inductors own self-induced or back emf value. Then for an inductor coil, this back emf voltage VL is proportional to the rate of change of the
current flowing through it.

This current will continue to rise until it reaches its maximum steady state condition which is around five time constants when this self-induced back emf has decayed to zero. At this point a steady state DC current is flowing through the coil, no more back emf is induced to oppose the current flow and therefore, the coil acts more like a short circuit allowing maximum current to flow through it.
However, in an alternating current circuit which contains an AC Inductance, the flow of current through an inductor behaves very differently to that of a steady state DC voltage. Now in an AC circuit, the opposition to the current flowing through the coils windings not only depends upon the inductance of the coil but also the frequency of the applied voltage waveform as it varies from its positive to negativevalues.
The actual opposition to the current flowing through a coil in an AC circuit is determined by the AC Resistance of the coil with this AC resistance being represented by a complex number. Butto

distinguish a DC resistance value from an AC resistance value,
which is also known as Impedance, the term Reactance is used.
Like resistance, reactance is measured in Ohm"s but is given the symbol "X" to distinguish it from a purely resistive "R" value and asthecomponentinquestionisaninductor,thereactanceofan
inductor is called Inductive Reactance, ( XL ) and is measured in

Ohms. Its value can be found from the formula.

Inductive Reactance

Where: XL is the Inductive Reactance in Ohms, $f$ is the frequency in Hertz and L is the inductance of the coil in Henries.

We can also define inductive reactance in radians, where Omega, ω equals$2\pi f$.

XL= **ω**L

So whenever a sinusoidal voltage is applied to an inductive coil, the back emf opposes the rise and fall of the current flowing through the coil and in a purely inductive coil which has zero resistance or losses, this impedance (which can be a complex number) is equal to its inductive reactance. Also reactance is represented by a vector as it has both a magnitude and a direction (angle). Consider the circuit below. (Fig 14.1)

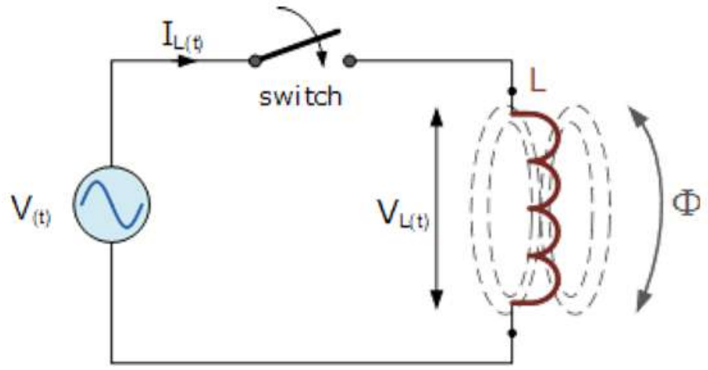



Fig. 14.1 AC Inductance with a Sinusoidal Supply

of L Henries ( H ), connected across a sinusoidal voltage given by the expression: V(t) = Vmax sin ωt. When the switch is closed this sinusoidal voltage will cause a current to flow and rise from zero to its maximum value. This rise or change in the current will induce a magnetic field within the coil which in turn will oppose or restrict this change in thecurrent.

But before the current has had time to reach its maximum value as it would in a DC circuit, the voltage changes polarity causing the current to change direction. This change in the other direction once again being delayed by the self-induced back emf in the coil, and in a circuit containing a pure inductance only, the current is delayed by90o.

The applied voltage reaches its maximum positive value a quarter ($1/4f$)ofacycleearlierthanthecurrentreachesitsmaximum 0o s shown below.(fig 14.2)

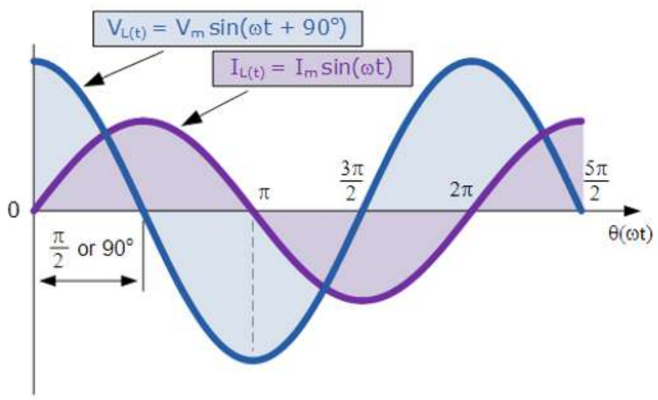



Fig. 14.2 Sinusoidal Waveforms for AC Inductance

This effect can also be represented by a phasor diagram were in a purely inductive circuit the voltage

"LEADS" the current by 90o. But by using the voltage as our reference, we can also say that the current "LAGS" the voltage by one quarter of a cycle or 90o as shown in the vector diagram14.3.

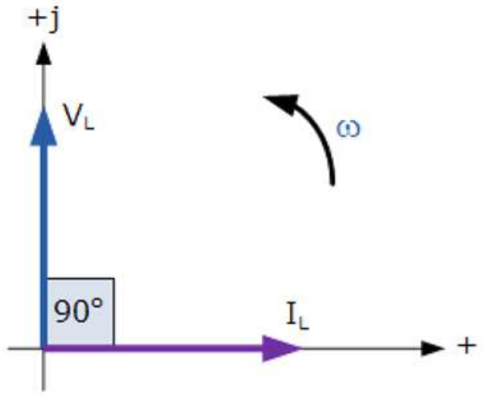



Fig. 14.3 Phasor Diagram for AC Inductance

So for a pure loss less inductor, VL "leads" IL by 90o, or we can say that IL "lags" VL by90o.
There are many different ways to remember the phase relationship between the voltage and current flowing through a pure inductor circuit, but one very simple and easy to remember way is to use the mnemonic expression "ELI" .ELI stands forElectromotive
force first in an AC inductance, L before the current I. In other words, voltage before the current in an inductor, E, L, I equals "ELI", and whichever phase angle the voltage starts at, this expression always holds true for a pure inductorcircuit.

The Effect of Frequency on Inductive Reactance

When a 50Hz supply is connected across a suitable AC Inductance, the current will be delayed by 90o as described previously and will obtain a peak value of I amps before the voltage reverses polarity at the end of each half cycle, i.e. the current rises up to its maximum value in "T secs".
If we now apply a 100Hz supply of the same peak voltage to the coil, the current will still be delayed by 90o but its maximum value will be lower than the 50Hz value because the time it requires to reach its maximum value has been reduced due to the increase in frequency because now it only has "1/2 T secs" to reach its peak value. Also, the rate of change of the flux within the coil has also increased due to the increase in frequency.

Thenfromtheaboveequationforinductivereactance,itcanbe
seen that if either the Frequency OR the Inductance is increased the overall inductive reactance value of the coil would also increase. As the frequency increases and approaches infinity,the
inductors reactance and therefore its impedance would also increase towards infinity acting like an open circuit.

Likewise, as the frequency approaches zero or DC, the inductors reactance would also decrease to zero, acting like a short circuit which may damage inductive components. This means then that inductive reactance is "directly proportional to frequency" and has a small value at low frequencies and a high value at higher frequencies as shown.(fig 14.4)

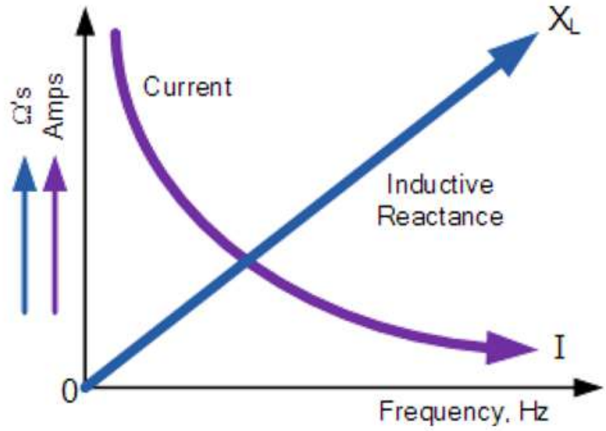



Fig. 14.4 Inductive Reactance against Frequency

The inductive reactance of an inductor increases as the frequency across it increases therefore inductive reactance is proportional to frequency ( XL α $f$ ) as the back emf generated in the inductor is equal to its inductance multiplied by the rate of change of current in the inductor.

Also as the frequency increases the current flowing through the inductor also reduces in value.
We can present the effect of very low and very high frequencies on a the reactance of a pure AC Inductance as follows:

Where: VL=IωLwhich is the voltage amplitude
and θ=+90o
between the voltage and current.

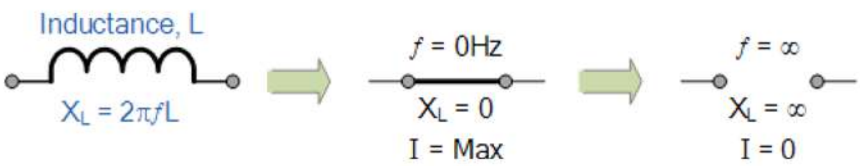


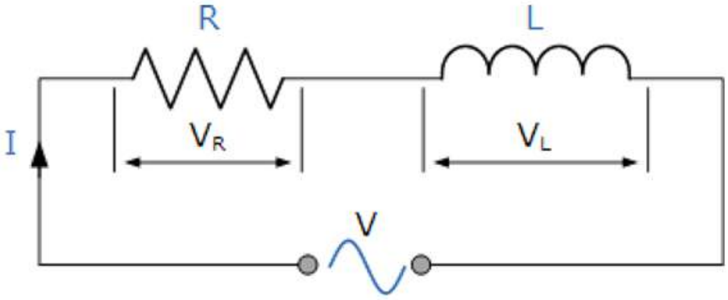

Fig. 14. 5

AC through a Series R + L Circuit
We have seen above that the current flowing through a purely inductive coil lags the voltage by 90o and when we say a purely inductive coil we mean one that has no ohmic resistance and therefore, no I2R losses. But in the real world, it is impossible to have a purely AC Inductance only.
All electrical coils, relays, solenoids and transformers will have a certain amount of resistance no matter how small associated with the coil turns of wire being used. This is because copper wire has resistivity. Then we can consider our inductive coil as being one that has a resistance, R in series with an inductance, L producing what can be loosely called an "impure inductance". In circuits containing large inductance such as relays, a capacitor is often placed in parallel in order to suppress the sparking.

If the coil has some "internal" resistance then we need to represent the total impedance of the coil as a resistance in series with an inductance and in an AC circuit that contains both inductance, L and resistance, R the voltage, V across the combination will be the phasor sum of the two component voltages, VR andVL.
This means then that the current flowing through the coil will still lag the voltage, but by an amount less than 90o depending upon the values of VR and VL, the phasor sum. The new angle between the

voltage and the current waveforms gives us their PhaseDifference which as we know is the phase angle of the circuit given the Greek symbol phi, Φ. Consider the circuit below were a pure non-inductive resistance, R is connected in series with a pure inductance,L.

Fig. 14.6 Series Resistance-Inductance Circuit




In the RL series circuit above(fig 14.6), we can see that the current is common to both the resistance and the inductance while the voltage is made up of the two component voltages, VR and VL. The resulting voltage of these two components can be found either mathematically or by drawing a vector diagram. To be able to produce the vector diagram a reference or common component must be found and in a series AC circuit the current is the referencesourceasthesamecurrentflowsthroughtheresistance

and the inductance. The individual vector diagrams for a pure resistance and a pure inductance are given as:

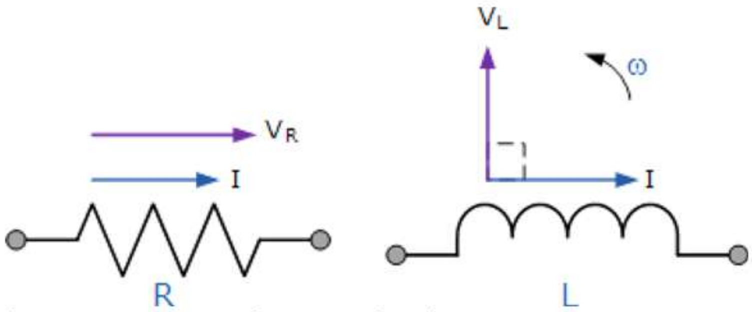



Fig. 14.7 Vector Diagrams for the Two Pure Components

We can see from above and from our previous tutorial about ACResistance that the voltage and current in a resistive circuit are both in phase and therefore vector VR is drawn superimposed to scale onto the current vector. Also from above (fig 14.7)it is known that the current lags the voltage in an AC inductance (pure) circuit therefore vector VL is drawn 90o in front of the current and to the same scale as VR as shown.

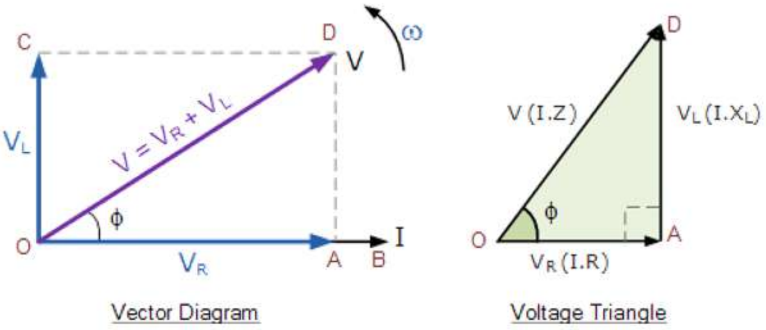



Fig. 14.8 Vector Diagram of the Resultant Voltage

From the vector diagram fig 14.8, we can see that line OB is the horizontal current reference and line OA is the voltage across the resistive component which is in-phase with the current. Line OC shows the inductive voltage which is 90o in front of the current therefore it can still be seen that the current lags the purely inductive voltage by 90o. Line OD gives us the resulting supply voltage.Then:

- V equals the r.m.s value of the appliedvoltage
- I equals the r.m.s. value of the seriescurrent.
- VR equals the I.R voltage drop across the resistance which is in-phase with thecurrent.
- VL equals the I.XL voltage drop across the inductance which leads the current by90o.

As the current lags the voltage in a pure inductance by exactly 90o the resultant phasor diagram drawn from the individual voltage drops VR and VL represents a right angled voltage triangle shown above as OAD. Then we can also use Pythagoras"s theorem to mathematically find the value of this resultant voltage across the resistor/inductor ( RL )circuit.

As VR = I.R and VL = I.XL the applied voltage will be the vector sum of the two as follows:

The quantity represents the impedance, Z of the circuit.

The Impedance of an AC Inductance Impedance, Zis the "TOTAL" opposition to current flowing in an he real part )and Reactance ( the imaginary part ). Impedance also has the units of

together.

Impedance can also be represented by a complex number, Z = R + jXL but it is not a phasor, it is the result of two or more phasors combined together. If we divide the sides of the voltage triangle above by I, another triangle is obtained whose sides represent the resistance, reactance and impedance of the circuit as shown below(fig14.9).

Likewise, the total reactance for the inductive elements would be equal to: X1 + X2 + X3 etc, giving a total reactance value for the circuit. This way a circuit containing many chokes, coils and resistors can be easily reduced down to an impedance value, Z comprising of a single resistance in series with a single reactance, Z2 = R2 +X2.

$$\text{Impedance, } Z = \frac{V}{I}$$

$$Z = \sqrt{R^2 + X_L^2}$$

$$\therefore Z^2 = \left(R^2 + X_L^2\right)$$

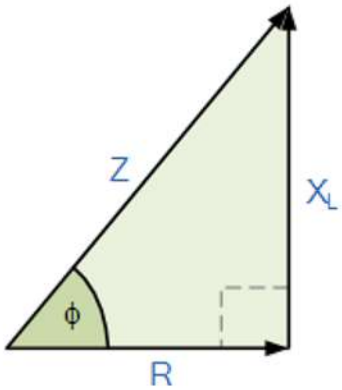



Fig. 14.9 The RL Impedance Triangle

Then: ( Impedance )2 = ( Resistance )2 + ( j Reactance )2 where j represents the 90o phase shift.
This means that the positive phase angle, θ between the voltage and current is given as.

While our example above represents a simple non-pure AC inductance, if two or more inductive coils are connected together in series or a single coil is connected in series with many non- inductive resistances, then the total resistance for the resistive elements would be equal to: R1 + R2 + R3 etc, giving a total resistive value for the circuit.

AC Inductance Example No1

In the following circuit, the supply voltage is defined as: V(t) = 230 sin( 314t - 30o ) and L = 2.2H. Determine the value of the current flowing through the coil and draw the resulting phasor diagram.

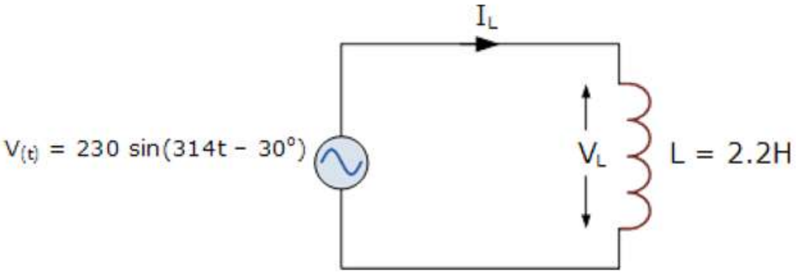



Fig.14.9

The voltage across the coil will be the same as the supply voltage. Converting this time domain value into polar form gives us: VL = 230 ∠-30o (v). The inductive reactance of the coil is: XL = ωL = 314 x 2.2 = 690Ω. Then the current flowing through the coil can be found using Ohms lawas:

With the current lagging the voltage by 90o the phasor diagram will be.(fig 14.10)

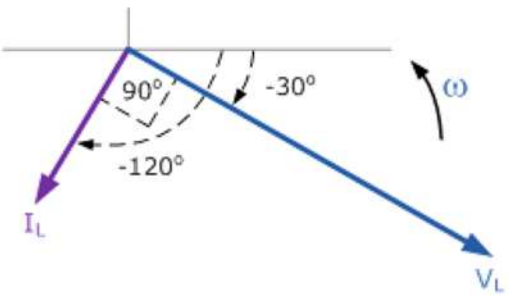



Fig. 14.10

AC Inductance Example No2

A coil has a resistance of 30Ω and an inductance of 0.5H. If the current flowing through the coil is 4amps. What will be the value of the supply voltage if its frequency is 50Hz.(fig 14.11)

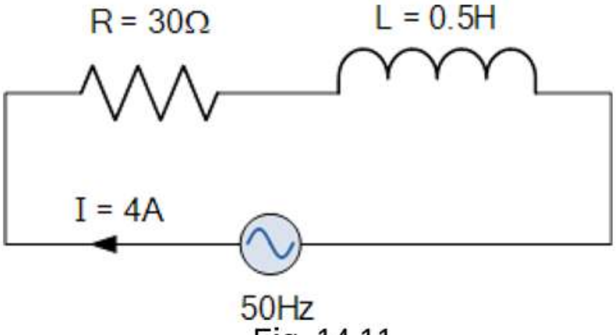



Fig. 14.11

The impedance of the circuit will be:

$$X_L = 2\pi f L = 2\pi \times 50 \times 0.5 = 157\Omega$$

$$Z = \sqrt{R^2 + X_L^2}$$
$$Z = \sqrt{30^2 + 157^2}$$
$$Z = 159.8\Omega$$

Then the voltage drops across each component is calculated as:

$$V_S = I.Z = 4 \times 159.8 = 640v$$

$$V_R = I.R = 4 \times 30 = 120v$$

$$V_L = I.X_L = 4 \times 157 = 628v$$

The phase angle between the current and supply voltage is calculated as (fig 14.12)

$$\tan^{-1}\phi = \frac{X_L}{R} = \frac{157}{30} = 79.2^{o}$$

The phasor diagram will be.

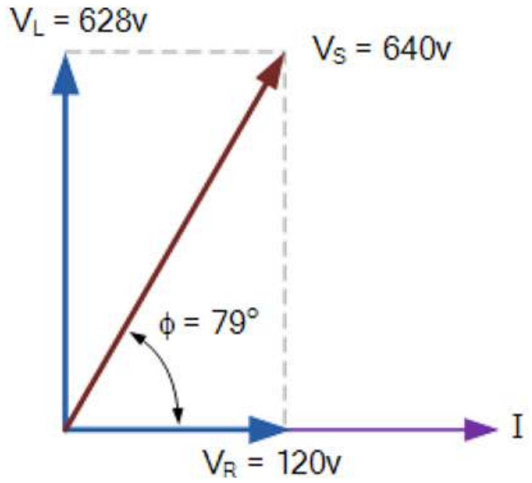



Fig. 14.12

Capacitance and Alternating Current

When capacitors are connected across a direct current DC supply voltage they become charged to the value of the applied voltage, acting like temporary storage devices and maintain or hold this

charge indefinitely as long as the supply voltage is present. During this charging process, a charging current, ( i ) will flow into the capacitor opposing any changes to the voltage at a rate that is equal to the rate of change of the electrical charge on theplates.

This charging current can be defined as: i = CdV/dt. Once the capacitor is "fully-charged" the capacitor blocks the flow of any more electrons onto its plates as they have become saturated. However, if we apply an alternating current or AC supply, the capacitor will alternately charge and discharge at a rate determinedbythefrequencyofthesupply.ThentheCapacitance in AC circuits varies with frequency as the capacitor is being constantly charged and discharged.

We know that the flow of electrons onto the plates of a Capacitor is directly proportional to the rate of change ofthe voltage across those plates. Then, we can see that capacitors in AC circuits like to pass current when the voltage across its plates is constantly changing with respect to time such as in AC signals, but it does not like to pass current when the applied voltage is of a constant value such as in DC signals. Consider the circuit fig 14.13.

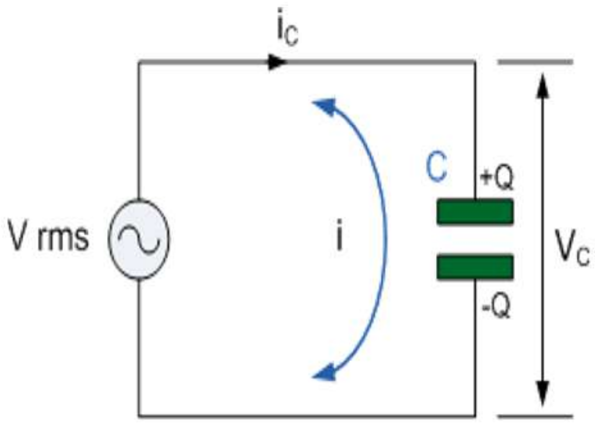



Fig. 14.13 AC Capacitor Circuit

In the purely capacitive circuit above, the capacitor is connected directly across the AC supply voltage. As the supply voltage increases and decreases, the capacitor charges and discharges with respect to this change. We know that the charging current is directly proportional to the rate of change of the voltage across the plates with this rate of change at its greatest as the supply voltage crosses over from its positive half cycle to its negative half cycle or vice versa at points, 0o and 180oalong the sine wave.
Consequently, the least voltage change occurs when the AC sine wave crosses over at its maximum or minimum peak voltage level, ( Vm ). At these positions in the cycle the maximum or minimum currents are flowing through the capacitor circuit and this is shown fig14.14.

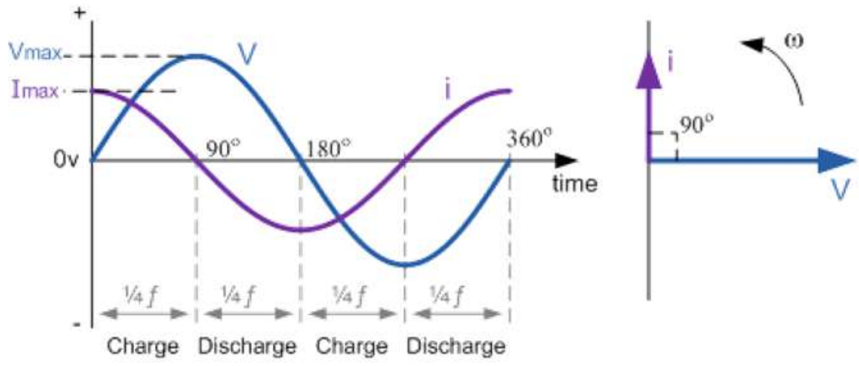



Fig. 14.14 AC Capacitor Phasor Diagram

At 0o the rate of change of the supply voltage is increasing in a positive direction resulting in a maximum charging current at that instant in time. As the applied voltage reaches its maximum peak value at 90o for a very brief instant in time the supply voltage is neither increasing nor decreasing so there is no current flowing through the circuit.
As the applied voltage begins to decrease to zero at 180o, the slope of the voltage is negative so the capacitor discharges in the negative direction. At the 180o point along the line the rate of change of the voltage is at its maximum again so maximum current flows at that instant and so on.
Then we can say that for capacitors in AC circuits the instantaneous current is at its minimum or zero

whenever the applied voltage is at its maximum and likewise the instantaneous value of the current is at its maximum or peak value when the applied voltage is at its minimum or zero.
From the waveform above, we can see that the current is leading the voltage by 1/4 cycle or 90o as shown by the vector diagram.

Then we can say that in a purely capacitive circuit the alternating voltage lags the current by 90o.
We know that the current flowing through the capacitance in AC circuits is in opposition to the rate of change of the applied voltage but just like resistors, capacitors also offer some form of resistance against the flow of current through the circuit, but with capacitors in AC circuits this AC resistance is known as Reactance or more commonly in capacitor circuits, Capacitive Reactance, so capacitance in AC circuits suffers from Capacitive Reactance.

Capacitive Reactance
Capacitive Reactance in a purely capacitive circuit is the opposition to current flow in AC circuits only. Like resistance, reactance is also measured in Ohm"s but is given the symbol X to distinguish it from a purely resistive value. As reactance isa
quantity that can also be applied to Inductors as wellas
Capacitors, when used with capacitors it is more commonly
known as Capacitive Reactance.
For capacitors in AC circuits, capacitive reactance is given the symbol Xc. Then we can actually say that Capacitive Reactance is a capacitors resistive value that varies with frequency. Also, capacitive reactance depends on the capacitance of the capacitor in Farads as well as the frequency of the AC waveform and the formula used to define capacitive reactance is given as:
Capacitive Reactance

$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$$

Where:
F is in Hertz and C is in Farads.
2πF can also be expressed collectively as the Greek letter Omega, ω to denote an angular frequency.
From the capacitive reactance formula above, it can be seen thatif
either of the Frequency or Capacitance where to be increased the
overall capacitive reactance would decrease. As the frequency
approachesinfinitythecapacitorsreactancewouldreducetozero
acting like a perfect conductor.
However, as the frequency approaches zero or DC, the capacitors reactance would increase up to infinity, acting like a very large resistance. This means then that capacitive reactance is "Inversely proportional" to frequency for any given value of Capacitance and this shown below(fig 14.15)

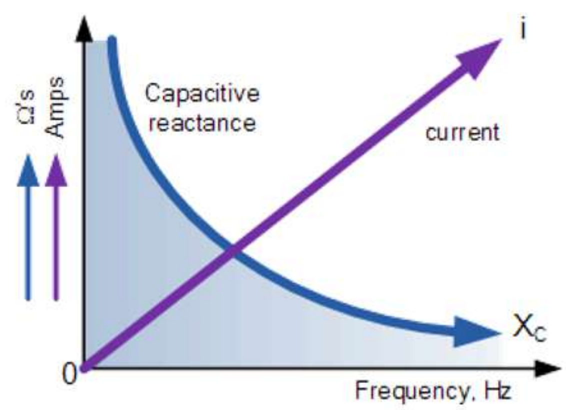


Fig. 14. 15 Capacitive Reactance against Frequency

The capacitive reactance of the capacitor decreases as the frequency across it increases therefore capacitive reactance is inversely proportional to frequency.
The opposition to current flow, the electrostatic charge on the plates (its AC capacitance value) remains constant as it becomes easier for the capacitor to fully absorb the change in charge on its plates during each half cycle.
Also as the frequency increases the current flowing through the capacitor increases in value because the rate of voltage change across its plates increases.
Then we can see that at DC a capacitor has infinite reactance (open-circuit), at very high frequencies a capacitor has zero reactance (short-circuit).

AC Capacitance Example No1.
Find the rms current flowing in an AC capacitive circuit when a 4uF capacitor is connected across a 880V, 60Hz supply.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 60 \times (4 \times 10^{-6})} = 663\Omega$$

$$I_{RMS} = \frac{V_{RMS}}{X_C} = \frac{880V}{663\Omega} = 1.33\text{Amperes}$$

So, the Capacitance in AC circuits varies with frequency as the capacitor is being constantly charged and discharged with the AC resistance of a capacitor being known as Reactance or more commonly in capacitor circuits, Capacitive Reactance.
This capacitive reactance is inversely proportional to frequency and produces the opposition to current flow around a capacitive

AC circuit. When frequency is decreased, the voltage across capacitor increases.
Phasor Diagram of Series RLC Circuit

When resistor, inductor and capacitor are connected in series across a voltage supply, the circuit so obtained is called series RLC circuit. The phasor diagram of series RLC circuit is drawn by combining the phasor diagram of resistor, inductor and capacitor. Before doing so, one should understand the relationship between voltage and current in case of resistor, capacitor and inductor.

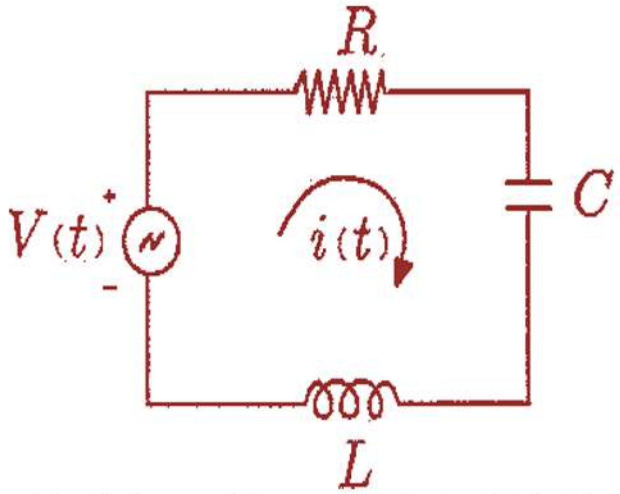



Fig. 14. 16 Phasor Diagram of Series RLC Circuit

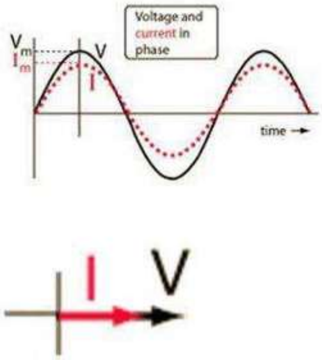



Fig. 14.17 Phasor Diagram of Series RLC Circuit

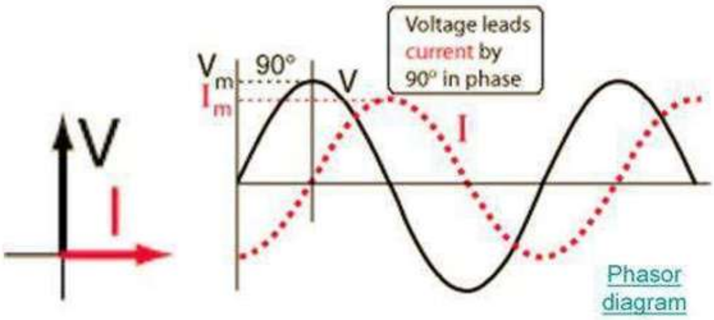



Fig. 14.18 Phasor Diagram of Series RLC Circuit

1. Resistor -In case of resistor, the voltageand thecurrent areinsamephaseorwecansaythatthephase angle difference between voltage and current is zero.

3 In case of capacitor, the current leads the voltage by 90° or in the other words, voltage attains its maximum and zero value 0° after the current attains it i.e the phasor diagram of capacitor is exactly opposite of inductor.

2. Inductor- In inductor, the voltage and the current are not

in phase. The voltage leads that of current by 90° or in the otherwords,voltageattainsitsmaximumandzerovalue 90° before the current attains it.

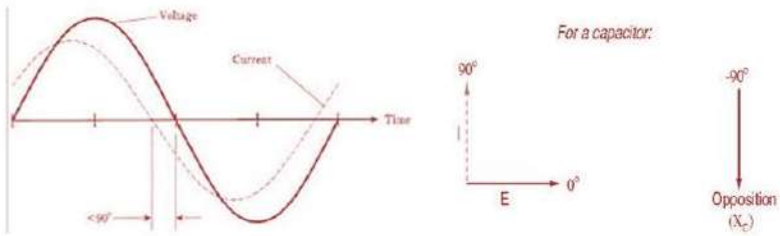



Fig. 14.19 Phasor Diagram of Series RLC Circuit

REACTANCE

In electrical and electronic systems, reactance is the opposition of a circuit element to a change of electric current or voltage,due tonductance or capacitance. A built-upelectric field resists the change of voltage on the element, while a magnetic field resists the change of current. The notion of reactance is similar to electrical resistance, but they differ in severalrespects. An ideal resistorhas zero reactance, while ideal inductors and capacitors consist entirely of reactance. The magnitude of the reactance of an inductor is proportional to frequency, while the magnitude of the reactance of a capacitor is inversely proportional tofrequency.
Both capacitive reactance and inductive reactance contribute to the total reactance.

where:

- is the capacitive reactance, measured inohms;
- is the inductive reactance, measured inohms;
- is the angular frequency, times the frequency inHz.

Although and are both positive by convention, the capacitive reactance makes a negative contributionto total reactance.

Hence:

- if , the reactance is said to beinductive; , then the impedance is purely resistive;

, the reactance is said to be capacitive.

Let's take the following example circuit and analyze it: (Figure14.20)

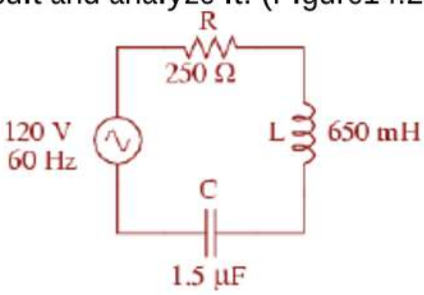



Fig. 14.20 Example series R, L, and C circuit.

The first step is to determine the reactances (in ohms) for the inductor and the capacitor.

X = XL – XC = 245.04-1.7684 = 243.2 Ω

IMPEDANCE

Electrical Impedance (Z), is the total opposition that a circuit presents to alternating current. Impedance is measured in ohms and may include resistance (R), inductive reactance (XL), and capacitive reactance (XC). Ohm"s Law states that current in a circuit is equal to the voltage divided by the resistance. However, in an ac ciruit, the effect of both capacitive and inductive reactances are considered. Impedance(Z) is the combined effect of resistance, capacitive reactance and inductive reactance.

Since, capacitive and inductive reactance have opposite effects in an ac circuits, therefore to find total reactance we use the difference in reactance. If we consider inductive reactance as positive as it causes the voltage to lead the current and capacitive reactance as negative as it causes voltage to lag, then the two algebraically can be added as

XL + (-XC) =Xt (total reactance)

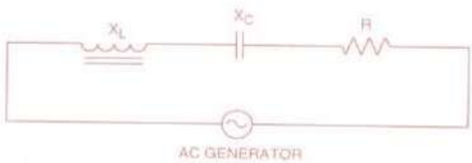
It may appear that we could add this result to find impedance but we must add the effect of resistance in the circuit. As resistance in a circuit does not cause current to lag or lead and for this reason its effect is 90° ahead of inductance and is 90° behind capacitance. So it is necessary to add resistance and reactancevectorially.

Vectors represent a given force. The strength of force is indicated by length of line representing the vector. The values for XL,XC and R can be shown in the figure below. Resistance is always shown in horizontal axis, inductive reactance on vertical axis pointing up and capacitive reactance on vertical axis pointing down. We can see the effect of XL and XC cancelling each other and effect of resistance are 90° from either reactance. As shown in

the figure (14.21) the three vectors XL, XC nad R can be combined into one resultant vector called impedance(Z).

Applying Pythagorean theorem, Z2= R2+Xt2
Z =R2+(XL-XC)2(INSERT SQUARE ROOT)

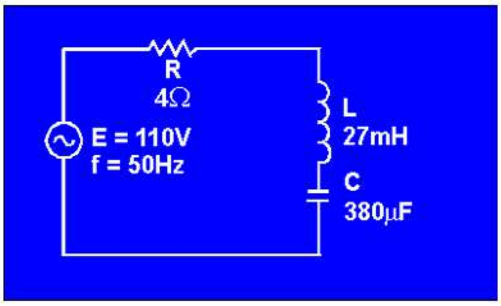
This formula is used to find impedance for series circuit only.




A simple series ac circuit.

Fig. 14.22

Current can be found by I = E/Z




Example series RLC circuit

Fig. 14.23

Type equation here.
Now solve for X

Given: $X_C = 7\ \Omega$
$X_L = 10\ \Omega$

Solution: $X = X_L - X_C$
$X = 10\Omega - 7\Omega$
$X = 3\Omega$ (Inductive)

Use the value of X to solve for Z.

Given: $X = 3\ \Omega$
$R = 4\ \Omega$

Solution: $Z = \sqrt{X^2 + R^2}$
$Z = \sqrt{(3\Omega)^2 + (4\Omega)^2}$
$Z = \sqrt{9 + 16\Omega}$
$Z = \sqrt{25\Omega}$
$Z = 5\Omega$

Impedance and Ohm's Law

In previous pages, Ohm's Law was discussed for a purely resistive circuit. When there is inductive reactance or capacitive reactance also present in the circuit, Ohm's Law must be written to include the total impedance in the circuit. Therefore, Ohm's law becomes:

I = V / Z

Ohm's law now simply states that the current (I), in amperes, is proportional to the voltage (V), in volts, divided by the impedance (Z), inohms.

Also note that when there is inductance in the circuit, the voltage and current are out of phase. This is because the voltage across the inductor will be a maximum when the rate of change of the current is greatest. For a sinusoidal wave form like AC, this is at the point where the actual current is zero. Thus the voltage applied to an inductor reaches its maximum value a quarter-cycle before the current does, and the voltage is said to lead the current by90o.

The familiar Ohm's Law triangle used for DC circuits can only be used at AC if the load is purely resistive. Most AC circuits however, contain series or parallel combinations of resistance, capacitance and inductance. This leads to the voltage and currents being out of phase and the load becomes complex. In purely capacitive circuits the current waveform leads the voltage waveform, whereas in inductive circuits the voltage will lead the current. Circuits containing both inductors and capacitors, the voltage and current waveform will not be in phase except at resonance. The general term for AC resistance is impedance and given the symbol Z. The impedance triangle is shown in fig 14.24:

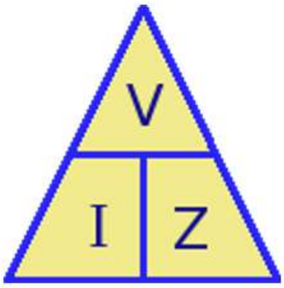


Fig. 14.24

The triangle is a used exactly the same as Ohm's Law at DC except that impedance now replaces resistance. It should be noted that when measuring ac voltages or currents, your meter will only indicate correct values over a limited frequency range. This is usually valid from DC up to 400Hz but can be found by checking the specifications for your meter.

For AC circuits where the voltage and current are in phase ONLY, the following pie chart may be used (fig 14.25)

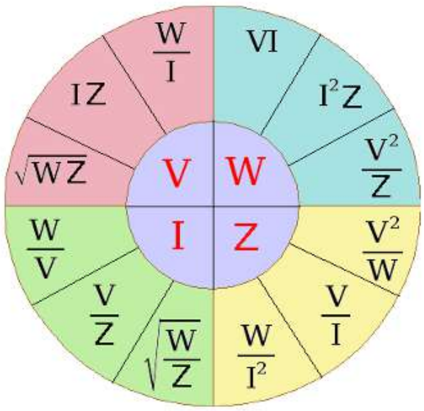



Fig. 14.25 Example series RLC circuit

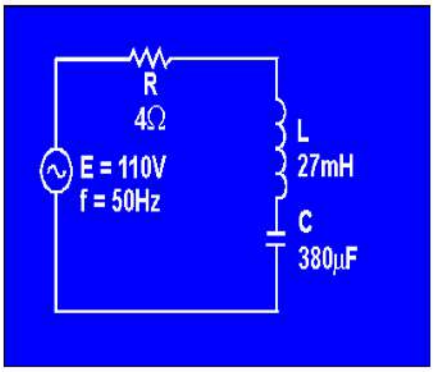



Fig. 14.26 Now solve for X

Given: $X = 3\ \Omega$

$R = 4\ \Omega$

Solution: $Z = \sqrt{X^2 + R^2}$

$Z = \sqrt{(3\ \Omega)^2 + (4\ \Omega)^2}$

$Z = \sqrt{9 + 16\ \Omega}$

$Z = \sqrt{25\ \Omega}$

$Z = 5\ \Omega$

Use the value of X to solve for Z.

Given: $X_C = 7\ \Omega$

$X_L = 10\ \Omega$

Solution: $X = X_L - X_C$

$X = 10\ \Omega - 7\ \Omega$

$X = 3\ \Omega$ (Inductive)

This value of Z can be used to solve for total current (IT ).

Given: $Z = 5\ \Omega$

$E = 110\ V$

Solution:

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{110\ V}{5\ \Omega}$$

$$I_T = 22\ A$$

Since current is equal in all parts of a series circuit, the value of IT can be used to solve for the various values ofpower.

Given: $I_T = 22\ A$

$R = 4\ \Omega$

$X = 3\ \Omega$

$Z = 5\ \Omega$

Solution:

$$\text{True Power} = (I_R)^2 R$$

$$\text{True Power} = (22\ A)^2 \times 4\ \Omega$$

$$\text{True Power} = 1936\ W$$

$$\text{Reactive power} = (I_X)^2 X$$

$$\text{Reactive power} = (22\ A)^2 \times 3\ \Omega$$

$$\text{Reactive power} = 1452\ \text{var}$$

$$\text{Apparent power} = (I_Z)^2 Z$$

$$\text{Apparent Power} = (22\ A)^2 \times 5\ \Omega$$

$$\text{Apparent Power} = 2420\ VA$$

## POWER IN AN AC CIRCUIT

Youknowthatinadirectcurrentcircuitthepowerisequaltothevoltagetimesthecurrent,orP=EXI.Ifavoltageof100volts applied to a circuit produces a current of 10 amperes, the poweris 1000watts.Thisisalsotrueinanaccircuitwhenthecurrentand voltage are in phase; that is, when the circuit is effectively resistive. But, if the ac circuit contains reactance, the current will lead or lag the voltage by a certain amount (the phase angle). When the current is out of phase with the voltage, thepower indicated by the product of the applied voltage and the total currentgivesonlywhatisknownasthe APPARENT POWER.

TheTRUEPOWERdependsuponthephaseanglebetweenthe current and voltage. The symbol for phaseangleis (Theta).

When an alternating voltage is impressed across a capacitor, power is taken from the source and stored in the capacitor as the voltage increases from zero to its maximum value. Then, as the impressed voltage decreases from its maximum value to zero, the capacitor discharges and returns the power to the source. Likewise, as the current through an inductor increases from its zero value to its maximum value the field around the inductor builds up to a maximum, and when the current decreases from maximum to zero the field collapses and returns the power to the source. You can see therefore that no power is used up in either case,sincethepoweralternatelyflowstoandfromthesource.

In a purely resistive circuit all of the power is consumed and none is returned to the source; in a purely reactive circuit no power is consumed and all of the power is returned to the source. It follows that in a circuit which contains both resistance and reactance there must be some power dissipated in the resistance as well as some returned to the source by the reactance. In figure 14.27you can see the relationship between the voltage, the current, and the power in such a circuit. The part of the power curve which is shown below the horizontal reference line is the result of multiplying a positive instantaneous value of current by a negative instantaneous value of the voltage, or vice versa. As you know, the product obtained by multiplying a positive value by a negative value will be negative. Therefore the power at that instant must be considered as negative power. In other words, during this time the reactance was returning power to thesource.

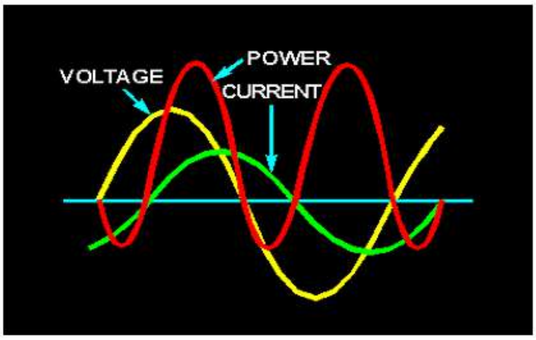


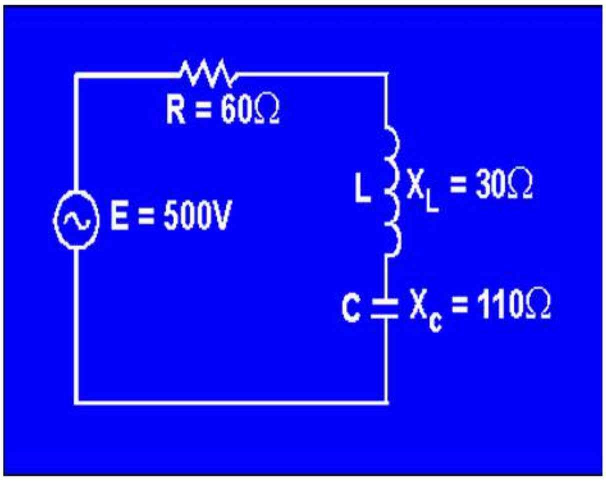

Fig. 14. 27 Instantaneous power when current and voltage are out of phase.

The instantaneous power in the circuit is equal to the product of the applied voltage and current through the circuit. When the voltage and current are of the same polarity they are acting together and taking power from the source. When the polarities are unlike they are acting in opposition and power is being returned to the source. Briefly then, in an ac circuit which contains reactance as well as resistance, the apparent power is reduced by the power returned to the source, so that in such a circuit the net power, or true power, is always less than the apparentpower.

Calculating True Power in AC Circuits

As mentioned before, the true power of a circuit is the power actually used in the circuit. This power, measured in watts, is the power associated with the total resistance in the circuit. To
calculate true power, the voltage and current associated with the resistance must be used. Since the voltage drop across the resistance is equal to the resistance multiplied by the current through the resistance, true power can be calculated by the formula:

For example, find the true power of the circuit shown in figure 14.28




14.28 Example circuit for determiningpower.

Given:

$$R = 60\ \Omega$$
$$X_L = 30\ \Omega$$
$$X_C = 110\ \Omega$$
$$E = 500\ V$$

Solution:

$$X = X_C - X_L$$
$$X = 110\Omega - 30\Omega$$
$$X = 80\ \Omega$$
$$Z = \sqrt{R^2 + X^2}$$
$$Z = \sqrt{(60\ \Omega)^2 + (80\ \Omega)^2}$$
$$Z = \sqrt{3600 + 6400\ \Omega}$$
$$Z = \sqrt{10{,}000\ \Omega}$$
$$Z = 100\ \Omega$$
$$I = \frac{E}{Z}$$
$$I = \frac{500\ V}{100\ \Omega}$$
$$I = 5\ A$$

Since the current in a series circuit is the same in all parts of the circuit:

$$\text{TruePower} = (I_R)^2 R$$
$$\text{TruePower} = (5\ A)^2 \times 60\ \Omega$$
$$\text{True Power} = 1500\ \text{watts}$$

APPARENT AND REACTIVE POWER

We know that reactive loads such as inductors andcapacitors dissipatezeropower,yetthefactthattheydropvoltageanddraw current gives the deceptiveimpression that they actuallydo dissipate power. This “phantom power” is calledreactivepower,anditismeasuredinaunitcalledVolt-Amps-Reactive (VAR), rather than watts. The mathematical symbol for reactive power is (unfortunately) the capital letter Q. The actual amount of power being used, or dissipated, in a circuit is called true power, and it is measured in watts (symbolized by the capital letter P, as always). The combination of reactive power and true power is called apparent power, and it is the product of a circuit's voltage and current, without reference to phase angle. Apparent power is measured in the unit of Volt-Amps (VA) and is symbolized by the capital letterS.

As a rule, true power is a function of a circuit's dissipative elements, usually resistances (R). Reactive power is a function of acircuit'sreactance(X).Apparentpowerisafunctionofa circuit's total impedance (Z). Since we're dealing with scalar quantities for power calculation, any complex starting quantities such as voltage, current, and impedance must be represented by their polar magnitudes, not by real or imaginary rectangular components. For instance, if I'm calculating true power from current and resistance, I must use the polar magnitude for current, and not merely the “real” or “imaginary” portion of the current. If calculating apparent power from voltage and impedance, both of these formerly complex quantities must be reduced to their polar magnitudes for the scalar arithmetic.

There are several power equations relating the three types of power to resistance, reactance, and impedance (all using scalar quantities):

**P** = true power $\quad P = I^2R \quad P = \frac{E^2}{R}$

*Measured in units of* ***Watts***

**Q** = reactive power $\quad Q = I^2X \quad Q = \frac{E^2}{X}$

*Measured in units of* ***Volt-Amps-Reactive (VAR)***

**S** = apparent power $\quad S = I^2Z \quad S = \frac{E^2}{Z} \quad S = IE$

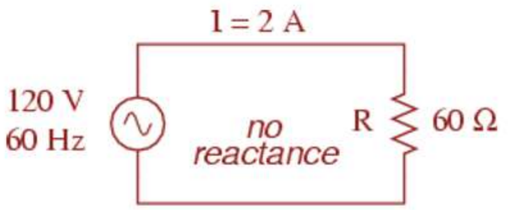
*Measured in units of* ***Volt-Amps (VA)***

Please note that there are two equations each for the calculation of true and reactive power. There are three equations available for

the calculation of apparent power, P=IE being useful only for that purpose. Examine the following circuits and see how these three types of power interrelate for: a purely resistive load in Figure 14.29, a purely reactive load in Figure 14.30, and a resistive/reactive load inFigure14.31.

Resistive load only:

\




$P = \text{true power} = I^2R = 240\ W$

$Q = \text{reactive power} = I^2X = 0\ VAR$

$S = \text{apparent power} = I^2Z = 240\ VA$

Fig. 14.29 True power, reactive power, and apparent power for a purely resistiveload.

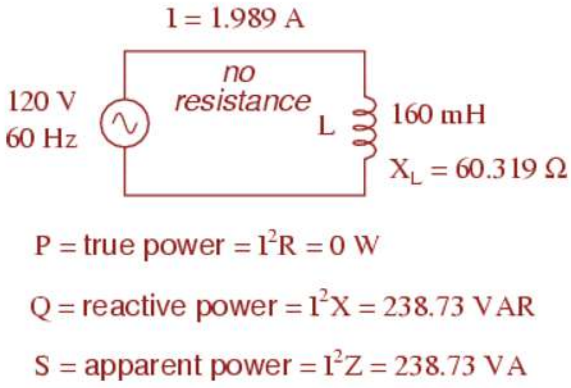



Fig. 14.30 True power, reactive power, and apparent power for a purely reactiveload.
Resistive/reactive load:

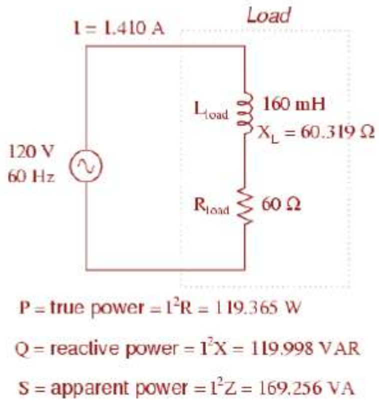
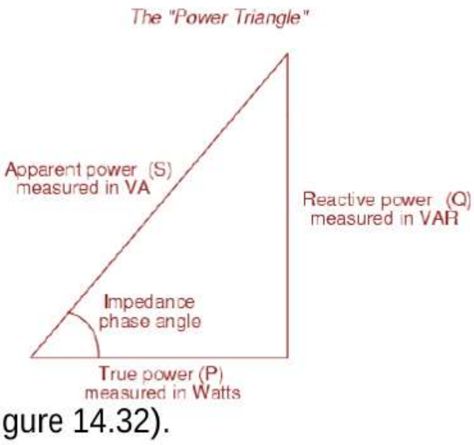



Fig. 14.31 True power, reactive power, and apparent power for a resistive/reactiveload.

These three types of power -- true, reactive, and apparent -- relate to one another in trigonometric form.




We call this the power triangle: (Figure 14.32).

Fig. 14. 32

POWER FACTOR

Electrical Power Factor

In general power is the capacity to do work. In electrical domain, electrical power is the amount of electrical energy that canbetransferredtosomeotherform(heat,lightetc)perunit time.
Considering first the DC circuits, having only DC voltage sources, the inductors and capacitors behave

as short circuit and open circuit respectively in steady state. Hence the entire circuit behaves as resistive circuit and the entire electrical poweris dissipated in the form of heat. Here the voltageand currentare in same phase and the total electrical poweris givenby

Electrical power = Voltage across the element X Current through the element. Its unit is Watt = Joule/sec.

Now coming to AC circuits, here both inductor and capacitor offer certain amount of impedance given by,

$X = 2\pi f L$ and Xc =
$f$

The inductor stores electrical energy in the form of magnetic energy and capacitor stores electrical energy in the form of electrostatic energy. Neither of them dissipates it. Further there is a phase shift of 90-°between voltage and current. Hence when we consider the entire circuit consisting of resistor, inductor and capacitor, there exists some phase difference between the source voltage and current. The cosine of this phase difference is called electrical powerfactor.

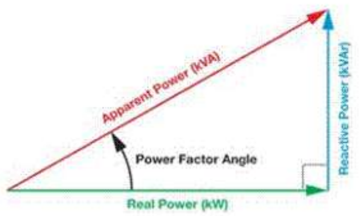



Fig. 14.33 Power Factor Triangle

Mathematically, S2 = p2+Q2 and electrical power factor is active power/apparent power.

Power Factor Improvement

The term power comes into picture in AC circuits only. Mathematically is is cosine of the phase difference between source voltage and current, it refers to the fraction of total power (apparent power) which is utilized to do the useful work called activepower.

Cos ⌀ =

Need for power Factor Improvement

- Real power is given by P = VI cos⌀. To transfer a given amount of power at certain voltage, the electrical current is inversely proportional to cos⌀. Hence high pf lower will be the current flowing. A small current flow requires less cross sectional area of conductor and thus it saves conductor and money.

- above relation we saw having poor power factor increases the current flowing in conductor and thus copper loss increase. Further large voltage drop occurs in alternator, electrical transformer and transmission and distribution lines which gives very poor voltage regulation.

• Further the KVA rating to machines is also reduced by Hence the size and cost of machine also reducedso, electricalpowerfactorshouldbemaintainedcloseto unity.

Methods of power Factor Improvement

Capacitors: Improving power factor means reducing the phase differencebetweenvoltageandcurrent.Sincemajorityofloads are of inductive nature, they require some amount ofreactive power for them to function. this reactive power is provided by the capacitor or bank of capacitors installed parallel to the load. They act as a source of local reactive power and thus less reactive power flows through the line. Basically they reduces the phase difference between the voltage andcurrent.

Synchronous condenser: They are 3 phase synchronousmotor withnoloadattachedtoitsshaft.Thesynchronousmotorhasthe characteristic of operating under any power factor leadinglagging or unity depending upon the excitation. For inductiveloads,

Power Factor Calculation

In power factor calculation we measure the source voltage and current drawn using a voltmeter and ammeter respectively. A wattmeter is used to get the active power. Now we known

P = VIco∅ watt

Hence we can get the electrical power factor. Now we can get the electrical power factor
This reactive power can now be supplied form the capacitor installed in parallel with load in local.

Phase advance: This is ac exciter mainly used to improve of induction motor. They are mounted on shaft of the motor and is connected in the rotor circuit of the motor. It improves the power factor by providing the exciting ampere turns to produce required flux at slip frequency. Further if ampere turns are increased it can be made to operate at leading power factor.

Important: In power factor improvement, the reactive power requirementbytheloaddoesnotchange.Itisjustsuppliedby some device in local, thus reducing the burden on source to provide the required reactive power.

SERIES RLC CIRCUIT

The principles and formulas that have been presented in this chapter are used in all ac circuits. The examples given have been series circuits.

This section of the chapter will not present any new material, but will be an example of using all the principles presented so far. You should follow each example problem step by step to see how each formula used depends upon the information determined in earlier steps. When an example calls for solving for square root, you can practice using the square-root table by looking up the valuesgiven.

The example series RLC circuit shown in figure 14.34 will be used to solve for XL, XC, X, Z, IT, true power, reactive power, apparent power, and power factor. The values solved for will be rounded off to the nearest wholenumber.

First solve for XL and XC.

Given: $f = 60\,Hz$

$L = 27\,mH$

$C = 380\,\mu F$

Solution: $X_L = 2\pi fl$

$X_L = 6.28 \times 60\,Hz \times 27\,mH$

$X_L = 10\ \Omega$

$X_C = \frac{1}{2\pi fc}$

$X_C = \frac{1}{6.28 \times 60\,Hz \times 380\,\mu F}$

$X_C = \frac{1}{0.143}\Omega$

$X_C = 7\,\Omega$

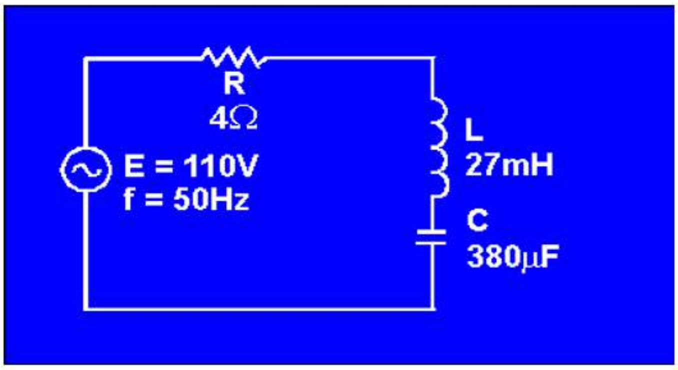



Fig.14.34 - Example series RLC circuit

Now solve for X

Given: $X_C = 7\,\Omega$

$X_L = 10\,\Omega$

Solution: $X = X_L - X_C$

$X = 10\,\Omega - 7\,\Omega$

$X = 3\,\Omega$ (Inductive)

Use the value of X to solve for Z.

Given: $X = 3\,\Omega$

$R = 4\,\Omega$

Solution: $Z = \sqrt{X^2 + R^2}$

$Z = \sqrt{(3\,\Omega)^2 + (4\,\Omega)^2}$

$Z = \sqrt{9 + 16\,\Omega}$

$Z = \sqrt{25\,\Omega}$

$Z = 5\,\Omega$

$I_X = I_L - I_C$ or $I_X = I_C - I_L$

$I_Z = \sqrt{(I_R)^2 + (I_X)^2}$

$PF = \frac{I_R}{I_Z}$

(The impedance of a parallel circuit is found by the formula $Z = \frac{E}{I_Z}$)

This value of Z can be used to solve for total current (IT ).

Given: $Z = 5\,\Omega$

$E = 110\text{ V}$

Solution:

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{110\text{ V}}{5\,\Omega}$$

$$I_T = 22\text{ A}$$

Since current is equal in all parts of a series circuit, the value of IT can be used to solve for the various values ofpower.

Given: $I_T = 22\text{ A}$

$R = 4\,\Omega$

$X = 3\,\Omega$

$Z = 5\,\Omega$

Solution:

$$\text{True Power} = (I_R)^2 R$$

$$\text{True Power} = (22\text{A})^2 \times 4\,\Omega$$

$$\text{True Power} = 1936\text{ W}$$

$$\text{Reactive power} = (I_X)^2 X$$

$$\text{Reactive power} = (22\text{A})^2 \times 3\,\Omega$$

$$\text{Reactive power} = 1452\text{ var}$$

$$\text{Apparent power} = (I_Z)^2 Z$$

$$\text{Apparent Power} = (22\text{A})^2 \times 5\,\Omega$$

$$\text{Apparent Power} = 2420\text{ VA}$$

The power factor can now be found using either apparent power and true power or resistance and impedance. The mathematics in this example is easier if you use impedance and resistance.

Given: $R = 4\Omega$

$Z = 5\Omega$

$$PF = \frac{R}{Z}$$

$$PF = \frac{4\Omega}{5\Omega}$$

$$PF = .8 \text{ or } 80\%$$

## PARALLEL RLC CIRCUITS

When dealing with a parallel ac circuit, you will find that the concepts presented in this chapter for series ac circuits still apply. There is one major difference between a series circuit and a parallel circuit that must be considered. The difference is that current is the same in all parts of a series circuit, whereas voltage is the same across all branches of a parallel circuit. Because of this difference, the total impedance of a parallel circuit must be computed on the basis of the current in thecircuit.

You should remember that in the series RLC circuit the following three formulas were used to find reactance, impedance, and power factor:

$$X = X_L - X_C \text{ or } X = X_C - X_L$$

$$Z = \sqrt{(I_R)^2 + X^2}$$

$$PF = \frac{R}{Z}$$

When working with a parallel circuit you must use the following formulas instead:

NOTE: If no value for E is given in a circuit, any value of E can be assumed to find the values of IL, IC, IX, IR, and IZ. The same value of voltage is then used to find impedance.

For example, find the value of Z in the circuit shown in figure 14.35

Given: $E = 300\ V$

$R = 100\ \Omega$

$X_L = 50\ \Omega$

$X_C = 150\ \Omega$

The first step in solving for Z is to calculate the individual branch currents.

Solution:

$$I_R = \frac{E}{R}$$

$$I_R = \frac{300\ V}{100\ \Omega}$$

$$I_R = 3\ A$$

$$I_L = \frac{E}{X_L}$$

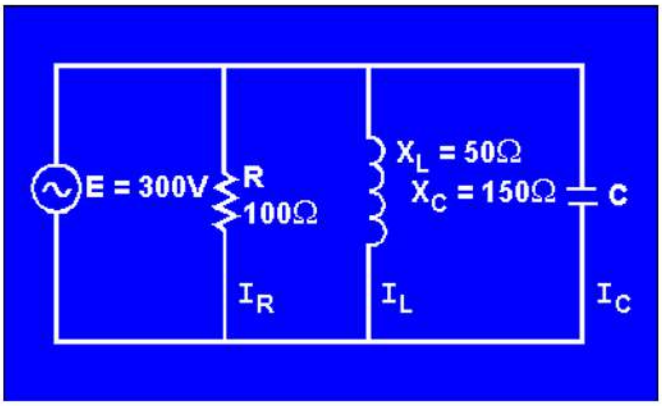
$$I_L = \frac{300\ V}{50\ \Omega}$$

$$I_L = 6\ A$$

$$I_C = \frac{E}{X_C}$$

$$I_C = \frac{300\ V}{150\ \Omega}$$

$$I_C = 2\ A$$




$$I_X = I_L - I_C$$

$$I_X = 6\ A - 2\ A$$

$$I_X = 4\ A \text{ (inductive)}$$

$$I_Z = \sqrt{(I_R)^2 + (I_X)^2}$$

$$I_Z = \sqrt{(3\ A)^2 + (4\ A)^2}$$

$$I_Z = \sqrt{25\ A}$$

$$I_Z = 5\ A$$

Fig. 14.35 Parallel RLC circuit.

Using the values for IR, IL, and IC, solve for IX and IZ.

$$Z = \frac{E}{I_Z}$$

$$Z = \frac{300\ V}{5\ A}$$

$$Z = 60\ \Omega$$

Using this value of IZ, solve for Z.

If the value for E were not given and you were asked to solve for Z, any value of E could be assumed. If, in the example problem above, you assume a value of 50 volts for E, the solution would be:

Given: $R = 100\ \Omega$

$X_L = 50\ \Omega$

$X_C = 150\ \Omega$

$E = 50\ V$ (assumed)

First solve for the values of current in the same manner as before.
Solve for IX and IZ.

Solve for Z.

When the voltage is given, you can use the values of currents, I R, IX, and IZ, to calculate for the true power, reactive power, apparent power, and power factor. For the circuit shown in figure 14.35, the calculations would be asfollows.

To find true power,

To find reactive power, first find the value of reactance (X).

To find apparent power,

The power factor in a parallel circuit is found by either of the following methods.

RESONANT CIRCUITS

Resonance of a circuit involving capacitors and inductorsoccurs because the collapsing magnetic field of the inductor generates an electric current in its windings that charges the capacitor, andthen the discharging capacitor provides an electric current that builds the magnetic field in the inductor. This process is repeated continually. An analogy is a mechanical pendulum.
At resonance, the series impedance of the two elements is at a minimum and the parallel impedance is at maximum. Resonance is used for tuning and filtering, because it occurs at a t
particular frequency for given values
of inductance and capacitance. It can be detrimental to the operation of communications circuits by causing unwanted sustained and transient oscillations that may cause noise, signal distortion, and damage to circuit elements.

Parallel resonance or near-to-resonance circuits can be used to prevent the waste of electrical energy, which would otherwise occur while the inductor built its field or the capacitor charged and discharged. As an example, asynchronous motors waste inductive current while synchronous ones waste capacitive current. The use of the two types in parallel makes the inductor feed the capacitor, and vice versa, maintaining the same resonant current in the circuit, and converting all the current into useful work.
Since the inductive reactance and the capacitive reactance are of equal magnitude, $\omega L = 1/\omega C$, so:

where $\omega = 2\pi f$, in which f is the resonance frequency in hertz, L is the inductance in henries, and C is the capacitance in farads when standard SI units are used.
The quality of the resonance (how long it will ring when excited) is determined by its Q factor, which is a function of resistance. A true LC circuit would have infinite Q, but all real circuits have some resistance and smaller Q and are usually approximated more accurately by an RLC circuit.

The Series Resonance Circuit
Thus far we have analysed the behaviour of a series RLC circuit whose source voltage is a fixed frequency steady state sinusoidal supply. We have also seen that two or more sinusoidal signals can be combined using phasors providing that they have the same frequency supply.

But what would happen to the characteristics of the circuit if a supply voltage of fixed amplitude but of different frequencies was applied to the circuit. Also what would the circuits "frequency response" be haviourbe upon the two reactive components due to this varying frequency.
In a series RLC circuit there becomes a frequency point were the inductive reactance of the inductor becomes equal in value to the capacitive reactance of the capacitor. In other words, XL = XC. The point at which this occurs is called the Resonant Frequency point, ( $fr$ ) of the circuit, and as we are analysinga series RLC circuit this resonance frequency produces a Series Resonance.
Series Resonance circuits are one of the most important circuits used electrical and electronic circuits. They can be found in various forms such as in AC mains filters, noise filters and also in radio and television tuning circuits producing a very selective tuning circuit for the receiving of the differentfrequency channels. Consider the simple series RLC circuit below.(fig 14.36)

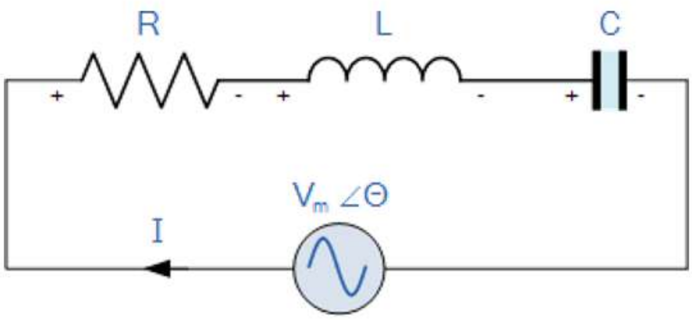
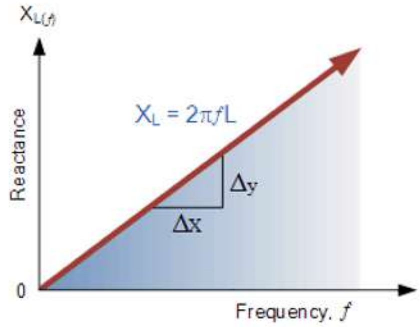



Fig. 14.36

Firstly, let us define what we already know about series RLC circuits.

From the above equation for inductive reactance, if either the Frequency or the Inductance is increased the overall inductive reactance value of the inductor would also increase. As the frequency approaches infinity the inductors reactance would also increase towards infinity with the circuit element acting like an opencircuit.

However, as the frequency approaches zero or DC, theinductors reactance would decrease to zero, causing the opposite effect acting like a short circuit. This means




then that inductive reactance is "Proportional"to frequency and is small at low frequenciesandhighathigherfrequenciesandthisdemonstrated in the following curve:

Fig. 14.37 Inductive Reactance against Frequency

The graph of inductive reactance against frequency is a straight line linear curve. The inductive reactance value of an inductor increases linearly as the frequency across it increases. Therefore, inductive reactance is positive and is directly proportional to frequency ( $X_L \propto f$) The same is also true for the capacitive reactance formula above but in reverse. If either the Frequency or the Capacitance is increased the overall capacitive reactance would decrease. As the frequency approaches infinity the capacitors reactance would reduce to zero causing the circuit element to act like a perfect conductor of0Ω"s.

But as the frequency approaches zero or DC level, the capacitors reactance would rapidly increase up to infinity causing it to act like a very large resistance acting like an open circuit condition. This means then that capacitive reactance is "Inversely proportional" to frequency for any given value of capacitance and this shown in fig14.38

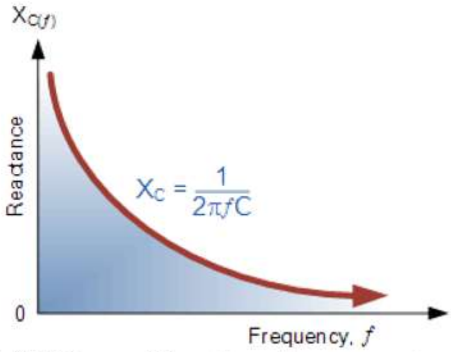



Fig. 14.38 Capacitive Reactance against Frequency

The graph of capacitive reactance against frequency is a hyperbolic curve. The Reactance value of a capacitor has a very high value at low frequencies but quickly decreases as the frequency across it increases. Therefore, capacitive reactance is negative and is inversely proportional to frequency ( $X_C \propto f^{-1}$ )

We can see that the values of these resistances depends upon the frequency of the supply. At a higher frequency XL is high and at a low frequency XC is high. Then there must be a frequency point were the value of XL is the same as the value of XC and there is. If we now place the curve for inductive reactance on top of the curve for capacitive reactance so that both curves are on the same axes, the point of intersection will give us the series resonance frequency point, ( $f_r$ or $\omega_r$ ) as shown below.(fig14.39)

Series Resonance Frequency

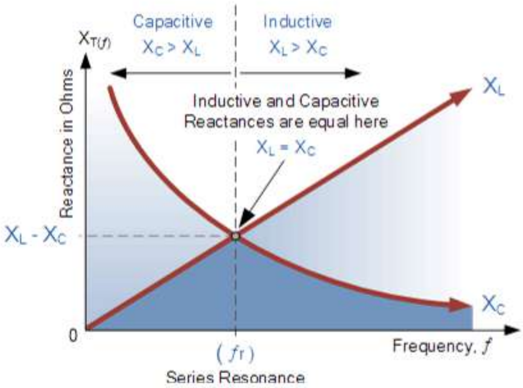



Fig. 14.39 Series Resonance Frequency

where: $fr$ is in Hertz, L is in Henries and C is in Farads.
Electrical resonance occurs in an AC circuit when the two reactances which are opposite and equal cancel each other out as XL = XC and the point on the graph at which this happens is werethetworeactancecurvescrosseachother.Inaseries
resonant circuit, the resonant frequency, $fr$ point can be calculated as follows.

$$X_L = X_C \quad \Rightarrow \quad 2\pi f L = \frac{1}{2\pi f C}$$

$$f^2 = \frac{1}{2\pi L \times 2\pi C} = \frac{1}{4\pi^2 LC}$$

$$f = \sqrt{\frac{1}{4\pi^2 LC}}$$

$$\therefore \ f_r = \frac{1}{2\pi\sqrt{LC}} \text{ (Hz)} \quad \text{or} \quad \omega_r = \frac{1}{\sqrt{LC}} \text{ (rads)}$$

We can see then that at resonance, the two reactances cancel each other out thereby making a series LC combination act as a short circuit with the only opposition to current flow in a series resonance circuit being the resistance, R. In complex form, the resonant frequency is the frequency at which the total impedance of a series RLC circuit becomes purely "real", that is no imaginary impedance"s exist. This is because at resonance they are cancelled out. So the total impedance of the series circuit becomes just the value of the resistance and therefore: Z =R.
Then at resonance the impedance of the series circuit is at its minimum value and equal only to the resistance, R of the circuit. The circuit impedance at resonance is called the "dynamic impedance" of the circuit and depending upon the frequency, XC (typically at high frequencies) or XL (typicallyat

low frequencies) will dominate either side of resonance as shown below.

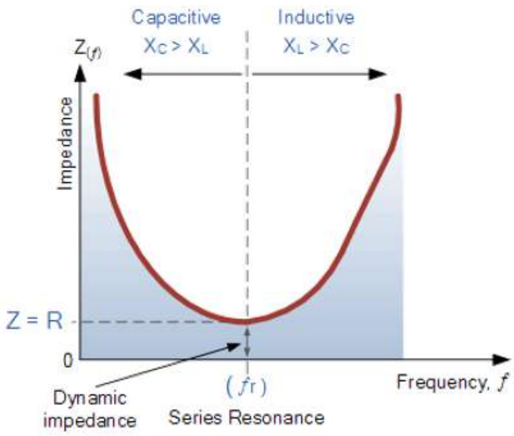
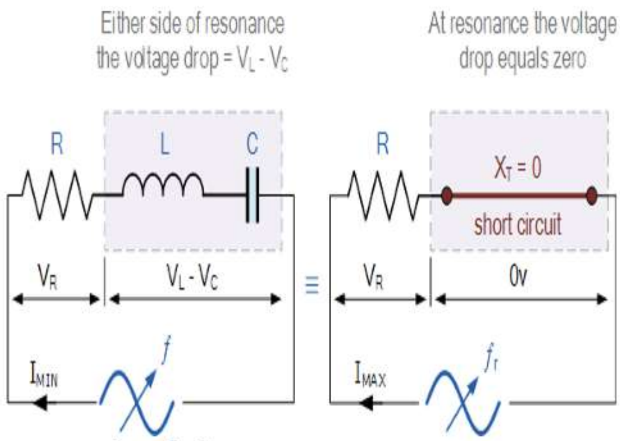



Fig. 14. 40 Impedance in a Series Resonance Circuit

Note that when the capacitive reactance dominates the circuit the impedance curve has a hyperbolic shape to itself, but when the inductive reactance dominates the circuit the curve is non- symmetrical due to the linear response of XL.You may alsonote
that if the circuits impedance is at its minimum at resonancethen
consequently, the circuits admittance must be at its maximum and one of the characteristics of a series resonance circuit is that admittance is very high. But this can be a bad thing because a very low value of resistance at resonance means that the resulting current flowing through the circuit may be dangerouslyhigh.
We recall from the previous tutorial about series RLC circuits that the voltage across a series combination is the phasor sum

of VR, VL and VC. Then if at resonance the two reactances are equal and cancelling, the two voltages representing VL and VC must also be opposite and equal in value thereby cancelling each other out because with pure components the phasor voltages are drawn at +90o and -90o respectively.
Then in a series resonance circuit as VL = -VC the resulting reactive voltages are zero and all the supply voltage is dropped across the resistor. Therefore, VR = Vsupply and it is for this reason that series resonance circuits are known as voltage resonance circuits, (as opposed to parallel resonance




circuits which are current resonance circuits).
Fig. 14.41 Series RLC Circuit at Resonance

Since the current flowing through a series resonance circuit is the product of voltage divided by impedance, at resonance the impedance, Z is at its minimum value, ( =R ). Therefore, the circuit current at this frequency will be at its maximum value of V/R as shown below. (fig14.42)

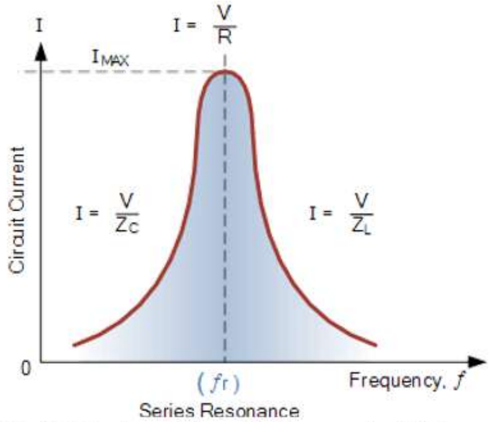


Fig. 14.42 Series Circuit Current at Resonance

The frequency response curve of a series resonance circuit shows that the magnitude of the current is a function of frequency and plotting this onto a graph shows us that the response starts at near to zero, reaches maximum value at the resonance frequency when IMAX = IR and then drops again to nearly zero as $f$ becomes infinite. The result of this is that the magnitudes of the voltages across the inductor, L and the capacitor, C can become many times larger than the supply voltage, even at resonance but as they are equal and at opposition they cancel each otherout.

You may also notice that as the maximum current through the circuit at resonance is limited only by the value of the resistance (a pure and real value), the source voltage and circuit current must thereforebeinphasewitheachotheratthisfrequency.Thenthe

phase angle between the voltage and current of a series resonance circuit is also a function of frequency for a fixed supply voltage and which is zero at the resonant frequency point when: V, I and VR are all in phase with each other as shown below. Consequently, if the phase angle is zero then the power factor must therefore beunity.

Bandwidth of a Series Resonance Circuit

If the series RLC circuit is driven by a variable frequency at a constant voltage, then the magnitude of the current, I is proportional to the impedance, Z, therefore at resonance thepower absorbed by the circuit must be at its maximum value as P =I 2Z.

If we now reduce or increase the frequency until theaverage power absorbed by the resistor in the series resonance circuit is half that of its maximum value at resonance, we producetwo frequency points called the half-power points which are -3dB down from maximum, taking 0dB as the maximum current reference.

These -3dB points give us a current value that is 70.7% of its maximum resonant value which is defined as: 0.5(I2 R) = (0.707 x I)2 R. Then the point corresponding to the lower frequency at half the power is called the "lower cut-off frequency", labelled $f$L with the point corresponding to the upper frequency at half power being called the "upper cut-off frequency", labelled $f$H. The distance between these two points, i.e. ($f$H – $f$L) is called the Bandwidth, (BW) and is the range of frequencies over which at least half of the maximum power and current is provided as shown. (fig14.43)

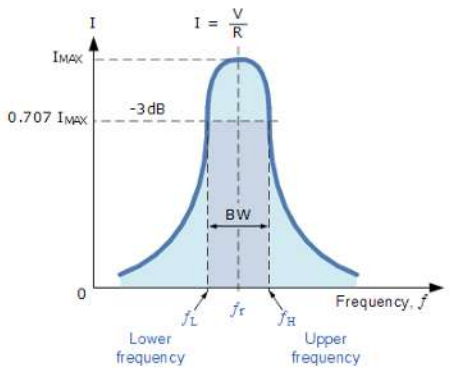



Fig. 14. 43 Bandwidth of a Series Resonance Circuit

The frequency response of the circuits current magnitude above, relates to the "sharpness" of the resonance in a series resonance circuit. The sharpness of the peak is measured quantitatively and is called the Quality factor, Q of the circuit. The quality factor relates the maximum or peak energy stored in the circuit (the reactance) to the energy dissipated (the resistance) during each cycle of oscillation meaning that it is a ratio of resonant frequency to bandwidth and the higher the circuit Q, the smaller the bandwidth, $Q = fr/BW$.

As the bandwidth is taken between the two -3dB points, the selectivity of the circuit is a measure of its ability to reject any frequencies either side of these points. A more selective circuit will have a narrower bandwidth whereas a less selective circuit will have a wider bandwidth. The selectivity of a series resonance circuit can be controlled by adjusting the value of the resistance only, keeping all the other components the same, since Q = (XL or XC)/R.

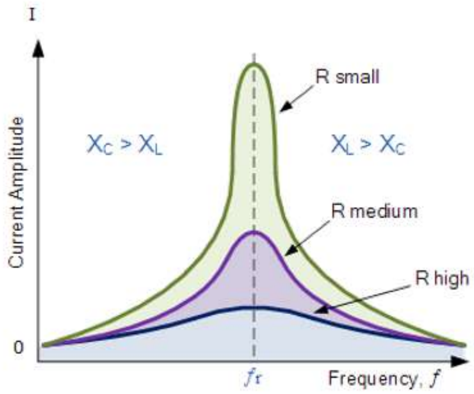



Fig. 14.44 Series Resonance Example No1

A series resonance network consisting of a resistor of 30Ω, a capacitor of 2uF and an inductor of 20mH is connected across a sinusoidal supply voltage which has a constant output of 9 volts at all frequencies (fig 14.45). Calculate, the resonant frequency, the current at resonance, the voltage across the inductor and capacitor at resonance, the quality factor and the bandwidth of the circuit. Also sketch the corresponding current waveform for all frequencies.

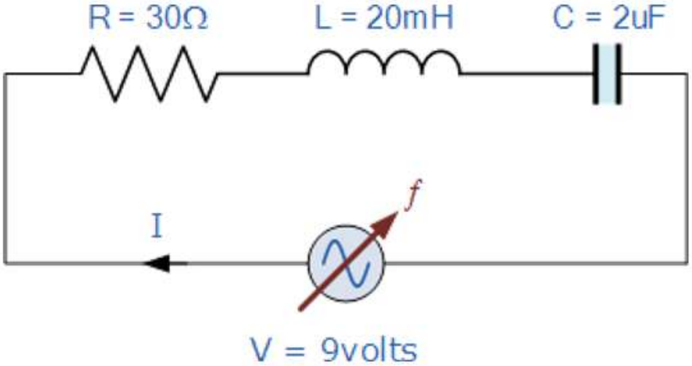


Fig. 14.45

Resonant Frequency, $f$r

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.02\times2\times10^{-6}}} = 796\text{Hz}$$

Circuit Current at Resonance, Im

$$I = \frac{V}{R} = \frac{9}{30} = 0.3\text{A or } 300\text{mA}$$

Inductive Reactance at Resonance, XL

$$X_L = 2\pi f L = 2\pi\times796\times0.02 = 100\Omega$$

Voltages across the inductor and the capacitor, VL, VC

$$V_L = V_C$$
$$V_L = I\times X_L = 300\text{mA}\times100\Omega$$
$$V_L = 30\text{volts}$$

( Note: the supply voltage is only 9 volts, but at resonance the reactive voltages are 30 volts peak! )
Quality factor, Q

$$Q = \frac{X_L}{R} = \frac{100}{30} = 3.33$$

Bandwidth, BW

$$BW = \frac{f_r}{Q} = \frac{796}{3.33} = 238\text{Hz}$$

The upper and lower -3dB frequency points, $f$H and $f$L

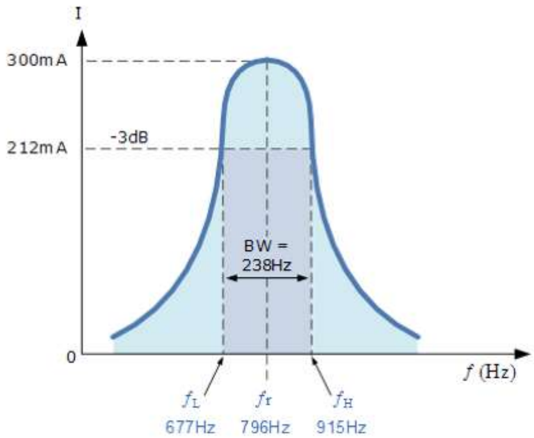


Fig. 14.46 CurrentWaveform

Series Resonance ExampleNo2

A series circuit consists of a resistance of 4Ω, an inductance of 500mH and a variable capacitance connected across a 100V, 50Hz supply. Calculate the capacitance require to give series resonance and the voltages generated across both the inductor and the capacitor.

Resonant Frequency, $f$r

$$X_L = 2\pi f L = 2\pi \times 50 \times 0.5 = 157.1\Omega$$

$$\text{at resonance: } X_C = X_L = 157.1\Omega$$

$$\therefore C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi .50.157.1} = 20.3\mu F$$

Voltages across the inductor and the capacitor, VL, VC

$$I_S = \frac{V}{R} = \frac{100}{4} = 25\,\text{Amps}$$

$$\text{at resonance: } V_L = V_C$$

$$V_L = I \times X_L = 25 \times 157.1$$

$$\therefore V_L = 3{,}927.5\,\text{volts}$$

PARALLEL RESONANT CIRCUIT

A condition of resonance will be experienced in a tank circuit (Figure 14.47) when the reactances of the capacitor and inductor are equal to each other. Because inductive reactanceincreases with increasing frequency and capacitive reactance decreaseswith

these two reactances will be equal.

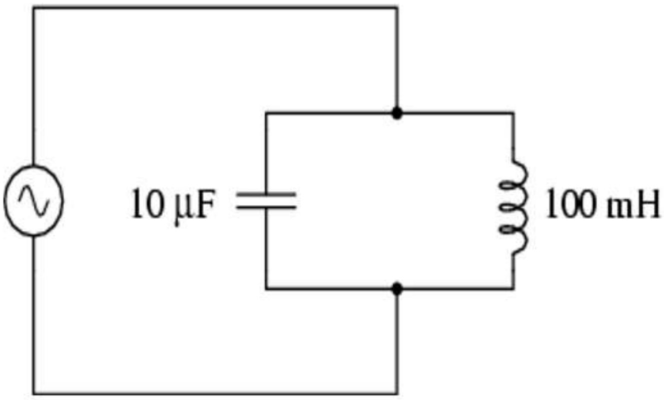



Fig. 14.47 Simple parallel resonant circuit (tank circuit).

In the above circuit, we have a 10 µF capacitor and a 100 mH inductor. Since we know the equations for determining the reactance of each at a given frequency, and we're looking for that point where the two reactances are equal to each other, we can set the two reactance formulae equal to each other and solve for frequency algebraically:

XL= 2πƒL  Xc =
ƒ
…….setting the two equal to each other,
representing a condition of equal reactance (resonance)….
22πƒL=
ƒ

Multiplying both sides by ƒeliminates the ƒ term in the denominator of the fraction ….
2πƒ2L=
ƒ

Dividing both sides by 2 πL leaves ƒ by itself on the left- hand side of the equation …

Taking the square root of both sides of the equation leaves ƒ by itself on the left side ….

….. simplifying……

$$f = \frac{1}{2\pi\sqrt{LC}}$$

So there we have it: a formula to tell us the resonant frequency of a tank circuit, given the values of inductance (L) in Henrys and capacitance (C) in Farads. Plugging in the values of L and C in our example circuit, we arrive at a resonant frequency of 159.155 Hz.

What happens at resonance is quite interesting. With capacitive and inductive reactances equal to each other, the total impedance increases to infinity, meaning that the tank circuit draws no current from the AC power source! We can calculate the individual impedances of the 10 µF capacitor and the 100 mH inductor and work through the parallel impedance formula to demonstrate thismathematically:

$$X_L = 2\pi f L$$

$$X_L = (2)(\pi)(159.155\ \text{Hz})(100\ \text{mH})$$

$$X_L = 100\ \Omega$$

$$X_C = \frac{1}{2\pi f C}$$

$$X_C = \frac{1}{(2)(\pi)(159.155\ \text{Hz})(10\ \mu\text{F})}$$

$$X_C = 100\ \Omega$$

As you might have guessed, I chose these component values to give resonance impedances that were

$$Z_{parallel} = \frac{1}{\frac{1}{Z_L} + \frac{1}{Z_C}}$$

$$Z_{parallel} = \frac{1}{\frac{1}{100\ \Omega\ \angle 90^\circ} + \frac{1}{100\ \Omega\ \angle -90^\circ}}$$

$$Z_{parallel} = \frac{1}{0.01\ \angle -90^\circ + 0.01\ \angle 90^\circ}$$

$$Z_{parallel} = \frac{1}{0} \quad \textit{Undefined!}$$

easy to work with (100 Ω even). Now, we use the parallel impedance formula to see what happens to totalZ:

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$$Z_{parallel} = \frac{1}{0.01 \angle -90^\circ + 0.01 \angle 90^\circ}$$

$$Z_{parallel} = \frac{1}{0} \quad \textit{Undefined!}$$

We can't divide any number by zero and arrive at a meaningful result, but we can say that the result approaches a value of in finity as the two parallel impedances get closer to each other. What this means in practical terms is that, the total impedance of a tank circuit is infinite (behaving as an open circuit) atresonance.

a

Module 3.15: Transformers

Certification Statement

INTRODUCTION

Principle operation of the transformer:

BASIC OPERATION OF A TRANSFORMER

In its most basic form a transformer consists of:

• A primary coil or winding.

A secondary coil orwinding.

A core that supports the coils or windings

The primary winding in the fig 15.1 is connected to a 60 hertz ac voltage source. The magnetic field (flux) builds up (expands) and collapses (contracts) about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an alternating voltage into the winding. This voltage causes alternating current to flow through the load. The voltage may be stepped up or down depending on the design of the primary and secondary windings. (fig 15.1). The parameter which does not change during transformer action in a transformer isfrequency.

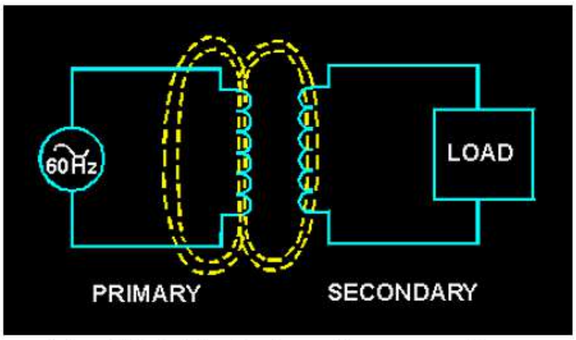


Fig. 15.1 Basic transformer action

THE COMPONENTS OF A TRANSFORMER

Two coils of wire (called windings) are wound on some type of
core material. In some cases the coils of wire are wound on a cylindrical or rectangular cardboard form. In effect, the core material is air and the transformer is called an AIR-CORE TRANSFORMER. Transformers used at low frequencies, such as 60 hertz and 400 hertz, require a core of low-reluctance magnetic material, usually iron. This type of transformer is called an IRON- CORE TRANSFORMER. Most power transformers are of the iron-core type. The principle parts of a transformer and their functions are:

• TheCORE,whichprovidesapathforthemagneticlines
of flux.
The PRIMARY WINDING, which receives energyfrom

The SECONDARY WINDING, which receives energy
from the primary winding and delivers it to the load.

from dirt, moisture, and mechanical damage.

CORE CHARACTERISTICS

Thecompositionofatransformercoredependsonsuchfactorsas
voltage,current,andfrequency.Sizelimitationsandconstruction costsare alsofactorsto be considered. Commonly used core materialsare air, softiron, and steel. Each of thesematerialsis suitable for particular applicationsand unsuitable for others. Generally,air-coretransformersareusedwhenthevoltage source has a high frequency (above 20kHz). Iron-core transformersareusuallyusedwhenthesourcefrequencyis

low(below20kHz).Asoft-iron-coretransformerisveryuseful
where the transformer must be physically small, yet efficient. The
iron-core transformer provides better power transfer than doesthe
air-coretransformer.Atransformerwhosecoreisconstructedof
laminatedsheetsofsteeldissipatesheatreadily;thusitprovides
fortheefficienttransferofpower.Themajorityoftransformers
you will encounter in Navy equipment containlaminated-steel
cores. These steel laminations (see figure 15.2) are insulated with a non conducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick. The purpose of the laminations is to reduce certain losses which will be discussed later in this chapter.

An important point to remember is that the most efficient transformer core is one that offers the best path for the most lines of flux with the least loss in magnetic and electricalenergy

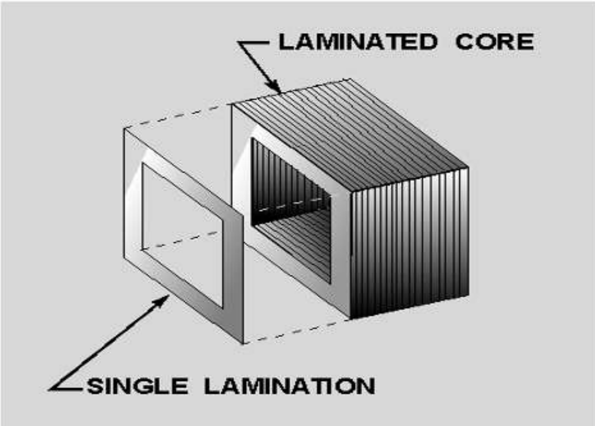



Fig. 15.2 Hollow-core construction. Transformers

There are two main shapes of cores used in laminated-steel-core transformers. One is the HOLLOW-CORE, so named because the core is shaped with a hollow square through the center. Figure illustrates this shape of core. Notice that the core is made up of many laminations of steel. Figure 15.3 illustrates how the transformer windings are wrapped around both sides of the core.

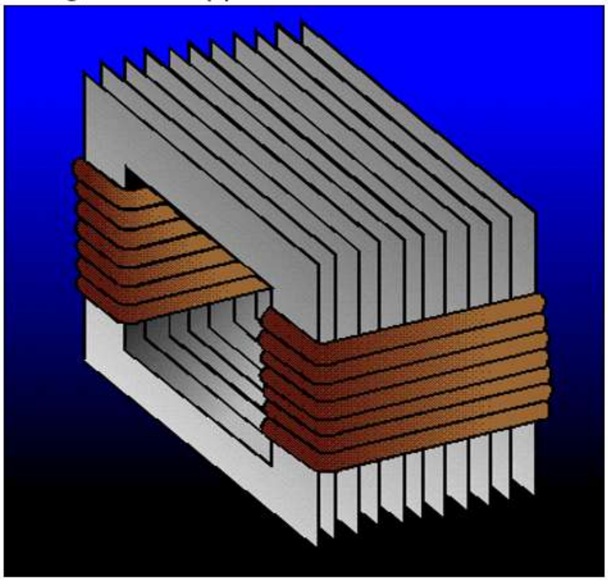


Fig. 15.3 Windings wrapped around laminations.

Shell-Core Transformers

The most popular and efficient transformer core is the SHELL CORE, as illustrated in figure15.4. As shown, each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form the laminations. The laminations are insulated from each other and then pressed together to form the core.

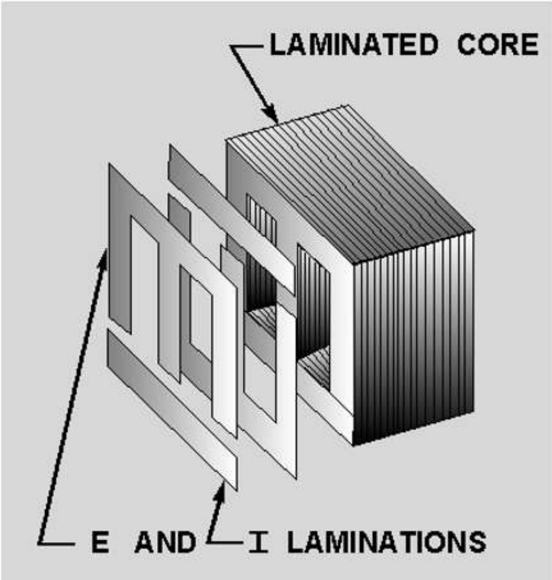


Fig. 15.4 Shell-type core construction

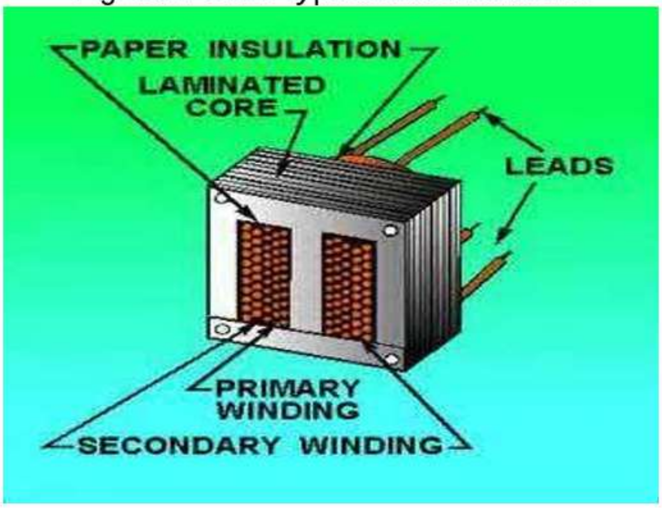



Fig. 15.5 Construction Of A Transformer

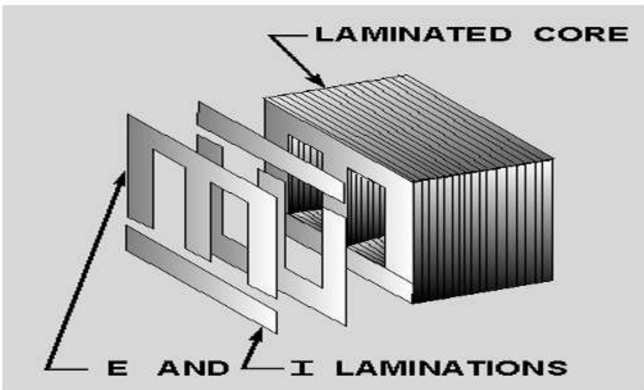
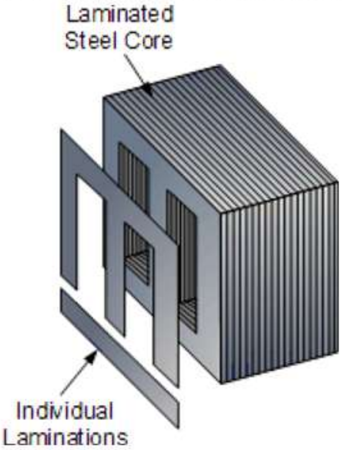



Fig. 15.6 Transformer Construction

The construction of a simple two-winding transformer consists of each winding being wound on a separate limb or core of the soft iron form which provides the necessary magnetic circuit. This magneticcircuit,knowmorecommonlyasthe―transformercore‖ is designed to provide a path for the magnetic field to flow around, which is necessary for induction of the voltage between the twowindings.

However, this type of transformer construction were the twowindings are wound on separate limbs is not very efficient since the primary and secondary windings are well separated from each other. This results in a low magnetic coupling between the two windings as well as large amounts of magnetic flux leakage from the transformer itself. But as well as this ―O‖shapes construction, there are different types of ―transformer construction‖and designs available which are used to overcome these inefficiencies producing a smaller more compact transformer.

Fig. 15. 7 Transformer Constructions




The efficiency of a simple TRANSFORMER can be improved bybringing the two windings within close contact with each otherthereby improving the magnetic coupling. Increasing andconcentrating the magnetic circuit around the coils may improvethe magnetic coupling between the two windings, but it also hasthe effect of increasing the magnetic losses of the transformercore.

As well as providing a low reluctance path for the magnetic field,the core is designed to prevent circulating electric currents withinthe iron core itself. Circulating currents, called ―eddy currents‖,cause heating and energy losses within the core decreasing thetransformersefficiency.

These losses are due mainly to voltages induced in the iron circuit,which is constantly being subjected to the alternating magneticfields setup by the external sinusoidal supply voltage. One way toreduce these unwanted power losses is to construct thetransformer core from thin steellaminations.

Inalltypesoftransformerconstruction,thecentralironcoreis constructedfromofahighlypermeablematerialmadefromthin silicon steel laminations assembled together to provide the required magnetic path with the minimum of losses. The

resistivity of the steel sheet itself is high reducing the f lossesby making the laminations very thin.

These steel transformer laminations vary in thickness's from between 0.25mm to 0.5mm and as steel is a conductor, thelaminations are electrically insulated from each other by a verythincoatingofinsulatingvarnishorbytheuseofanoxidelayer

on the surface.

Transformer Construction of the Core

Generally, the name associated with the construction of a transformer is dependent upon how the primary and secondary windings are wound around the central laminated steel core. The two most common and basic designs of transformer construction are the Closed-core Transformer and the Shell-core Transformer.

In the ―closed-core‖ type (core form) transformer, the primary and secondary windings are wound outside and surround the core ring. In the ―shell type‖ (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit (core) which forms a shell around the windings as shown fig 15.8.

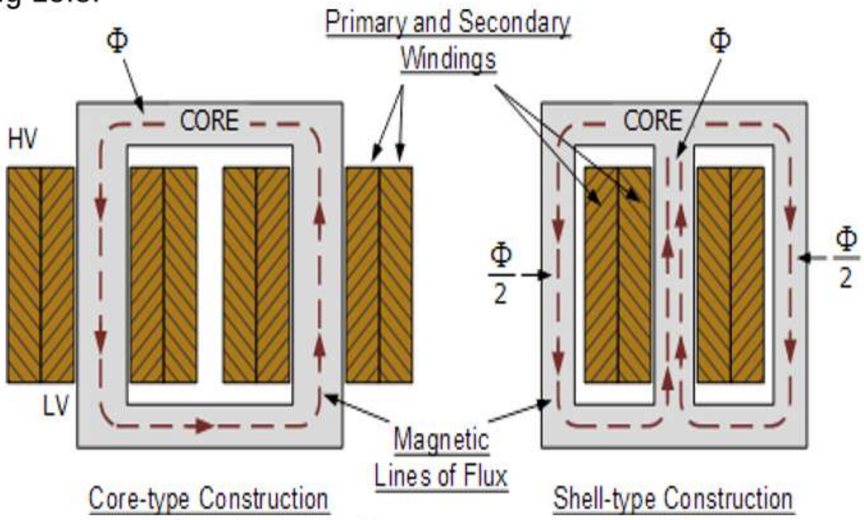



Fig. 15.8Transformer Core Construction

In both types of transformer core design, the magnetic flux linking the primary and secondary windings travels entirely within the core with no loss of magnetic flux through air. In the core type transformer construction, one half of each winding is wrapped around each leg (or limb) of the transformers magnetic circuit as shown above.

The coils are not arranged with the primary winding on one leg and the secondary on the other but instead half of the primary winding and half of the secondary winding are placed one over the other concentrically on each leg in order to increase magnetic coupling allowing practically all of the magnetic lines of force go through both the primary and secondary windings at the same time. However, with this type of transformer construction, a small percentage of the magnetic lines of force flow outside of the core, and this is called ―leakage flux‖.

Shell type transformer cores overcome this leakage flux as both the primary and secondary windings are wound on the same centre leg or limb which has twice the cross-sectional area of the two outer limbs. The advantage here is that the magnetic flux has two closed magnetic paths to flow around external to the coils on both left and right hand sides before returning back to the central coils.

This means that the magnetic flux circulating around the outer limbs of this type of transformer construction is equal to Φ/2. As the magnetic flux has a closed path around the coils, this has the advantage of decreasing core losses and increasing overall efficiency.

Transformer Laminations

But you may be wondering as to how the primary and secondary windings are wound around these laminated iron or steel cores for this type of transformer constructions. The coils are firstly wound on a former which has a cylindrical, rectangular or oval type cross section to suit the construction of the laminated core. In both the shell and core type transformer constructions, in order to mount the coil windings, the individual laminations are stamped or punched out from larger steel sheets and formed into strips of thin steelresemblingtheletters―E's‖,―L's‖,―U's‖and―I's‖asshownfig 15.9.

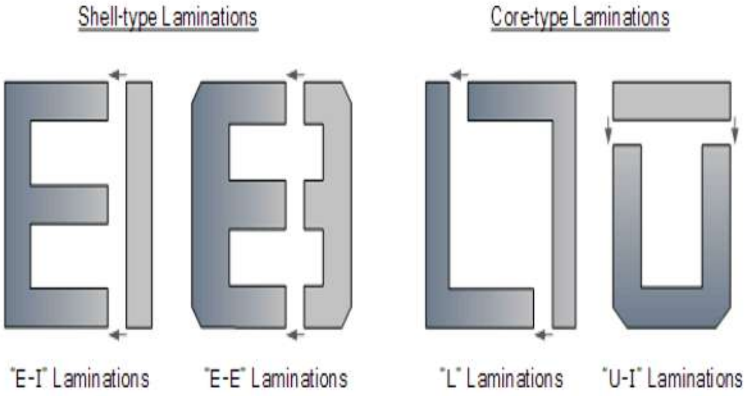



Fig. 15.9Transformer Core Types

These lamination stampings when connected together form the requiredcoreshape.Forexample,two—E‖stampingsplustwoend closing—I‖stampingstogiveanE-Icoreformingoneelementofa standard shell-type transformer core. These individual laminations are tightly butted together during the transformers construction to reduce the reluctance of the air gap at the joints producinga highly saturated magnetic fluxdensity.
Transformer core laminations are usually stacked alternately to each other to produce an overlapping joint with more lamination pairs being added to make up the correct core thickness. This alternate stacking of the laminations also gives the transformer the advantage of reduced flux leakage and iron losses. E-I core laminated transformer construction is mostly used in isolation transformers, step-up and step-down transformers as well as auto transformers.

Transformer Winding Arrangements

Transformer windings form another important part of a transformer construction, because they are the main current- carrying conductors wound around the laminated sections of the core. In a single-phase two winding transformer, two windings would be present as shown. The one which is connected to the voltage source and creates the magnetic flux called the primary winding, and the second winding called the secondary in which a voltage is induced as a result of mutual induction.
If the secondary output voltage is less than that of the primary input voltage the transformer is known as a —Step-down Transformer‖. If the secondary output voltage is greater then the primary input voltage it is called a —Step-up Transformer‖.

Fig. 15.10Core-type Construction

The type of wire used as the main current carrying conductor in a transformer winding is either copper or aluminium.While aluminium wire is lighter and generally less expensive than copper wire, a larger cross sectional area of conductor must be used to carry the same amount of current as with copper so it is used mainly in larger power transformerapplications.

Small kVA power and voltage transformers used in low voltage electrical and electronic circuits tend to use copper conductors as these have a higher mechanical strength and smaller conductor size than equivalent aluminium types. The downside is that when complete with their core, these transformers are muchheavier.

Transformer windings and coils can be broadly classified into concentric coils and sandwiched coils. In core-type transformer construction, the windings are usually arranged concentrically around the core limb as shown in fig 15.10 with the highervoltage primarywindingbeingwoundoverthelowervoltagesecondary winding.

Sandwiched or ―pancake‖ coils consist of flat conductors wound in a spiral form and are so named due to the arrangement of conductors into discs. Alternate discs are made to spiral from outside towards the centre in an interleaved arrangement with individual coils being stacked together and separated by insulating materials such as paper of plastic sheet. Sandwich coils and windings are more common with shell type core construction.

Helical Windings also known as screw windings are another very common cylindrical coil arrangement used in low voltage high current transformer applications. The windings are made up of large cross sectional rectangular conductors wound on its side with the insulated strands wound in parallel continuously along the length of the cylinder, with suitable spacers inserted between adjacent turns or discs to minimize circulating currents between the parallel strands. The coil progresses outwards as a helix resembling that of acorkscrew.

Fig. 15.11 TransformerCores

The insulation used to prevent the conductors shorting together in a transformer is usually a thin layer of varnish or enamel in air cooled transformers. This thin varnish or enamel paint is painted onto the wire before it is wound around the core.

In larger power and distribution transformers the conductors are insulated from each other using oil impregnated paper or cloth. The whole core and windings is immersed and sealed in a protective tank containing transformer oil. The transformer oil acts as an insulator and also as acoolant

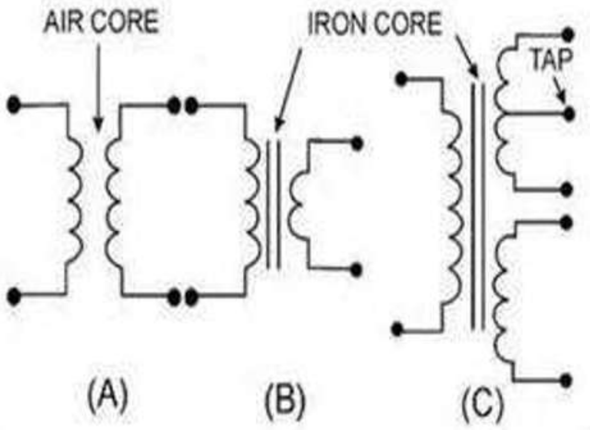



Fig. 15.12 Schematic Symbol Of A Transformer

TURNS RATIO OF A TRANSFORMER

The voltage of the windings in a transformer is directly proportional to the number of turns on the coils. This relationship is expressed by
VP /VS=NP/NS where
VP = voltage on primary coil VS = voltage on secondary coil NP = number of turns on the primary coil NS = number of turns on the secondarycoil
The ratio of primary voltage to secondary voltage is known as the voltage ratio (VR). As mentioned previously, the ratio of primary turns of wire to secondary turns of wire is known as the turns ratio (TR). By substituting into the Equation, we find that the voltage ratio is equal to the turns ratio. VR = TRA voltage ratio of 1:5 means that for each volt on the primary, there will be 5 volts on the secondary. If the secondary voltage of a transformer is greater than the primary voltage, the transformer is referred to as a "step-up" transformer. A ratio of 5:1 means that for every 5 volts on the primary, there will only be 1 volt on the secondary. When secondary voltage is less than primary voltage, the transformer is referred to as a "step-down"transformer.
Example 1: A transformer reduces voltage from 120 volts in the primary to 6 volts in the secondary. If the primary winding has 300 turns and the secondary has 15 turns, find the voltage and turnsratio.

Solution: VR =VP/VS =120/60 =20/1 =20:1 TR=NP/NS=300 /15 =20/1=20:1

NO LOAD CONDITION

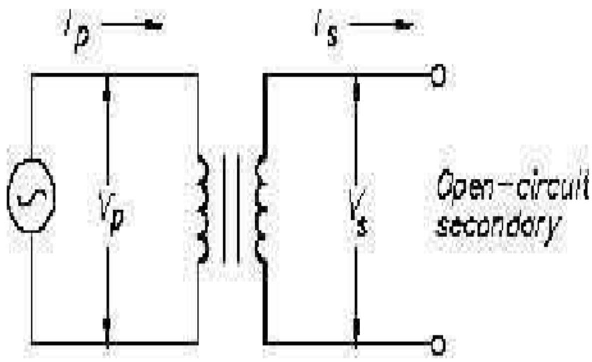



Fig. 15.13

If the secondary of a transformer is left open-circuited, primary current is very low and is called the no-load current. No-load current produces the magnetic flux and supplies the hysteresis and eddy current losses in the core. The no-load current (IE) consists of two components: the magnetizing current (Im) and the core loss (IH). Magnetizing current lags applied voltage by 90°, while core loss is in phase with the applied voltage (Figure 6b). VP and VS are shown 180° out of phase. IH is very small in comparison with Im, and Im is nearly equal to IE. No-load current, IE, is also referred to as excitingcurrent.

## TRANSFORMER UNDER LOAD

When a load device is connected across the secondary winding of a transformer, current flows through the secondary and the load. The magnetic field produced by the current in the secondary interacts with the magnetic field produced by the current in the primary. This interaction results from the mutual inductance between the primary and secondary windings. Copper loss is determined by this method.

## PRODUCING A COUNTER EMF

When an alternating current flows through a primary winding, a magnetic field is established around the winding. As the lines of flux expand outward, relative motion is present, and a counter emf is induced in the winding. This is the same counter emf that you learned about in the part on inductors. Flux leaves the primary at the north pole and enters the primary at the south pole. The counter emf induced in the primary has a polarity that opposes the applied voltage, thus opposing the flow of current in the primary. It is the counter emf that limits exciting current to a very low value.

## INDUCING A VOLTAGE IN THE SECONDARY

As the exciting current flows through the primary, magnetic lines of force are generated. During the time current is increasing in the primary, magnetic lines of force expand outward from the primary and cut the secondary. As you remember, a voltage is induced into a coil when magnetic lines cut across it. Therefore, the voltage across the primary causes a voltage to be induced across the secondary.

## PRIMARY AND SECONDARY PHASE RELATIONSHIP

The secondary voltage of a simple transformer may be either in phase or out of phase with the primary voltage. This depends on the direction in which the windings are wound and the arrangement of the connections to the external circuit (load). Simply, this means that the two voltages may rise and fall together or one may rise while the other is falling. Transformers in which the secondary voltage is in phase with the primary are referred to as LIKE-WOUND transformers, while those in which the voltages are 180 degrees out of phase are called UNLIKE-WOUND transformers. Dots are used to indicate points on a transformer schematic symbol that have the same instantaneous polarity (points that are in phase). The use of phase-indicating dots is illustrated in figure 15.14. In part (A) of the figure, both the primary and secondary windings are wound from top to bottom in a clockwise direction, as viewed from above the windings. When constructed in this manner, the top lead of the primary and the top lead of the secondary have the SAME polarity. This is indicated by the dots on the transformer symbol. A lack of phasing dots indicates a reversal ofpolarity.

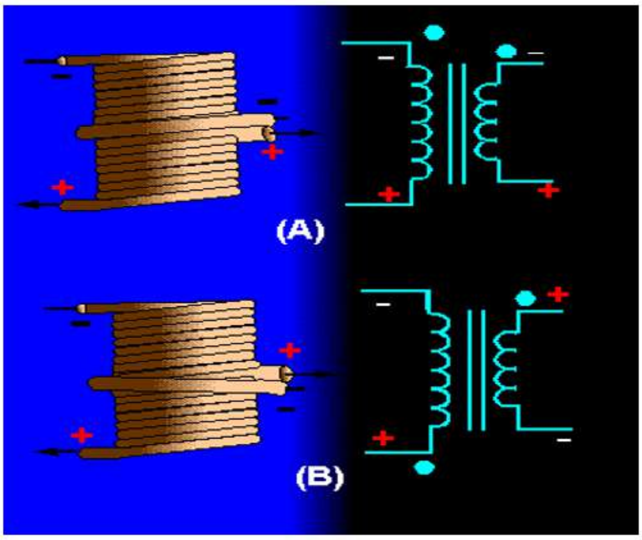



Fig. 15.14 Instantaneous polarity depends on directionof winding.

Part (B) of the figure 15.14 illustrates a transformer in which the primary and secondary are wound in opposite directions. As viewed from above the windings, the primary is wound in a clockwise direction from top to bottom, while the secondary is wound in a counterclockwise direction. Notice that the top leads of the primary and secondary have OPPOSITE polarities. This is indicated by the dots being placed on opposite ends of the transformer symbol. Thus, the polarity of the voltage at the terminals of the secondary of a transformer depends on the direction in which the secondary is wound with respect to the primary.

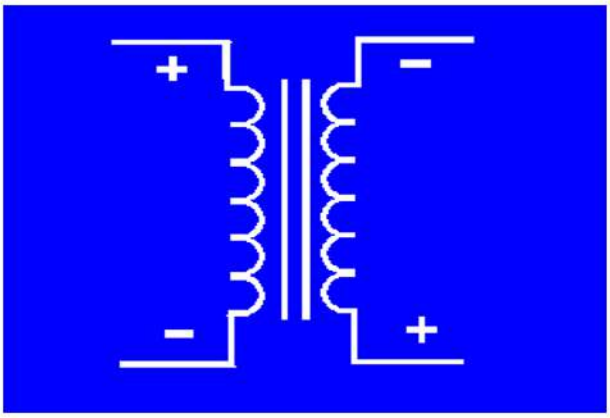


Fig. 15.15

COEFFICIENT OF COUPLING

silicon steel cores and close spacing between the windings to provide a high coefficient of coupling. Lines of flux generated by one winding which do not link with the other winding are called LEAKAGE

FLUX. Since leakage flux generated by the primary does not cut the secondary, it cannot induce a voltage into the secondary. The voltage induced into the secondary is therefore lessthanitwouldbeiftheleakagefluxdidnotexist.Sincethe

effect of leakage flux is to lower the voltage induced into the secondary, the effect can be duplicated by assuming an inductor to be connected in series with the primary. This series LEAKAGE INDUCTANCE is assumed to drop part of the applied voltage, leaving less voltage across the primary.

## MUTUAL FLUX

The total flux in the core of the transformer is common to both the primary and secondary windings. It is also the means by which energy is transferred from the primary winding to the secondary winding. Since this flux links both windings, it is called MUTUAL FLUX. The inductance which produces this flux is also common to both windings and is called mutualinductance.

Figure 15.16 shows the flux produced by the currents in the primary and secondary windings of a transformer when source current is flowing in the primary winding.

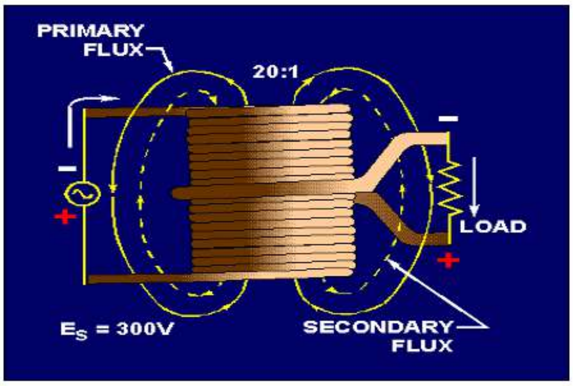



Fig. 15.16Simple transformer indicating primary- and secondary-winding flux relationship.

When a load resistance is connected to the secondary winding, the voltage induced into the secondary winding causes current to flow in the secondary winding. This current produces a flux field about the secondary (shown as broken lines) which is in opposition to the flux field about the primary (Lenz's law). Thus, the flux about the secondary cancels some of the flux about the primary. With less flux surrounding the primary, the counter emf is reduced and more current is drawn from the source. The additional current in the primary generates more lines of flux, nearly reestablishing the original number of total fluxlines.

## TURNS AND CURRENT RATIOS

The number of flux lines developed in a core is proportional to the magnetizing force (IN AMPERE-TURNS) of the primary and secondary windings. The ampere-turn (I X N) is a measure of magneto motive force; it is defined as the magneto motive force developed by one ampere of current flowing in a coil of one turn. The flux which exists in the core of a transformer surrounds both the primary and secondary windings. Since the flux is the same for both windings, the ampere-turns in both the primary and secondary windings must be thesame.

Therefore:

Where :

IPNP= ampere-turns in the primary winding

ISNS= ampere –turns in the secondary winding

By dividing both sides of the equation by IpN s, you obtain:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

Since: $$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Then: $$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

And: $$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

Where :

EP = voltage a applied to the primary in volts ES = voltage a cross the secondary in volts IP = current in the primary inamperes
IS = current in the secondary in amperes

Notice the equations show the current ratio to be the inverse of the turns ratio and the voltage ratio. This means, a transformerhaving
lessturnsinthesecondarythaninthe primarywouldstepdown
the voltage, but would step up the current.

Transformers can be of two types:

Step-up Transformer

On a step-up transformer there are more turns on the secondary coil than the primary coil. The induced voltage across the secondary coil is greater than the applied voltage across the primary coil or in other words the voltage has been ―stepped-up‖.
Step-down Transformer

A step down transformer has less turns on the secondary coil that the primary coil. The induced voltage across the secondary coil is less the applied voltage across the primary coil or in other words the voltage is ―stepped-down‖.
Transformers are very efficient. If it is assumed that a transformer is 100% efficient (and this is a safe assumption as transformers may be up to 99% efficient) then the power in the primary coil has to be equal to the power in the secondary coil, as per the law of conservation of energy.
Power in primary coil = Power in secondary coil Remember, power = potential difference x current Thus,

x secondary coil current

So if the potential difference is stepped up by a transformer then the current is stepped down by roughly the same ratio. In the case of the potential being stepped down by the transformer then the current is stepped up by the same ratio.

A transformer is made from two or more coils of insulated wire wound around a core made of iron. When voltage is applied to one coil (frequently called the primary or input) it magnetizes the iron core, which induces a voltage in the other coil, (frequently called the secondary or output). The turns ratio of the two sets of windings determines the amount of voltage transformation. An example of this would be: 100 turns on the primary and 50 turns on the secondary, a ratio of 2 to 1.Transformers can be considered nothing more than a voltage ratiodevice.

With a step up transformer or step down transformer the voltage ratio between primary and secondary will mirror the "turns ratio" (except for single phase smaller than 1 kva which have compensated secondaries). A practical application of this 2 to 1 turns ratio would be a 480 to 240 voltage step down. Note that if the input were 440 volts then the output would be 220 volts. The ratio between input and output voltage will stay constant. Transformers should not be operated at voltages higher than the nameplate rating, but may be operated at lower voltages than rated. Because of this it is possible to do some non- standard applications using standardtransformers.

Single phase transformers 1 kva and larger may also be reverse connected to step-down or step-up voltages. (Note: single phase step up or step down transformers sized less than 1 KVA should not be reverse connected because the secondary windings have additional turns to overcome a voltage drop when the load is applied. If reverse connected, the output voltage will be less than desired.) Step up transformers and step down transformers have a longlife.

## POWER IN A TRANSFORMER

The turns ratio of a transformer affects current as well as voltage. If voltage is doubled in the secondary, current is halved in the secondary. Conversely, if voltage is halved in the secondary, current is doubled in the secondary. In this manner, all the power delivered to the primary by the source is also delivered to the load by the secondary (minus whatever power is consumed by the transformer in the form of losses). Refer again to the transformer illustrated in figure The turns ratio is 20:1. If the input to the primary is 0.1 ampere at 300 volts, the power in the primary is P = E X I = 30. If the transformer has no losses, 30 watts is delivered to the secondary. The secondary steps down the voltage to 15 volts and steps up the current to 2 amperes. Thus, the power delivered to the load by the secondary is P = E X I = 15 volts X 2 amps = 30watts.

The reason for this is that when the number of turns in the secondary is decreased, the opposition to the flow of the current is also decreased.

Hence, more current will flow in the secondary. If the turns ratio of the transformer is increased to 1:2, the number of turns on the secondary is twice the number of turns on the primary. This means the opposition to current is doubled. Thus, voltage is doubled, but current is halved due to the increased opposition to current in the secondary. The important thing to remember is that with the exception of the power consumed within the transformer, all power delivered to the primary by the source will be delivered to the load. The form of the power may change, but the power in the secondary almost equals the power in the primary.

As a formula :

Where :

$P_s$ = power delivered to the load by the secondary $P_P$= power delivered to the primary by the source $P_L$= power losses in thetransformer

## LOSSES IN ATRANSFORMER

Energy losses

Real transformer energy losses are dominated by winding resistance joule and core losses. Transformers' efficiency tends to improve with increasing transformer capacity. The efficiency of typical distribution transformers is between about 98 and 99 percent.

As transformer losses vary with load, it is often useful to express these losses in terms of no-load loss, full-load loss, half-load loss, and so on. Hysteresis and eddy current losses are constant at all load levels and dominate overwhelmingly without load, while variable winding joule losses dominating increasingly as load increases. The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply. Designing energy efficient transformers for lower loss requires a larger core, good-quality silicon steel, or even amorphous steel for the core and thicker wire, increasing initial cost. The choice of construction represents a trade-off between initial cost and operatingcost.

Transformer losses arise from:

Winding joule losses

Current flowing through winding conductors causes jouleheating. As frequency increases, skin effect and proximityeffect causes winding resistance and, hence, losses to increase.(I2R LOSSES)

Core losses Hysteresis losses

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. According to Steinmetz's formula, the heat energy due to hysteresis is givenby

, and, hysteresis loss is thus givenby

where, f is the frequency, η is the hysteresis coefficient and βmax is the maximum flux density, the empirical exponent of which varies from about 1.4 to 1 .8 but is often given as 1.6 foriron.

Eddy current losses

Ferromagnetic materials are also good conductors and a core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddycurrents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness. Eddy current losses can be reduced by making the core of a stack of plates electrically insulated from each other, rather than a solid block; all transformers operating at low frequencies use laminated or similarcores.

Magnetostriction related transformer hum

Magnetic flux in a ferromagnetic material, such as the core,causesittophysicallyexpandandcontractslightly witheachcycleofthemagneticfield,aneffectknownas magnetostriction,thefrictionalenergyofwhichproduces an audible noise known as mains hum or transformerhum.

Stray losses

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat. There are also radiative losses due to the oscillating magnetic field but these are usually small.

Mechanical vibration and audible noise transmission

In addition to magneto striction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. This energy incites vibration transmission in interconnected metalwork, thus amplifying audible transformer hum

TRANSFORMER EFFICIENCY

Consider an ideal transformer.

In an ideal transformer due to no power loss, power input is equal to power output i.e.

Power input = Power out put Pp=Ps [power =VI]

VpIp = Vs Is Vp/Vs = Is/Ip

This expression indicates that current and voltage have an inverse relation with each other in transformer.

Efficiency of a device is equal to the ratio of output to input.

Since,

Output = Ps

or

Output = Vs Is

and

Input = Pp

or

Input = VpIp

Efficiency = output / input Efficiency = Ps / Pp Efficiency = Vs Is / VpIp

Efficiency in percent = (Vs Is / VpIp) x 100

In actual practice output is not equal to input therefore actual transformers are not 100% efficient.However commercialtransformershaveveryhighefficiencyinthe range of 95% to 99%

RATING OF A TRANSFORMER

Transformers are rated in KVA.

When a transformer is to be used in a circuit, more than just the turns ratio must be considered. The voltage, current, and power- handling capabilities of the primary and secondary windings must also be considered.

The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings.

The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may be sufficiently high to causethe insulation around the wire to break down. If this happens, the transformer may be permanently damaged. The power-handling capacity of a transformer is dependent upon its ability to dissipate heat. If the heat can safely be removed, the power-handling capacity of the transformer can be increased. This is sometimes accomplished by immersing the transformer in oil, or by the use of cooling fins. The power-handling capacity of a transformer is measured in either the volt-ampere unit or the watt unit. Two common power generator frequencies (60 hertz and 400 hertz) have been mentioned, but the effect of varying frequency has not beendiscussed.

## TYPES OF TRANSFORMERS

### Laminated core

Fig. 15. 17 Laminated core transformer

This is the most common type of transformer, widely used in electric power transmission and appliances to convert mains voltage to low voltage to power electronic devices. They are available in power ratings ranging from mW to MW. The insulated laminations minimizes eddy current losses in the iron core.(fig 15.17)
Small appliance and electronic transformers may use a split bobbin, giving a high level of insulation between the windings. The rectangular cores are made up of stampings, often in E-I shape pairs, but other shapes are sometimes used. Shields between primary and secondary may be fitted to reduce EMI (electromagnetic interference), or a screen winding is occasionally used. Small appliance and electronics transformers may have a thermal cut out built into thewinding.

### Toroidal

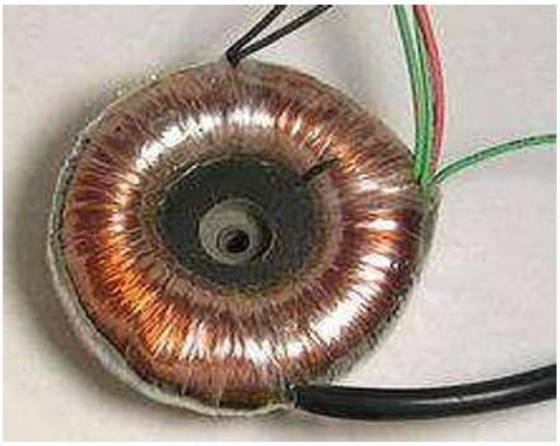


Fig. 15.18 Toroidal transformer

Doughnut shaped toroidal transformers are used to save space compared to EI cores, and sometimes to reduce external magnetic field. These use a ring shaped core, copper windings wrapped round this ring (and thus threaded through the ring during winding), and tape for insulation. To roidal transformers have a lower external magnetic field compared to rectangular transformers, and can be smaller for a given power rating.

However, they cost more to make, as winding requires more complex and slower equipment. They can be mounted by a

bolt through the center, using washers and rubber pads or by potting in resin. (fig 15.18)

Autotransformer

An autotransformer has one winding which is tapped at some point along the winding(fig 15.19). Voltage is applied across a portion of the winding, and a higher (or lower) voltage is produced across another portion of the same winding. The equivalent power rating of the auto transfomer is lower than the actual load power rating. It is calculated by: (|Vin-Vout|)/Vin x load VA. For example, an auto transformer used to adapt a 1000 VA load rated at 120 volts to a 240 volt supply has an equivalent rating of atleast:(240V-120V)/240Vx1,000VA=500VA.

However, the actual rating (which is what is shown on the tally plate) would have to be at least 1000 VA. For voltage ratios not exceeding about 3:1, an autotransformer is cheaper, lighter, smaller and more efficient than an isolating (two-winding) transformer of the same rating. Large three-phase autotransformers are used in electric power distribution systems, for example, to interconnect 33 kV and 66 kV sub-transmissionnetworks

Fig 15.19(variable autotransformer)

By exposing part of the winding coils of an autotransformer, and making the secondary connection through a sliding carbon brush, an autotransformer with a near-continuously variable turns ratio can be obtained, allowing for wide voltage adjustment in very small increments.

Fig. 15.20Polyphase transformer

Cutaway view of a polyphase transformer

For polyphase systems, multiple single-phase transformers can be used, or all phases can be connected to a single polyphase transformer. For a three phase transformer, the three primary windings are connected together and the three secondary windings are connected together. Examples of connections are wye-delta, delta-wye, delta- delta and wye-wye. A vector group indicates the configuration of the windings and the phase angle difference between them. If a winding is connected to earth (grounded), the earth connection point is usually the center point of a wye winding. If the secondary is a delta winding, the ground may be connected to a center tap on one winding (high leg delta) or one phase may be grounded (corner grounded delta). A special purpose polyphase transformer is the zigzag transformer. There are many possible configurations that may involve more or fewer than six windings and various tap connections. (fig15.20)

Grounding transformer

Grounding transformers are used to allow three wire (delta) polyphase system supplies to accommodate phase to neutral loads by providing a return path for current to a neutral. Grounding transformers most commonly incorporate a single winding transformer with a zigzag winding configuration but may also be created with a wye- delta isolated winding transformerconnection.


Fig. 15.21 Leakage (or stray field) transformers

Leakage transformer

A leakage transformer, also called a stray-field transformer, has a significantly higher leakage inductance than other transformers, sometimes increased by a magnetic bypass or shunt in its core between primary and secondary, which is sometimes adjustable with a set screw. This provides a transformer with an inherent current limitation due to the loose coupling between its primary and the secondary windings. The output and input currents are low enough to prevent thermal overload under all load conditions—even if the secondary is shorted. (fig15.21)

Use

Leakage transformers are used for arc welding and high voltage discharge lamps (neon lights and cold cathode fluorescent lamps, which are series connected upto 7.5kVAC).Itactsthenbothasavoltagetransformerand as a magnetic ballast.

Resonant transformer

A resonant transformer is a transformer in which one or both windings has a capacitor across it and functions as a tuned circuit. Used at radio frequencies, resonant transformers can function as high Q_factorbandpass filters. The transformer windings have either air or ferrite cores and the bandwidth can be adjusted by varying the coupling (mutual inductance). One common form is the IF (intermediate frequency) transformer, used in superheterodyne radio receivers. They are also used in radio transmitters.

Resonant transformers are also used in electronic ballasts for fluorescent lamps, and high voltage power supplies. They are also used in some types of switching powersupplies.Here often only one winding has a capacitor and acts as a tank circuit. The transformer is driven by a pulse or square wave for efficiency, generated by an electronicoscillator circuit. Each pulse serves to drive resonant sinusoidal oscillations in the tuned winding, and due to resonance a high voltage can be developed across the secondary.

Applications:

- Intermediate frequency (IF) transformer insuper heterodyne radio receiver.
- Tank transformers in radio transmitters.

- Tesla coil.
- Oudin coil (or Oudin resonator; named after its inventor Paul Oudin).
- D'Arsonval apparatus.
- Ignition coil or induction coil used in the ignition system of a petrol engine.
- Electrical breakdown and insulation testing ofhigh voltage equipment and cables. In the latter case,the transformer's secondary is resonated with the cable's capacitance.

Oil cooled transformer

For large transformers used in power distribution or electrical substations, the core and coils of the transformer are immersed in oil which cools and insulates. Oil circulates through ducts in the coil and around the coil and core assembly, moved by convection. The oil is cooled by the outside of the tank in small ratings, and in larger ratings an air-cooled radiator is used. Where a higher rating is required, or where the transformer is used in a building or underground, oil pumps are used to circulate the oil and an oil-to-water heat exchanger may also be used. Some transformers may contain PCBs where or when its use waspermitted.

Isolating transformer

An isolation transformer links two circuits magnetically, but provides no metallic conductive path between the circuits. An example application would be in the power supply for medical equipment, when it is necessary to prevent any leakage from the AC power system into devices connected to a patient. Special purpose isolation transformers may include shielding to prevent coupling of electromagnetic noise between circuits, or may have reinforced insulation to withstand thousands of volts of potential difference between primary and secondary circuits.(fig 15.22)

Fig. 15. 22 Instrument transformer

Instrument transformers

Instrument transformers are typically used tooperate instruments from high voltage lines or high current circuits, safely isolating measurement and control circuitry from the high voltages or currents. The primary winding of the transformer is connected to the high voltage or high current circuit, and the meter or relay is connected to the secondary circuit. Instrument transformers may also be used as an isolation transformer so that secondary quantities may be used without affecting the primary circuitry.

Current transformer

Fig. 15.23 Current transformer

Current transformers used in metering equipment for three-phase 400 ampere electricity supply

A current transformer (CT) is a series connected measurement device designed to provide a current in itssecondary coil proportional to the current flowing in its primary. Current transformers are commonly used in metering and protective relays in the electrical powerindustry.

Current transformers are often constructed by passing a single primary turn (either an insulated cable or an uninsulated bus bar) through a well-insulated toroidal core wrapped with many turns of wire. The CT is typically described by its current ratio from primary to secondary. For example, a 1000:1 CT would provide an output current of 1 amperes when 1000 amperes were passing through the primary winding. Standard secondary current ratings are 5 amperes or 1 ampere, compatible with standard measuring instruments. The secondary winding can be single ratio or have several tap points to provide a range of ratios. Care must be taken that the secondary winding is not disconnected from its low-impedance load while current flows in the primary, as this may produce a dangerously high voltage across the open secondary and may permanently affect the accuracy of the transformer.

A current clamp uses a current transformer with a split core that can be easily wrapped around a conductor in a circuit. This is a common method used in portable current measuring instruments but permanent installations use more economical types of current transformer. (fig15.23)

Potential transformer (Voltage transformer)

Voltage transformers (VT) (also called potential transformers (PT)) are a parallel connected type of instrument transformer, used for metering and protection in high-voltage circuits or phasor phase shift isolation. They are designed to present negligible load to the supply being measured and to have an accurate voltage ratio to enable accurate metering. A potential transformer may have several secondary windings on the same core as a primary winding, for use in different metering or protection circuits. The primary may be connectedphase

to ground or phase to phase. The secondary is usually grounded on one terminal.

There are three primary types of voltage transformers(VT): electromagnetic, capacitor, and optical. The electromagnetic voltage transformer is a wire-wound transformer. The capacitor voltage transformer uses a capacitance potential divider and is used at higher voltages due to a lower cost than an electromagnetic VT. An optical voltage transformer exploits the electrical properties of optical materials measurement of high voltages is possible by the potential transformers.

Audio transformer

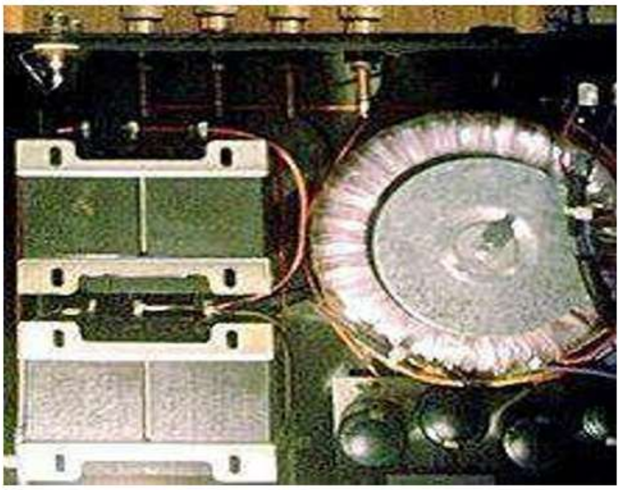


Fig. 15.24Audio transformer

Two speaker-level audio transformers in a tube amplifier are seen on the left. The power supply toroidal transformer is on right Audio transformers are those specifically designed for use in audio circuits to carry audio signal. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high impedance tube (valve) amplifier output and a low impedance loudspeaker, or between a high impedance instrument output and the low impedance input of a mixing console. Audio transformers that operate with loudspeaker voltages and current are larger than those which operate at microphone or line level, carrying much less power. (fig15.24)

Loudspeaker transformer

Fig. 15.25 Loudspeaker transformer in old radio

In the same way that transformers are used to create high voltage power transmission circuits that minimize transmission losses, loudspeaker transformers can be used to allow many individual loudspeakers to be powered from a single audio circuit operated at higher-than normal loudspeaker voltages. This application is common in public address applications. Such circuits are commonly referred to as constant voltage speaker systems. The loudspeaker transformers commonly have multiple primary taps, allowing the volume at each speaker to be adjusted in steps (fig15.25)

THREE PHASE TRANSFORMERS

Since three-phase is used so often for power distribution systems, it makes sense that we would need three-phase transformers to be able to step voltages up or down. This is only partially true, as regular single-phase transformers can be ganged together to transform power between two three-phase systems in a variety of configurations, eliminating the requirement for a special three-phase transformer. However, special three-phase transformers are built for those tasks, and are able to perform with less material requirement, less size, and less weight than their modularcounterparts.

A three-phase transformer is made of three sets of primary and secondary windings, each set wound around one leg of an iron core assembly. Essentially it looks like three single-phase transformers sharing a joined core as in Fig 15.26.

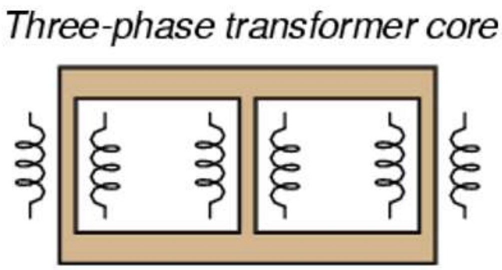



Fig. 15.26 Three phase transformer core

Three phase transformer core has three sets of windings. Those sets of primary and secondary windings will be
connected in either Δ or Y configurations to form a complete unit. The various combinations of ways that these windings can be connected together in will be the focus of this section.

Whether the winding sets share a common core assembly or each winding pair is a separate transformer, the winding connection options are the same:

- Primary -Secondary
- Y - Y
- Y - Δ
- Δ - Y
- Δ - Δ

The reasons for choosing a Y or Δ configuration for
transformer winding connections are the same as for any ee-phase application: Y connections providethe
opportunity for multiple voltages, while Δ connections enjoy a higher levelof reliability (if one windingfails open,theothertwocanstillmaintainfulllinevoltagesto the load).

Probably the most important aspect of connecting three sets of primary and secondary windings together to form a three-phase transformer bank is paying attention to proper winding phasing (the dots used to denote —polarity‖of windings). Remember the proper phase relationships between the phase windings of Δ and Y: (Figure15.27)

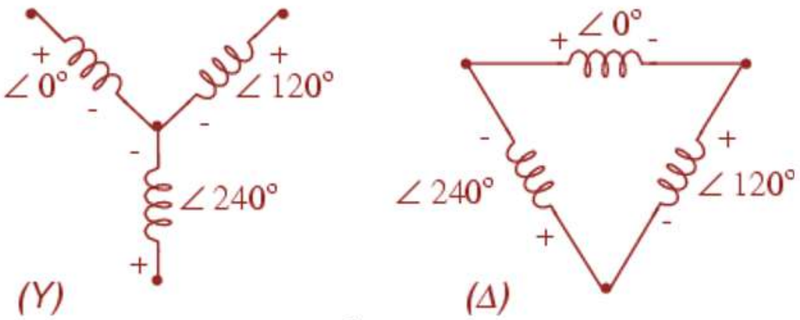



Fig. 15.27

(Y) Thecenterpointofthe—Y‖musttie either all the—-‖or all the —+‖winding points together. (Δ) The winding polarities must stack together in a complementary manner ( + to-).
Getting this phasing correct when the windings aren't shown in regular Y or Δ configuration can be tricky. Let illustrate, starting with Figure below (15.28).

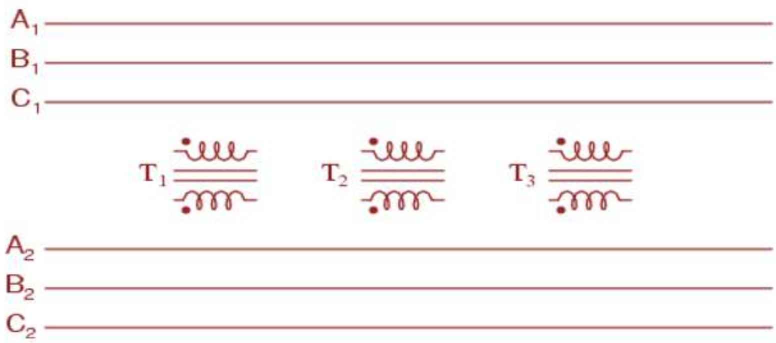



Fig. 15.28Inputs A1, A2, A3may be wired either —Δ‖or —Y‖, asmayoutputs B1, B2, B3.

Three individual transformers are to be connected together to transform power from one three-phase system to another. First, I'll show the wiring connections for a Y-Y configuration: Figure (15.29)

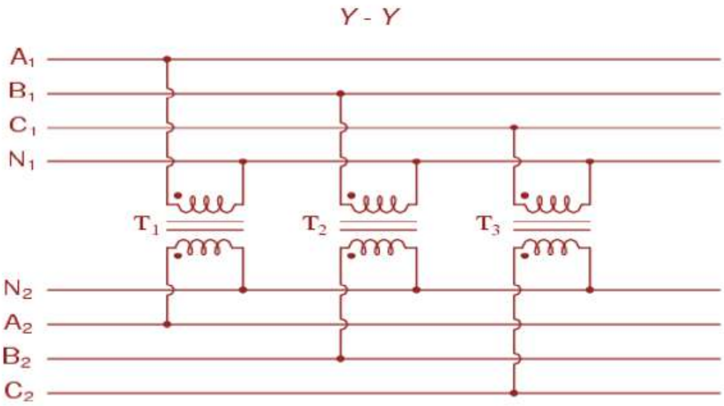



Fig. 15.29Phase wiring for “Y-Y” transformer.

Note in Figure 15.27 how all the winding ends marked with dots are connected to their respective phases A, B, and C, while the non-dot ends are connected together to form the centers of each —Y‖. Having both primary and secondary winding sets connected in —Y‖formations allows for the use of neutral conductors (N1 and N2) in each powersystem. Now, we'll take a look at a Y-Δ configuration: (Figure15.30)

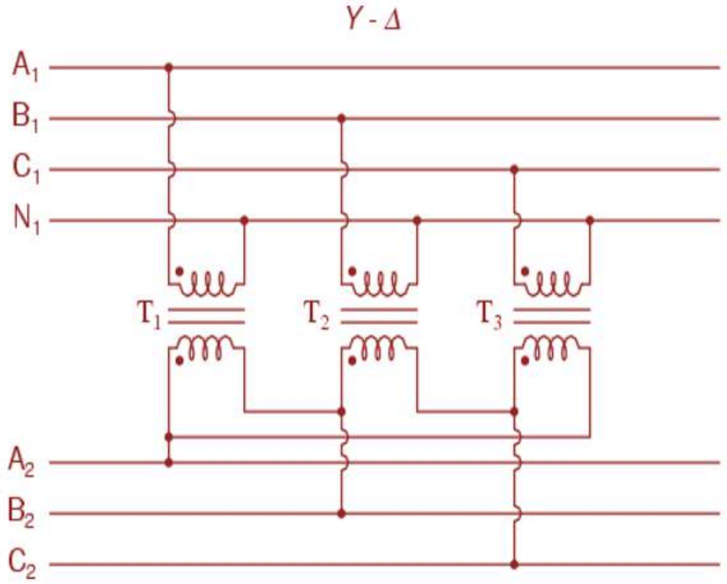



Fig. 15.30 Phase wiring for "Y-Δ" transformer.

Note how the secondary windings (bottom set, Figure 15.30) are connected in a chain, the ―dot‖side of one winding connected to the ―non-dot‖side of the next, forming the Δ loop. At every connection point between pairs of windings, a connection is made to a line of the second power system (A, B, and C). Now, let's examine a Δ-Y system in Figure15.31.

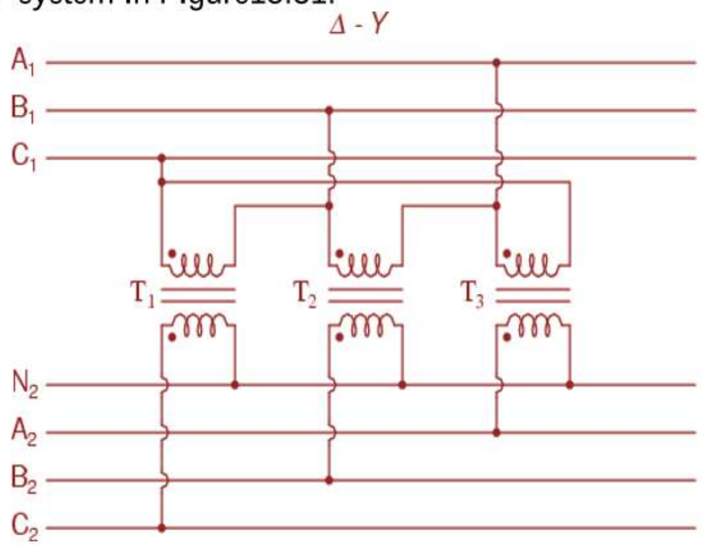



Fig. 15.31 Phase wiring for "Δ-Y"transformer.

Such a configuration (Figure 15.31) would allow for the provision of multiple voltages (line-to-line or line-to- neutral) in the second power system, from a source power system having no neutral. And finally, we turn to the Δ-Δ configuration: (Figure 15.32).

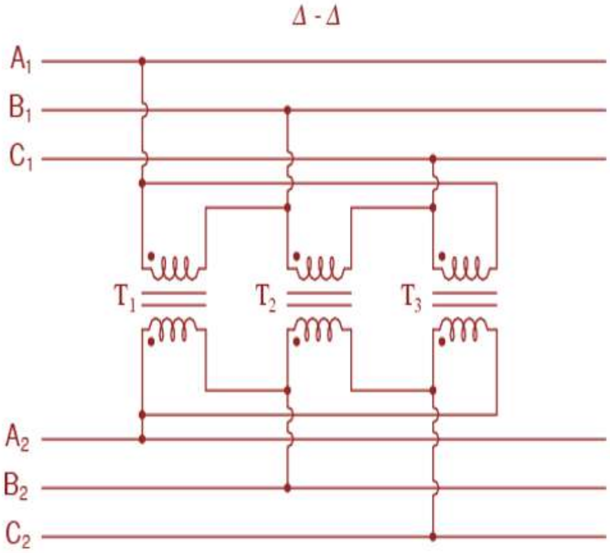



Fig. 15.32 Phase wiring for "Δ-Δ" transformer.

When there is no need for a neutral conductor in the secondary power system, Δ-Δ connection schemes (Figure 15.32) are preferred because of the inherent reliability of the Δ configuration.

Considering that a Δ configuration can operate satisfactorily missing one winding, some power system designers choose to create a three-phase transformer bank with only two transformers, representing a Δ-Δ configuration with a missing winding in both the primary and secondary sides: (Figure 15.33).

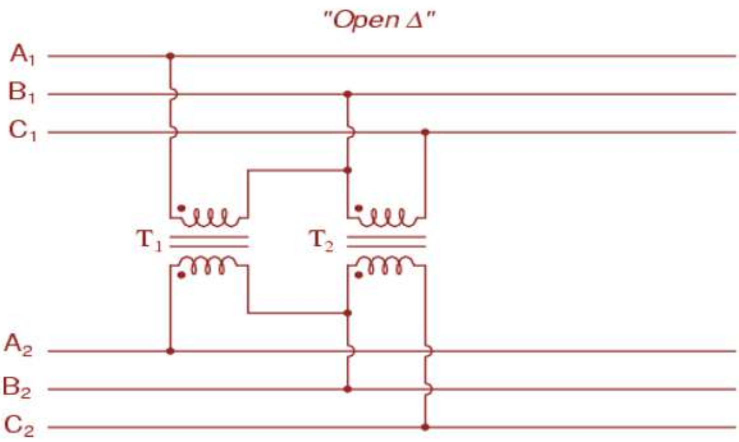



Fig. 15.33"V" or "open-Δ" provides 2-φ power with only two transformers.

Thisconfigurationiscalled—V‖or—Open-Δ.‖Ofcourse, each of the two transformers have to be oversized to handle the same amount of power as three in a standard Δ configuration, but the overall size, weight, and cost advantages are often worth it. Bear in mind, however, that with one winding set missing from the Δ shape, this system no longer provides the fault tolerance of a normal Δ-Δ system. If one of the two transformers were to fail, the load voltage and current would definitely beaffected.

The following photograph (Figure 15.34) shows a bank of step-up transformers at the Grand Coulee hydroelectric dam in Washington state. Several transformers (green in color) may be seen from this vantage point, and they are grouped in threes: three transformers per hydroelectric generator, wired together in some form of three-phase configuration. The photograph doesn't reveal the primary winding connections, but it appears the secondaries are connected in a Y configuration, being that there is only one large high-voltage insulator protruding fromeach transformer. This suggests the other side of each transformer's secondary winding is at or near ground potential, which could only be true in a Y system. The building to the left is the powerhouse, where the generators and turbines are housed. On the right, the sloping concrete wall is the downstream face of thedam:

Fig. 15.34

Module: 3.16 Filters

FILTERS

Introduction to Filters

An electric filter is a network designed to attenuatecertain frequencies but pass others without attenuation. A filter circuit, therefore, possesses at least one pass band — a band of frequencies in which the output is approximately equal to the input (that is, attenuation is zero) and an attenuation band in which output is zero (that is, attenuation is infinite). The frequencies that separate the different pass and attenuation bands are called the cut-offfrequencies.

Filters may be of any type such as electrical, mechanical, pneumatic, hydraulic, acoustical etc. but the most commonly used filters are of the electrical type.

Electrical filters are used in practically all circuits which require separation of signals according to theirfrequencies. Applications
include (but are certainly not limited to) noise rejection andsignal separation in industrial and measurement circuits, feedback of phase and amplitude control in servo-loops, smoothing ofdigitally generatedanalog(D-A)signals,audio-signalshapingandsound enhancement, channel separation, and signal enhancement in communication circuits.

Classification of Filters

An electric filter is usually a frequency-selective network that passes a specified band of frequencies and blocks or attenuates signals of frequencies outside this band. Filters may classified in a
number of ways as follows:

requency (AF) or radio-frequency (RF) filters.

Depending on the type of techniques used in the process of analog signals the filters may be analog or digital. Analog filters are designed to process analog signal using analog techniques, while digital filters process analog signals using digital techniques.
Depending on the type of elements used in their construction, filters may be passive or active. A

passive filter is built with passive components such as resistors, capacitors and inductors. Active filters, on the other hand, make use of transistors or op- amps (providing voltage amplification, and signal isolation or buffering) in addition to resistors and capacitors. The type of elements used dictates the operating frequency range of thefilter..

According to the operating frequency range, the filters may be classified as audio frequency (AF) or radio-frequency (RF)filters.

Filters may also be classified as

- Low-pass,
- High-pass
- Band-pass
- Band stop and allpass.

The filter circuit may be so designed that some frequencies are passed from the input to the output of the filter with very littleattenuation while others are greatly attenuated.

Frequency Response Analysis of Different Types of Filters

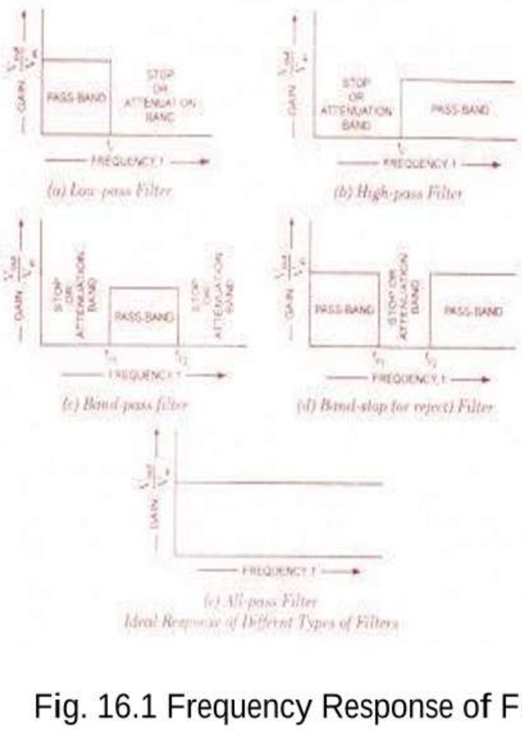



Fig. 16.1 Frequency Response of Filters

Figure 16.1 shows the frequency responses of the five types (mentioned above) of filters. These are ideal responses and cannot be achieved in, actual practice.

A filter that provides a constant output from dc upto a cut-off frequency fc and then passes no signal above that frequency is called an ideal low-pass filter. The ideal response of a low-pass filter is illustrated in fig. a. The voltage gain (the ratio of output voltage and input voltage, that is, Vout/Vin is constant over a frequency range from zero to cut-off frequency, fc. The output of any signal having a frequency exceeding fc will be attenuated i.e. there will be no output voltage for frequencies exceeding cut-off frequency fc. Hence output will be available faithfully from 0 to fc with constant gain, and is 0 from fc onward. The frequencies between 0 and f are, therefore, called the pass band frequencies, while the range of frequencies, those beyond fc, that are attenuated includes the stop band frequencies. The bandwidth (BW) is, therefore, fc.

A filter that provides or passes signals above a cut-off frequency is a high-pass filter, as idealized in fig.b. The high-pass filter has a zero gain starting from zero to a frequency fc, called the cut-off frequency, and above this frequency, the gain is constant, as illustrated in fig. b. Thus signal of any frequency beyond fc is faithfully reproduced with a constant gain, and frequencies from 0 to fc will beattenuated.

When the filter circuit passes signals that are above one cut-off frequency and below a second cut-off frequency, it is called a band-pass filter, as idealized in fig.c. Thus a band-pass filter has a pass band between two cut-off frequencies fc2 and fc1 where fc2> fcl and two stop-bands: 0 < f< fcl and f> fc2. The bandwidth of the band-pass filter is, therefore, equal to fc2 – fcl where fcl and fc2 are lower and higher cut-off frequenciesrespectively.

The band-stop or band-reject filter performs exactly opposite to the band-pass i.e. it has a band stop between two cut-off frequencies fc2 and fcl and two pass bands : 0 < f < fc1 and f> fc2. The ideal response of a band-stop filter is illustrated in fig. d. This is also called a band-elimination or notchfilter.

The ideal response of an all-pass filter is shown in fig. e.This filter passes all frequencies equally well, i.e., output andinput voltagesareequalinamplitudeforallfrequencies.Theimportant featureofthisfilteristhatitprovidespredictablephaseshiftfor frequencies of different input signals.

LOW PASS FILTERS

By definition, a low-pass filter is a circuit offering easy passage to low-frequency signals and difficult passage to high-frequency signals. The two circuits behave the same way for the most part, but there are some important differences. Both circuits operate as low-pass filters. That is, they will readily transmit signals below a certain frequency from input to output, with no appreciable loss in signal amplitude. (fig 16.2)
The first circuit shows a resistor and a capacitor, connected as a voltage divider. We have already looked at the behavior of this circuit with a single input frequency. The question now is, how does it behave for a range of frequencies?

One thing we can note at once: at very low frequencies, XC will be quite large, so C will have no practical effect on the signal. In essence, there will only be R in series with the signal, between vIN and vOUT. At the same time, C does provide dc isolation from ground. Sometimes this is important.

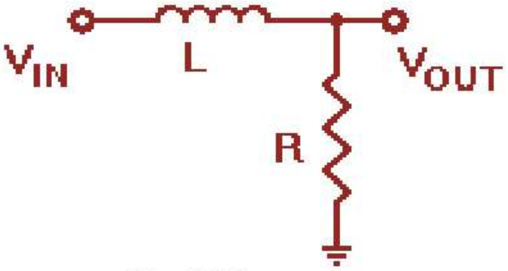



Fig. 16.2

Our second circuit on the right is a low-pass RL filter. At low frequencies, the series inductance has negligible effect on the signal, and we essentially have a resistor connecting the signal line to ground. This is often designated a shunt resistance, indicating that it is in parallel with thesignal.

As the frequency increases, XL also increases, thus increasing the total impedance of the filter. Since R doesn't change, more and more of the signal is dropped across L at higher frequencies, leaving less and less across R and available at vOUT.

At audio frequencies, the RC filter is generally preferred. This has nothing to do with any inherent benefit or lack of one circuit over the other, but rather is strictly a question of cost. Inductors for the audio frequency band are generally physically large and have heavy iron cores. This makes them expensive, and also causes them to take up a lot of space inside the cabinet of the device using it. In addition, inductors can be affected by external magnetic fields, such as the fields surrounding all power lines in homesandoffices.Capacitorsaremuchsmaller,lighter,cheaper, and less susceptible to external energies, so they are used far more often.

HIGH-PASS FILTER

A high-pass filter circuit passes all currents having a frequency higher than a specified frequency, while opposing all currents having a frequency lower than its specified frequency. This is illustrated in figure 16.3. A capacitor that is used in series with the source of both high and low frequencies, as shown in view (A) of figure 16.4, will respond differently to high-frequency, low- frequency, and direct currents. It will offer little opposition to the passage of high-frequency currents, great opposition to the passage of low-frequency currents, and completely block direct currents. The value of the capacitor must be chosen so that it allows the passage of all currents having frequencies above the desired value, and opposes those having frequencies below the desired value. Then, in order to shunt the undesired low-frequency currentsbacktothesource,aninductorisused,asshowninview
(B) of fig 16.5. This inductor must have a value that will allow it to pass currents having frequencies below the frequency cutoff point, and reject currents having frequencies above the frequency cutoff point, thus forcing them to pass through the capacitor. By combining inductance and capacitance, as shown in view (C)of fig 16.6, you obtain the simplest type of high-pass filter. At point P most of the high-frequency energy is passed on to the load by the capacitor, and most of the low-frequency energy is shunted back to the source through theinductor.

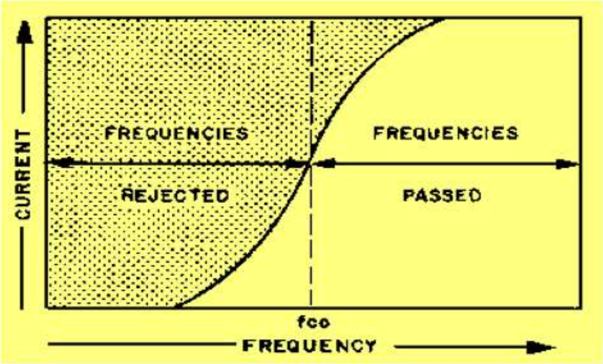



Fig. 16.3 High-pass filter response curve.

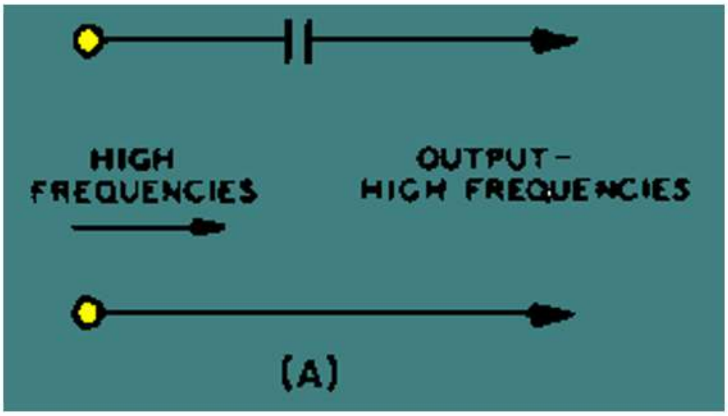



Fig. 16.4 - Components of a simple high-pass filter.

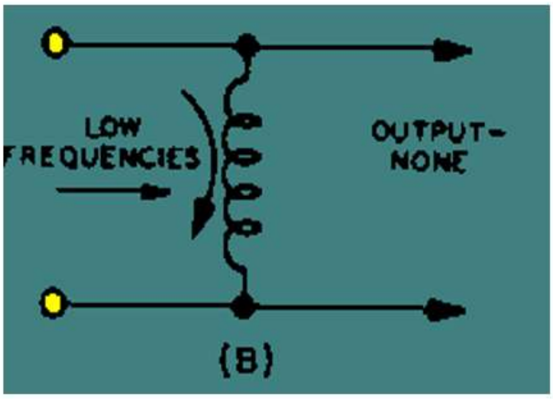



Fig. 16.5 Components of a simple high-pass filter.

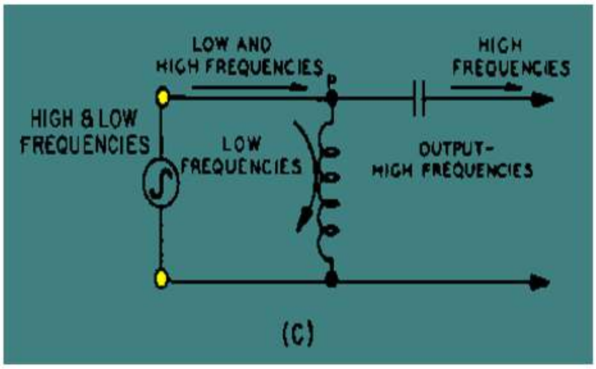



Fig. 16.6 Components of a simple high-pass filter.

## RESONANT CIRCUITS AS FILTERS

Resonant circuits can be made to serve as filters in a manner similar to the action of individual capacitors and inductors. As you know, the series-LC circuit offers minimum opposition to currents that have frequencies at or near the resonant frequency(cut-off), and maximum opposition to currents of all other frequencies.

You also know that a parallel-LC circuit offers a very high impedance to currents that have frequencies at or near the resonant frequency, and a relatively low impedance to currents of all otherfrequencies.

If you use these two basic concepts, the BANDPASS and BAND- REJECT filters can be constructed. The band pass filter and the band-reject filter are two common types of filters that use resonant circuits.

### Band pass Filter

A band pass filter passes a narrow band of frequencies through a circuit and attenuates all other frequencies that are higher or lower than the desired band of frequencies. This is shown in figure 16.7 where the greatest current exists at the center frequency (fr). Frequencies below resonance (f1) and frequencies above resonance (f2) drop off rapidly and arerejected.

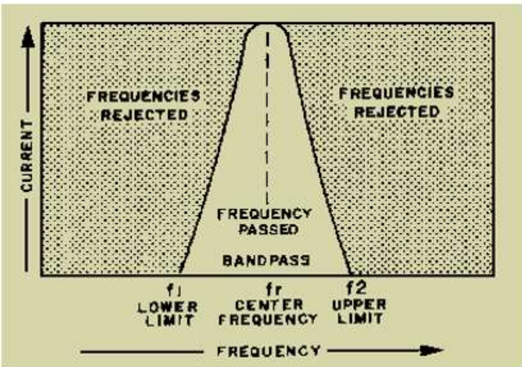



Fig. 16.7 Band pass filter response curve.

In the circuit of figure, view (A), the series-LC circuit replaces the inductor of figure 16.8, view (A), and acts as a BANDPASS filter. It passes currents having frequencies at or near its resonant frequency, and opposes the passage of all currents having frequencies outside this band.

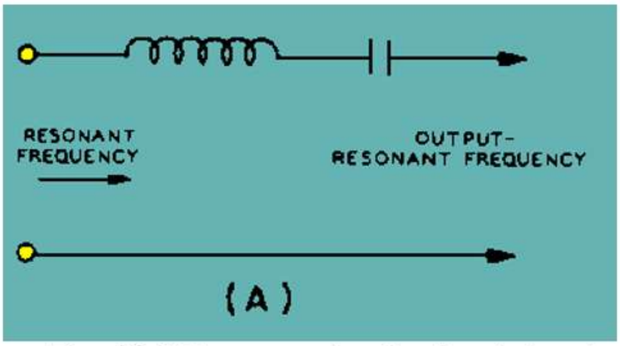



Fig. 16.8 Components of a simple band pass filter.

Thus, in the circuit of figure 16.9, view (B), the parallel-LC circuit replaces the capacitor of figure16.9, view (B). If this circuit is tuned to the same frequency as the series-LC circuit, it will provide a path for all currents having frequencies outside the limits of the frequency band passed by the series-resonant circuit. The simplest type of band pass filter is formed by connecting the two LC circuits as shown in figure 16.10, view (C ). The upper and lower frequency limits of the filter action are filter cutoff points.

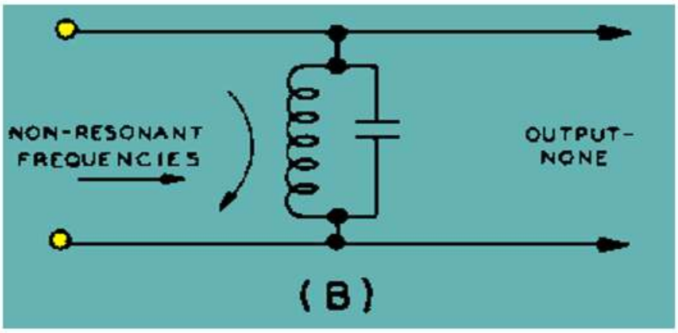



Fig. 16.9 Components of a simple band passfilter.

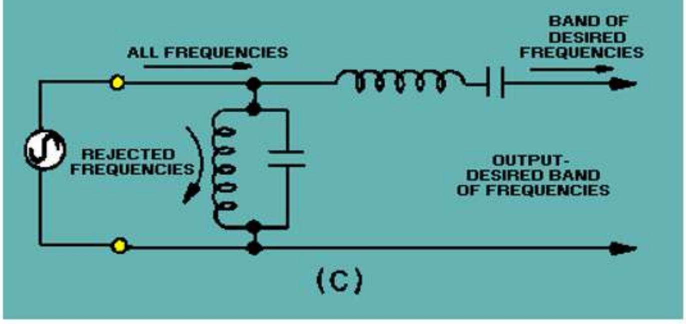



Fig. 16.10 Components of a simple band passfilter.

Band-Reject Filter

A band-reject filter circuit is used to block the passage of current for a narrow band of frequencies, while allowing current to flow at all frequencies above or below this band. This type of filter is also known as a BAND-SUPPRESSION or BAND-STOP filter. The way it responds is shown by the response curve offigure

16.11. Since the purpose of the band-reject filter is directly opposite to that of a band pass filter, the relative positions of the resonant circuits in the filter are interchanged. The parallel-LC circuit shown in figure 16.12, view (A), replaces the capacitor of figure 16.12, view (A). It acts as a band-reject filter, blocking the passage of currents having frequencies at or near resonant frequency and passing all currents having frequencies outside this band. The series-LC circuit shown in figure 16.13, view (B), replaces the inductor of figure, view (B). If this series circuit is tuned, to the same frequency as the parallel circuit, it acts as a bypass for the band of rejected frequencies. Then, the simplest type of band-reject filter is obtained by connecting the two circuits as shown in figure 16.15, view (C).

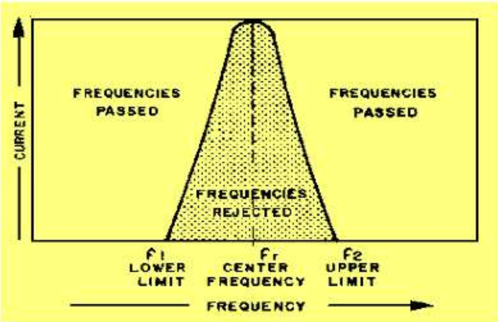



Fig 16.11

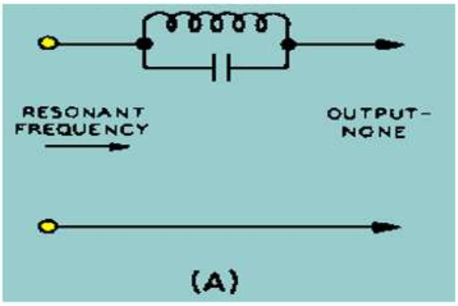



Fig. 16.12 Band-reject filter response curve.

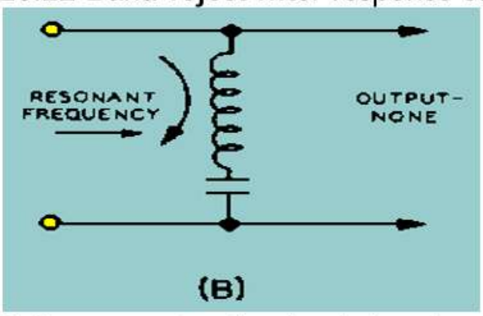



Fig. 16.13 Components of a simple band-rejectfilter.

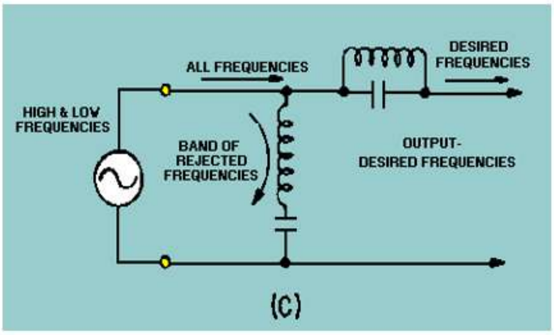



Fig. 16.14 Components of a simple band-rejectfilter.

AC Generators

INTRODUCTION

A.C.generatorsoralternators(astheyareusuallycalled)operate onthesamefundamentalprinciplesofelectromagneticinduction as D.C. generators.

Alternating voltage may be generated by rotating a coil in the magnetic field or by rotating a magnetic field within a stationary coil (fig 17.1). The value of the voltage generated depends on-

- The number of turns in thecoil.
- Strength of the field.
- The speed at which the coil or magnetic field rotates.

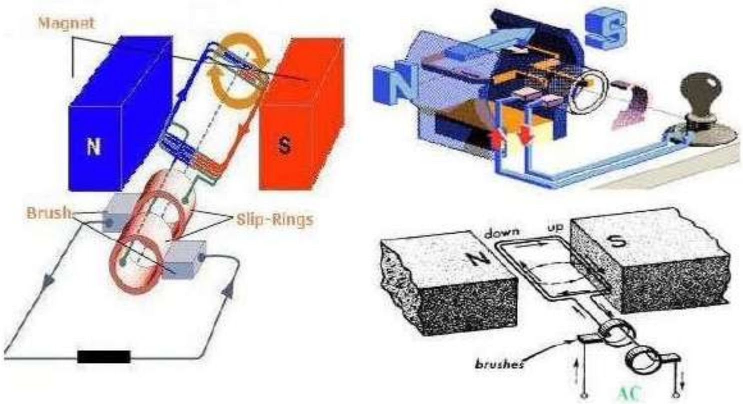



Fig. 17.1

WORKING OF AC GENERATOR

An Electrical Generator is a device that produces an Electromotive Force (e.m.f.) by changing the number of Magnetic Flux Lines (Lines of Force), Φ, passing through a Wire Coil. Figure17.2 is one type of Generator. When the Coil is rotated between the Poles of the Magnet by cranking the handle, an AC Voltage Waveform isproduced.

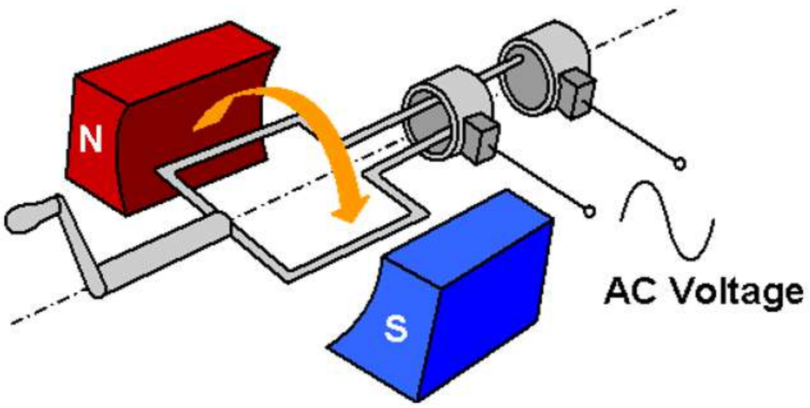



Fig. 17.2 Electrical Generator

Operation principle of a Generator is based on Electromagnetic Induction, which is defined by Faraday's Law, which states:

The Electromotive Force, Eemf, induced in a Coil is proportional to the number of turns, N, in the Coil and the Rate of Change, dΦ / dt, of the number of Magnetic Flux Lines, Φ, passing through the surface (A) enclosed by the Coil.

An Induced Effect is always such as to Oppose the cause that produced it.

In the Generator, the Coil is under a Stationary Magnetic Field. The Magnetic Flux Density, B, is constant and Φ = B x Aeff, so Φ is proportional to the Effective Area, Aeff, of the Loop. As the Loop rotates at different angles, there is a change in Aeff which is shown in Figure 17.3 .

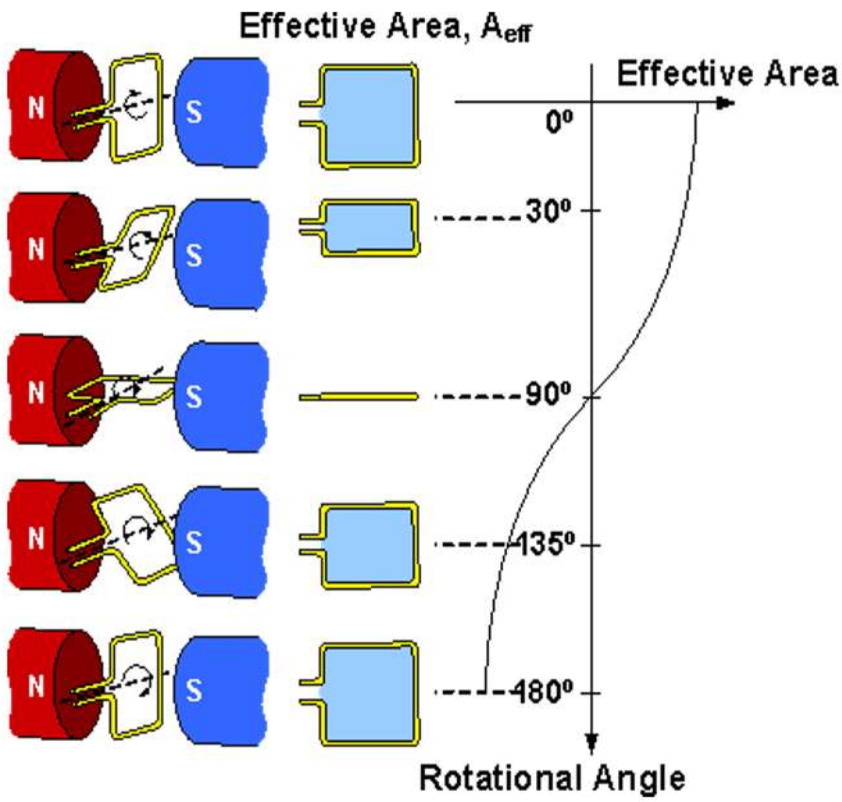



Fig. 17.3 Effective Area of the Wire Loop at Different Rotational Angles

The Rate of Change of Φ, dΦ / dt, is the largest at the zero points of the Waveform and is the smallest at the peaks of the Waveform, therefore the Induced Eemf is maximum at the zero points and minimum at the peaks, Figure 17.3. The Induced Eemf output by the Generator is an AC Voltage and its Waveform is shown in Figure17.4.

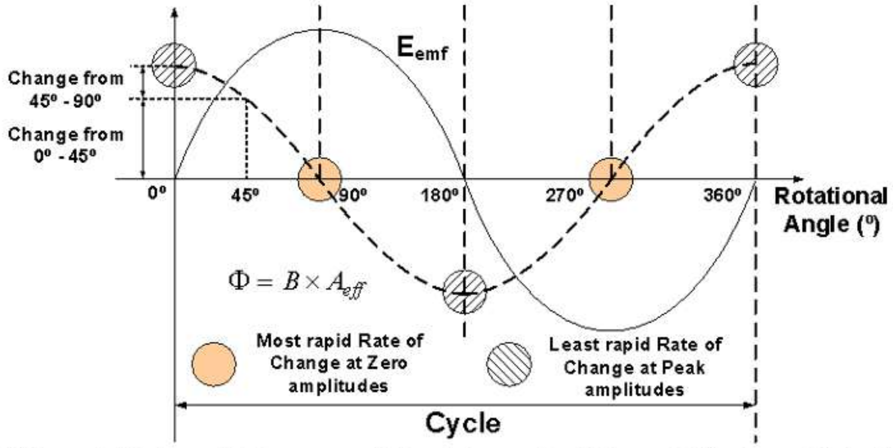



Fig. 17. 4 Different Rates of Change of the Magnetic Flux at Various Rotational Angles

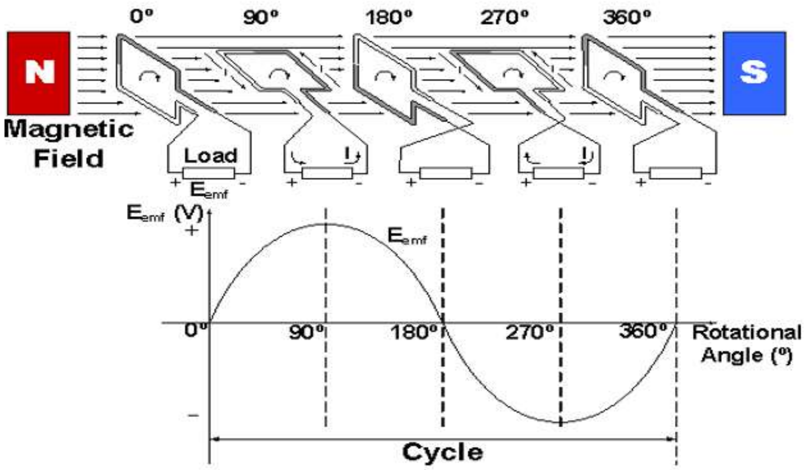



Fig. 17.5 Position of the Rotating Wire Coil Plane to the Magnetic Field Direction and the Induced Electromotive Force

ROTATING ARMATURE AC GENERATOR

Single-phase generator (also known as single-phasealternator)
is an alternating current electrical generator that produces asingle,
continuouslyalternatingvoltage.Single-phasegeneratorscanbe
usedtogeneratepowerinsingle-phaseelectricpowersystems.

Polyphase

However, polyphone generators are generally used todeliver
power in three-phase distribution system and the current is
converted to single-phase near the single-phase loads instead. Therefore, single-phase generators are found in applications that are most often used when the loads being driven are relatively light, and not connected to a three-phase distribution, for instance, portable engine-generators. Larger single-phase generators are also used in special applications such as single-phase tractionpower for railway electrification systems. (fig17.5)

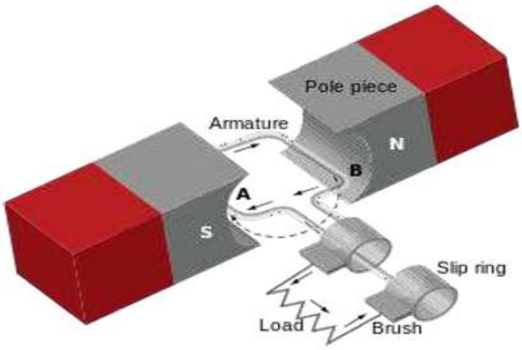
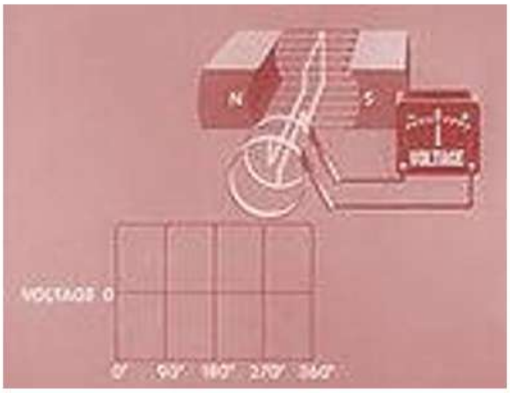



Fig. 17.5

Revolving armature

The design of revolving armature generators is to have the armature part on a rotor and the magnetic field part on stator. A basic design, called elementary generator, is to have a rectangular loop armature to cut the lines of force between the north and south poles. By cutting lines of force through rotation, it produces electrical current. The current is sent out of the generator unit through two sets of slip rings and brushes, one of which is used for each end of the armature. In this two-pole design, as the armature rotates one revolution, it generates one cycle of singlephase alternating current (AC). To generate an AC output, the armature is rotated at a constant speed having the number of rotations per second to match the desired frequency (in hertz) of the AC output.

Relationship of AC output and armature rotation




Armature at 0 degrees. Fig. 17.6

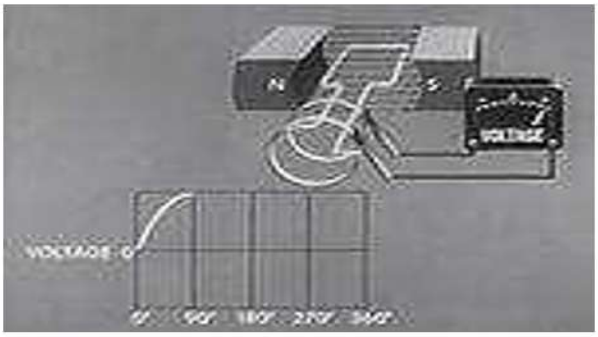



Fig. 17.7 Armature at 90 degrees.


Fig. 17.8 Armature at 180degrees.

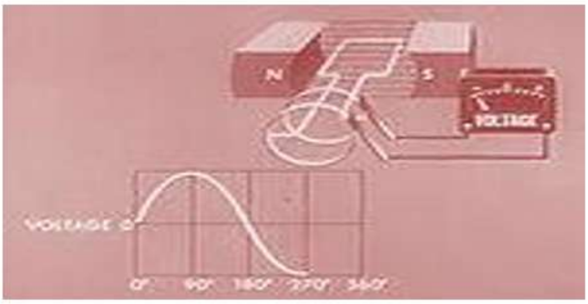



Fig. 17.9 Armature at 270degrees.

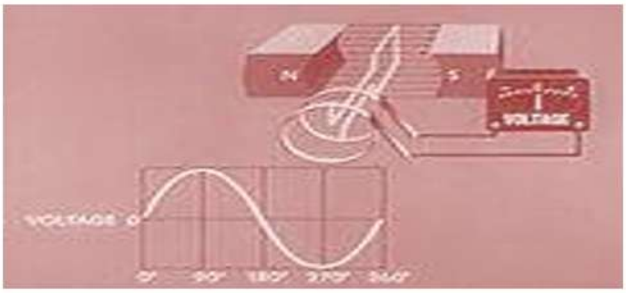



Fig. 17. 10 Armature at 360 degrees.

The relationship of armature rotation and the AC output can be seen in this series of pictures. Due to the circular motion of the armature against the straight lines of force, a variable number of lines of force will be cut even at a constant speed of the motion. At zero degrees (fig 17.6), the rectangular arm of the armature does not cut any lines of force, giving zero voltage output. As the armature arm rotates at a constant speed toward the 90° position (fig 17.7), more lines are cut. The lines of force are cut at most when the armature is at the 90° position, giving out the most current on one direction. As it turns toward the 180° position (fig 17.8), lesser number of lines of force are cut, giving out lesser voltage until it becomes zero again at the 180° position. The voltage starts to increase again as the armature heads to the opposite pole at the 270° position (fig 17.9). Toward this position, the current is generated on the opposite direction, giving out the maximum voltage on the opposite side. The voltage decrease again as it completes the full rotation. In one rotation, the AC output is produced with one complete cycle as represented in the sinewave.

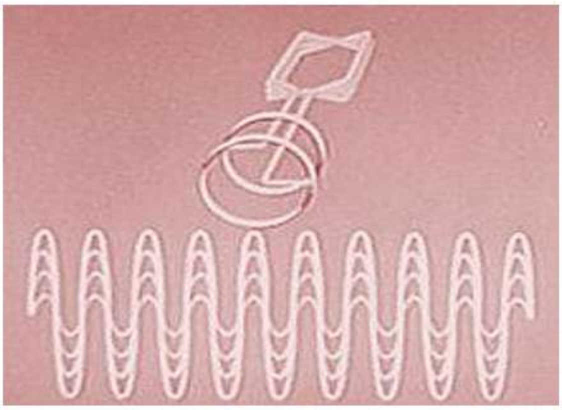


Fig. 17.11 Armature of revolving armature single-phase generator with 4 windings and its output sine wave.

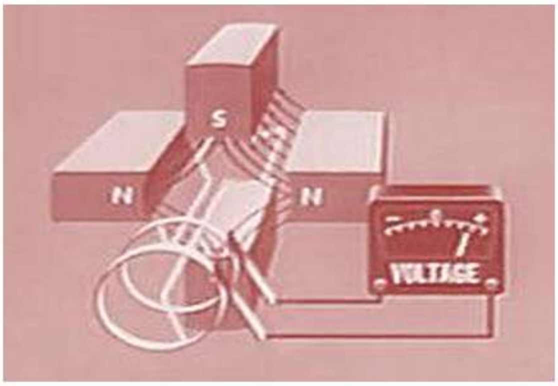



Fig. 17.12 Single phase generator with four poles

More poles can also be added to single-phase generator to allow one rotation to produce more than one cycle of AC output (fig 17.11). In an example on the left, the stator part is reconfigured to have 4 poles which are equally spaced. A north pole is adjacent to the two south poles. The shape of the armature at the rotor part is also changed. It is no longer a flat rectangle. The arm is bent 90 degrees. This allows one side of the armature to interact with a north pole while the other side interacts with a south pole similarly to the two-pole configuration. The current is still delivered out through the two sets of slip rings and brushes in the same fashion as in the two-pole configuration. The difference is that a cycle of AC output can be completed after a 180 degree rotation of the armature. In one rotation, the AC output will be two cycles. This increases the frequency of the output of the generator. More poles can be added to achieves higher frequency at the same rotation speed of the generator, or same frequency of output at the lower rotation speed of the generator depending on the applications. (fig17.12)

This design also allows us to increase the output voltage by modifying the shape of the armature. We can add more rectangular loops to the armature as seen on the picture on the right. The additional loops at the armature arm are connected in series, which are actually additional windings of the same conductor wire to form a coil in rectangular shape. In this example, there are 4 windings in the coil. Since the shapes of all windings are the same, the amount of the lines of force will be cut at the same amount in the same direction at the same time in all windings. This creates in phase AC output for these 4 windings. As a result, the output voltage is increased 4 time as shown in the sine wave in the diagram. (fig17.14)

Revolving field

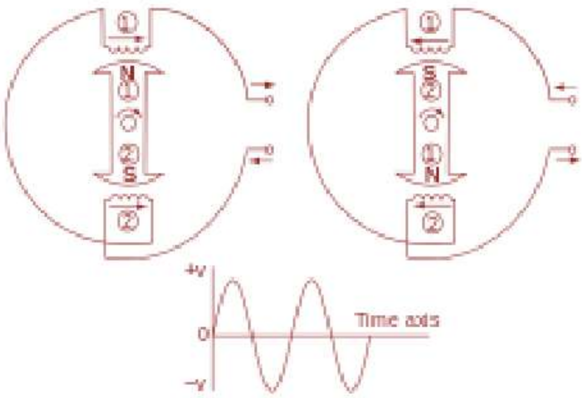



Fig. 17.13 Diagram of revolving field single-phase generator with two poles

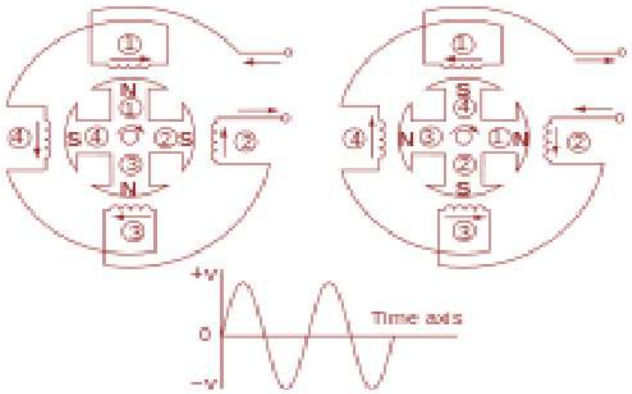



Fig. 17.14 Diagram of revolving field single-phase generator with four poles

The design of revolving field generators is to have the armature part on stator and the magnetic field part on rotor. A basic design of revolving field single-phase generator is shown on the right. There are two magnetic poles, north and south, attached to a rotor and two coils which are connected in series and equally spaced on stator. The windings of the two coils are in reverse direction to have the current to flow in the same direction because the two coils always interact with opposing polarities. Since poles and coils are equally spaced and the locations of the poles match to the locations of the coils, the magnetic lines of force are cut at the same amount at any degree of the rotor. As a result, the voltages induced to all windings have the same value at any given time. The voltages from both coils are "in phase" to each other. Therefore the total output voltage is two times the voltage induced in each winding. In the figure, at the position where pole number 1 and coil number 1 meet, the generator produces the highest output voltage on one direction. As the rotor turns 180 degrees, the output voltage is alternated to produce the highest voltage on the other direction. The frequency of the AC output in this case equals to the number of rotations of the rotor persecond.

This design can also allow us at increase the output frequency by adding more poles. In this example on the right, we have 4 coils connected in series at stator and the field on rotor has 4 poles. Both coils and poles are equally spaced. Each pole has opposite polarity to its neighbors which are angled at 90 degrees. Each coils also have opposite winding to its neighbors. This configuration allows the lines of force at 4 poles to be cut by 4 coils at the same amount at a given time. At each 90-degree rotation, the voltage output polarity is switched from onedirection to the other. Therefore, there are 4 cycles of the AC output in one rotation. As the 4 coils are wired in series and their outputs are "in phase", the AC output of this single-phase generator will have 4 times of voltages to the voltage generated by each coil.

A benefit of the revolving field design is that if the poles are permanent magnets, then there is no need to use any slip ring and brush to deliver electricity out of the generator as the coils are stationary and can be wired directly from the generator to the external loads.

AC GENERATOR COMPONENTS AND ITS FUNCTIONS (fig 17.15)

Field:The field in an AC generator consists of coils of conductors within the generator that receive a voltage from a source (called excitation) and produce a magnetic flux. The magnetic flux in the field cuts the armature to produce a voltage. This voltage is ultimately the output voltage of the AC generator.

Armature: The armature is the part of an AC generator in which voltage is produced. This component consists of many coils of wire that are large enough to carry the full- load current of thegenerator.

Prime Mover :The prime mover is the component that is used to drive the AC generator. The prime mover may be any type of rotating machine, such as a diesel engine, a steam turbine, or a motor.

Rotor The rotor of an AC generator is the rotating component of the generator, The rotor is driven by the generator's prime mover,

which may be a steam turbine, gas turbine, or diesel engine. Depending on the type of generator, this component may be the armature or the field. The rotor will be the armature if the voltage output is generated there; the rotor will be the field if the field excitation is appliedthere.

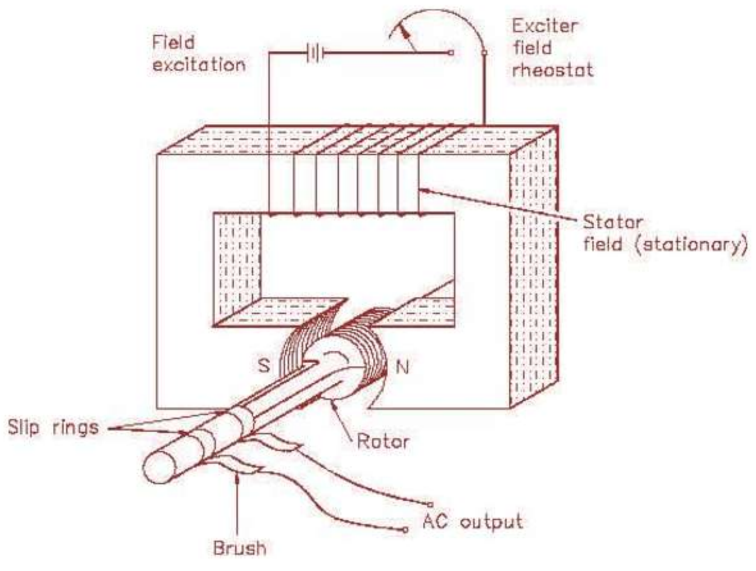



Fig. 17. 15

Stator The stator of an AC generator is the part that is stationary (refer to Figure 17.15 ). Like the rotor, this component may be the armature or the field, depending on the type of generator. The stator will be the armature if the voltage output is generated there; the stator will be the field if the field excitation is appliedthere.

Slip Rings Slip rings are electrical connections that are used to transfer power to and from the rotor of an AC generator (refer to Figure 17.15). The slip ring consists of a circular conducting material that is connected to the rotor windings and insulated from the shaft. Brushes ride on the slip ring as the rotor rotates. The electrical connection to the rotor is made by connections to the brushes. Slip rings are used in AC generators because the desired output of the generator is a sine wave. In a DC generator, a commutator was used to provide an output whose current always flowed in the positive direction, as shown in Figure. This is not necessary for an AC generator. Therefore, an AC generator may use slip rings, which will allow the output current and voltage to oscillate through positive and negative values. This oscillation of voltage and current takes the shape of a sinewave.

Comparison of AC and DC GENERATOR OUTPUT (fig 17.16 and fig 17.17)

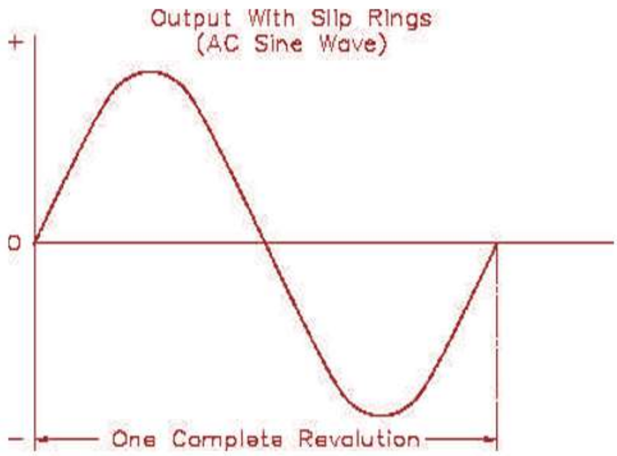



Fig.17.16

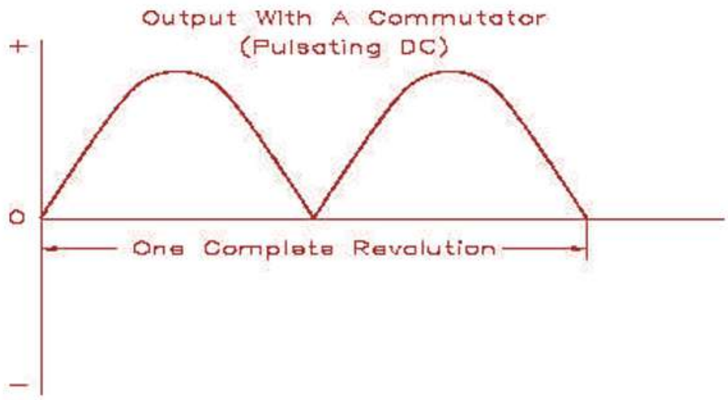



Fig.17.17

TWO PHASE AC GENERATOR

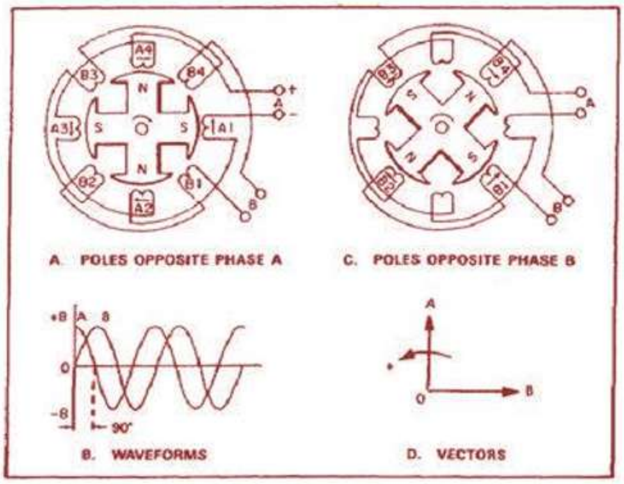


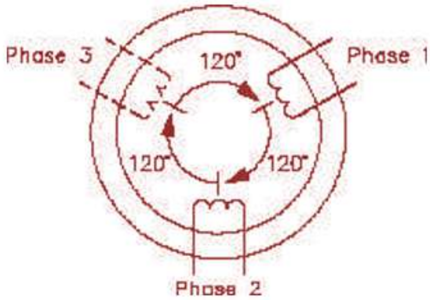

Fig. 17.18

Figure (17.18) above is a schematic diagram of a two-phase, four- pole, AC generator. The stator consists of two signal-phase windings (phases) completely separated from each other. Each phase is made up of four windings which are connected in series so that their voltages add. The rotor is identical to that used in the single-phase AC generator. In figure A, the rotor poles are opposite all of the coils in phase A. Therefore, the voltage induced in phase A is maximum, and the voltage induced in phase B is zero. As the rotor continues rotating in a clockwise direction, it moves away from the windings of phase A and approaches those in phase B. As a result, the voltage in phase A decreases from its maximum value and the voltage in phase B increases from zero. In figure B, the rotor poles are opposite the windings of phase B. Now the voltage induced in phase B is maximum, and the voltage induced in phase A has dropped to zero. Notice that in the four- pole AC generator, a 45 mechanical rotation ofthe rotor

corresponds electrically to one quarter cycle, or 90 degree. Fig C illustrates the voltage waveform in each of the two phases. Both are sine curves and A leads B by 90 degree.

THREE PHASE AC GENERATOR

The principles of a three-phase generator are basically the same as that of a single-phase generator, except that there are three equally-spaced windings and three output voltages that are all 120° out of phase with one another. Physically adjacent loops (Figure ) are separated by 60° of rotation; however, the loops are connected to the slip rings in such a manner that thereare
120 electrical degrees between phases. The individual coils of each winding are combined and represented asa
single coil. The significance of Figure 17.19 is that it shows that the three-phase generator has three separate armature windings that are 120 electrical degrees out ofphase.



Delta connection

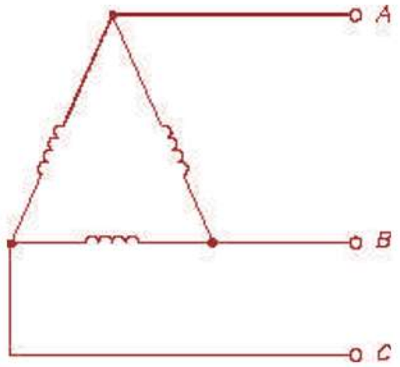
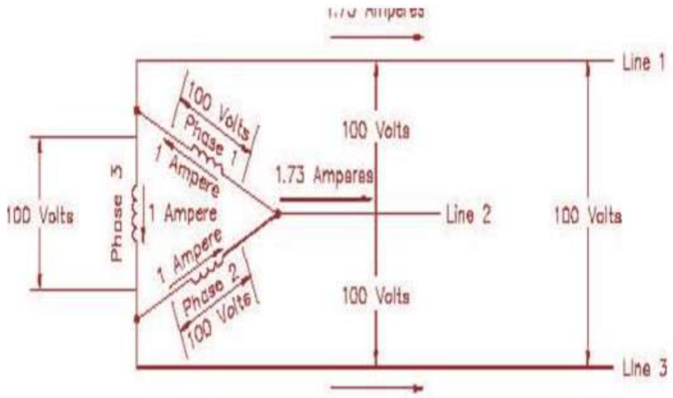



Fig. 17.20

Generator, and the output is connected to an external load. In actual practice, the windings are connected together, and only three leads are brought out and connected to the external load. Two means are available to connect the three armature windings. In one type of connection, the windings are connected in series, or delta-connected (D) (Figure 17.20). In a delta-connected generator, the voltage between any two of the phases, called line voltage, is the same as the voltage generated in any one phase. As shown in Figure 17.21, the three phase voltages are equal, as are the three line voltages. The current in any line is _3 times the phase current. You can see that a delta-connected generator providesanincreaseincurrent,butnoincreaseinvoltage




.

Fig. 17.21

The power consumed by the load connected in delta configuration will be three times as compared to star configuration.

WYE CONNECTION

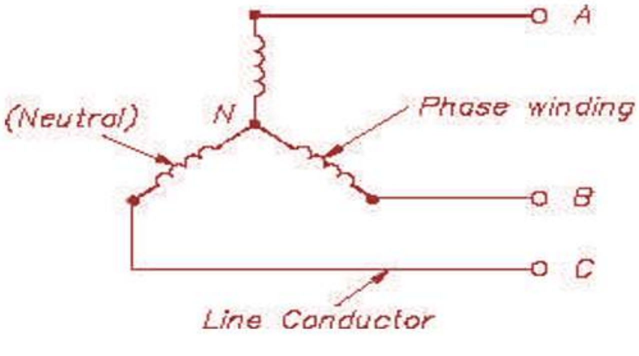


Fig. 17.22

In the other type of connection Wye/Star Connection, one of the leads of each winding is connected, and the remaining three leads are connected to an external load. This is called a wye connection (Y) (Figure17.22). The voltage and current characteristics of the wye-connected AC generator are opposite to that of the delta connection. Voltage between any two lines in a wye- connected AC generator is 1.73 (or) $\sqrt{3}$ times any one phase voltage, whileline currents are equal to phasecurrents. The wye-connectedACgeneratorprovidesanincreaseinvoltage,but no increase in current (Figure 17.23).

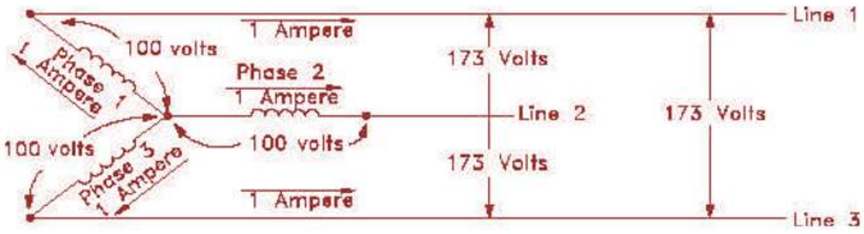



Fig. 17.23

An advantage of a wye-connected AC generator is that eachphase only has to carry 57.7% of line voltage and, therefore, can beused for high voltage generation.

## FREQUENCY OF AC GENERATOR

The output frequency of alternator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency. The lower the speed, the lower the frequency. The more poles there are on the rotor, the higher the frequency is for a given speed. (fig17.24)

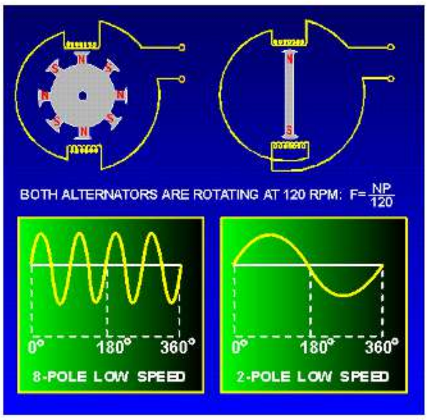



Fig. 17.24

When a rotor has rotated through an angle such that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle. For a given frequency, the more pairs of poles there are, the lower the speed of rotation. This principle is illustrated in figure above; a two-pole generator must rotate at four times the speed of an eight-pole generator to producethe

same frequency of generated voltage. The frequency of anyac generator in hertz (Hz), which is the number of cycles persecond, is related to the number of poles and the speed of rotation, as

Expressed by the equation where P is the number of poles, N is the speed of rotation in revolutions per minute (rpm), and 120 is a constant to allow for the conversion of minutes to seconds and from poles to pairs of poles. For example, a 2-pole, 3600-rpm alternator has a frequency of 60 Hz; determined as follows:

A 4-pole, 1800-rpm generator also has a frequency of 60 Hz. A 6- pole, 500-rpm generator has a frequency of

A 12-pole, 4000-rpm generator has a frequency of

## VOLTAGE REGULATION

As we have seen before, when the load on a generator is changed, the terminal voltage varies. The amount of variation depends on the design of the generator.

The voltage regulation of an alternator is the change of voltage from full load to no load, expressed as a percentage of full-load volts, when the speed and dc field current are held constant.

Assume the no-load voltage of an alternator is 250 volts and the full-load voltage is 220 volts. The percent of regulation is

Remember, the lower the percent of regulation, the better it is in most applications.

## FACTORS DETERMINING VOLTAGE OF AN AC GENERATOR

In an alternator, an alternating voltage is induced in the armature windings when magnetic fields of alternating polarity are passed across these windings. The amount of voltage induced in the windings depends mainly on three things: (1) the number of conductorsinseriesperwinding,(2)thespeed(alternatorrpm)at which the magnetic field cuts the winding, and (3) the strength of themagneticfield.Anyofthesethreefactorscouldbeusedto control the amount of voltage induced in the alternator windings.

The number of windings, of course, is fixed when the alternator is manufactured. Also, if the output frequency is required to be of a constant value, then the speed of the rotating field must be held

constant. This prevents the use of the alternator rpm as a means of controlling the voltage output.

Thus, the only practical method for obtaining voltage control is to control the strength of the rotating magnetic field. The strength of this electromagnetic field may be varied by changing the amount of current flowing through the field coil. This is accomplished by varying the amount of voltage applied across the field coil.

## PARALLEL OPERATION OF ALTERNATORS

without interrupting power distribution.

When alternators are of sufficient size, and are operating at different frequencies and terminal voltages, severe damage may result if they are suddenly connected to each other through a common bus. To avoid this, the machines must be synchronized as closely as possible before connecting them together. This may be accomplished by connecting one generator to the bus (referred to as bus generator), and then synchronizing the other (incoming generator) to it before closing the incoming generator's main power contactor. The generators are synchronized when the following conditions areset:

Equal terminal voltages. This is obtained by adjustment of the incoming generator's field strength.

Equal frequency. This is obtained by adjustment of the incoming generator's prime-mover speed.

Phase voltages in proper phase relation. The procedure for synchronizing generators is not discussed in this chapter. At this point, it is enough for you to know that the above must be accomplished to prevent damage to the machines. All aircraft ac equipment's are rated in Volt-Amps.

A. Dcvoltagewaveform C.none ofabove
B. AC voltagewaveform

## Module 3.18 AC Motors

### AC MOTOR INTRODUCTION

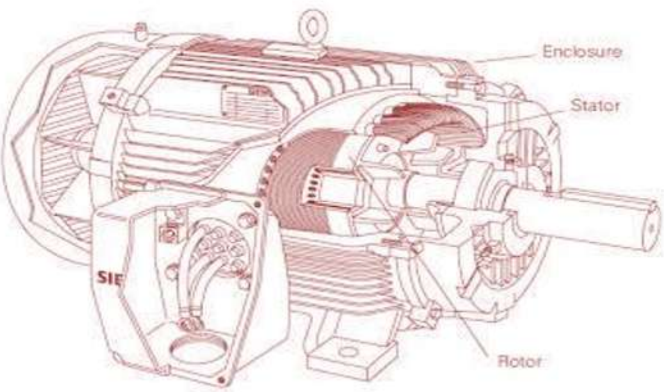



Fig. 18.1

AC motors are used worldwide in many applications totransform electrical energy into mechanical energy. There are many typesof AC motors, but three phase AC induction motors, is the most common type of motor used in industrial applications. An AC motor of this type may be part of a pump or fan or connected to some other form of mechanical equipment such as a winder, conveyor, or mixer. The electric motor in its simplest terms is a converter of electrical energy to useful mechanical energy. The electric motor has played a leading role in the high productivity of modern industry, and it is therefore directly responsible for the high standard of living being enjoyed throughout the industrialized world.

AC motors provide the motive power to lift, shift, pump, drive, blow, drill, and perform a variety of other tasks in industrial, domestic, and commercial applications. The induction motor, the most versatile of the AC motors, has truly emerged as the prime mover in industry, powering machine tools, pumps, fans, compressors, and a variety of industrial equipments.

### TYPES OF AC MOTORS

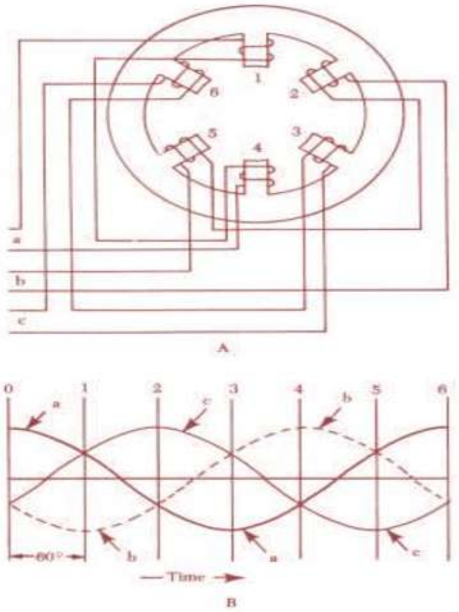
There are two general types of ac motors used in aircraft systems:
induction motors and synchronous motors. Either type may be single phase, two phase, or three phase. Three phase induction motors are used where large amounts of power are required. They operate such

devices as starters, flaps, landing gears, and hydraulic pumps. Single phase induction motors are used to operate devices such as surface locks, intercooler shutters, and oil shutoff valves in which the power requirement is low.

Three Phase Induction Motor

The three phase ac induction motor is also called a squirrel cage motor. Both single phase and three phase motors operate on the principle of a rotating magnetic field. A horseshoe magnet held over a compass needle is a simple illustration of the principle of the rotating field. The needle will take a position parallel to the magnetic flux passing between the two poles of the magnet. If the magnet is rotated, the compass needle will follow. A rotating magnetic field can be produced by a two or three phase current flowing through two or more groups of coils separated by $120_o$ wound on inwardly projecting poles of an iron frame. The coils on each group of poles are wound alternately in opposite directions to produce opposite polarity, and each group is connected to a separatephaseofvoltage.Theoperatingprincipledependsona revolving, or rotating, magnetic field to produce torque. Thekey tounderstandingtheinductionmotorisathoroughunderstanding of the rotating magnetic field.

Rotating Magnetic Field



Rotating magnetic field developed by application of three-phase voltages.

Figure 18.2

The field structure shown in A of figure 18.2 has poles whose windings are energized by three ac voltages, a, b, and c. These

voltages have equal magnitude but differ in phase, as shown in B of figure 18.2 At the instant of time shown as 0 in B of figure 18.2, the resultant magnetic field produced by the application of the three voltages has its greatest intensity in a direction extending from pole 1 to pole 4. Under this condition, pole 1 can be considered as a north pole and pole 4 as a southpole.

At the instant of time shown as 1, the resultant magnetic field will have its greatest intensity in the direction extending from pole 2 to pole 5; in this case, pole 2 can be considered as a north pole and pole 5 as a south pole. Thus, between instant 0 and instant 1, the magnetic field has rotated clockwise.

At instant 2, the resultant magnetic field has its greatest intensity in the direction from pole 3 to pole 6, and the resultant magnetic field has continued to rotate clockwise.

At instant 3, poles 4 and 1 can be considered as north and south poles, respectively, and the field has rotated still farther.

At later instants of time, the resultant magnetic field rotates to other positions while traveling in a clockwise direction, a single revolution of the field occurring in one cycle. If the exciting voltages have a frequency of 60 cps, the magnetic field makes 60 revolutions per second, or 3,600 rpm. This speed is known as the synchronous speed of the rotating field.

Construction of Induction Motor

The stationary portion of an induction motor is called a stator, and the rotating member is called a rotor. Instead of salient poles in the stator, as shown in A of figure 18.3, distributed windings are used; these windings are placed in slots around the periphery of thestator.

It is usually impossible to determine the number of poles in an induction motor by visual inspection, but the information can be obtained from the nameplate of the motor. The nameplate usually gives the number of poles and the speed at which the motor is designed to run. This rated, or nonsynchronous, speed is slightly less than the synchronous speed. To determine the number of poles per phase on the motor, divide 120 times the frequency by the rated speed; written as an equation:

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

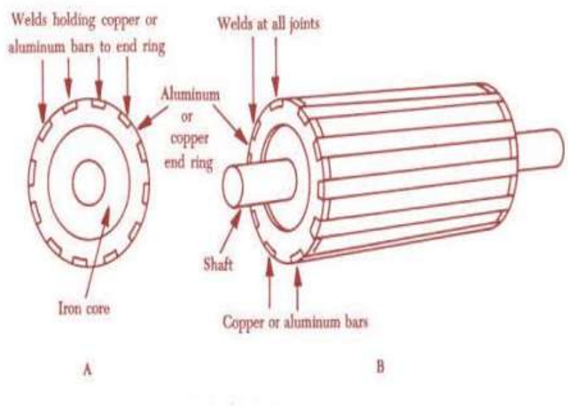
Where: P is the number of poles per phase, f is the frequency in cps, N is the rated speed in rpm, and 120 is a constant.

The result will be very nearly equal to the number of poles per phase. For example, consider a 60 cycle, three phase motor with a rated speed of 1,750 rpm. In this case:

$$P = \frac{120 \times 60}{1750} = \frac{7200}{1750} = 4.1$$

The rotor of an induction motor consists of an iron core having longitudinal slots around its circumference in which heavy copper or aluminum bars are embedded. These bars are welded to a heavy ring of high conductivity on either end.

The composite structure is sometimes called a squirrel cage,and motors containing such a rotor are



called squirrel cage induction motors. (See figure18.3)

Fig. 18.3 Squirrel – cage rotor for an a.c. induction motor

## Induction Motor Slip

When the rotor of an induction motor is subjected to the revolving magnetic field produced by the stator windings, a voltage is induced in the longitudinal bars. The induced voltage causes a current to flow through the bars. This current, in turn, produces its own magnetic field which combines with the revolving field so that the rotor assumes a position in which the induced voltage is minimized. As a result, the rotor revolves at very nearly the synchronous speed of the stator field, the difference in speed being just sufficient enough to induce the proper amount of current in the rotor to overcome the mechanical and electrical losses in the rotor.

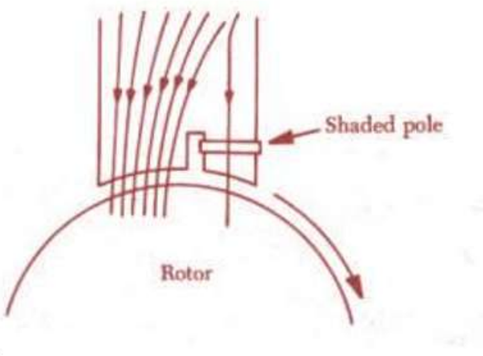
## Single Phase Induction Motor

The previous discussion has applied only to polyphone motors. A single phase motor has only one stator winding. This winding generates a field which merely pulsates, instead of rotating. When the rotor is stationary, the expanding and collapsing stator field induces currents in the rotor. These currents generate a rotor field opposite in polarity to that of the stator. The opposition of the field exerts a turning force on the upper and lower parts of the rotor trying to turn it 180° from its position. Since these forces are exerted through the center of the rotor, the turning force is equal in each direction. As a result, the rotor does not turn. If the rotor is started turning, it will continue to rotate in the direction in which it is started, since the turning force in that direction is aided by the momentum of therotor.

## Shaded Pole Induction Motor

The first effort in the development of a self-starting, single phase motor was the shaded pole induction motor (figure 18.4). This motor has salient poles, a portion of each pole being encircled by a heavy copper ring. The presence of the ring causes themagnetic

field through the ringed portion of the pole face to lag appreciably behind that through the other part of the pole face. The net effect is the production of a slight component of rotation of the field, sufficient to cause the rotor to revolve. As the rotor accelerates, the torque increases until the rated speed is obtained. Such motors have low starting torque and find their greatest application in small fan motors




where the initial torque required islow.

Figure 18.4 Diagram of a shaded – pole motor.

In figure 18.4, a diagram of a pole and the rotor is shown. The poles of the shaded pole motor resemble those of a dc motor. A low resistance, short circuited coil or copper band is placed across one tip of each small pole, from which, the motor gets the name of shaded pole. The rotor of this motor is the squirrel cage type.

As the current increases in the stator winding, the flux increases. A portion of this flux cuts the low resistance shading coil. This induces a current in the shading coil, and by Lenz's law, the current sets up a flux which opposes the flux inducing the current. Hence, most of the flux passes through the unshaded portion of the poles, as shown in figure18.4.

When the current in the winding and the main flux reaches a maximum, the rate of change is zero; thus, no e.m.f. is induced in the shading coil. A little later, the shading coil current, which causes the induced e.m.f. to lag, reaches zero, and there is no opposing flux. Therefore, the main field flux passes through the shaded portion of the field pole.

The main field flux, which is now decreasing, induces a current in the shading coil. By Lenz's law, this current sets up a flux which opposes the decrease of the main field flux in the shaded portion of the pole. The effect is to concentrate the lines of force in the shaded portion of the poleface.

In effect, the shading coil retards, in time phase, the portion of the flux passing through the shaded part of the pole. This lag in time phase of the flux in the shaded tip causes the flux to produce the effect of sweeping across the face of the pole, from left to right in the direction of the shaded tip. This behaves like a very weak rotating magnetic field, and sufficient torque is produced to start a small motor.

The starting torque of the shaded pole motor is exceedingly weak, and the power factor is low. Consequently, it is built in sizes suitable for driving such devices as small fans.

Split Phase Motor

There are various types of self starting motors, known as split phase motors. Such motors have a starting winding displaced 90 electrical degrees from the main or running winding. In some types, the starting winding has a fairly high resistance, which causes the current in this winding to be out of phase with the current in the running winding. This condition produces, in effect, a rotating field and the rotor revolves. A centrifugal switch

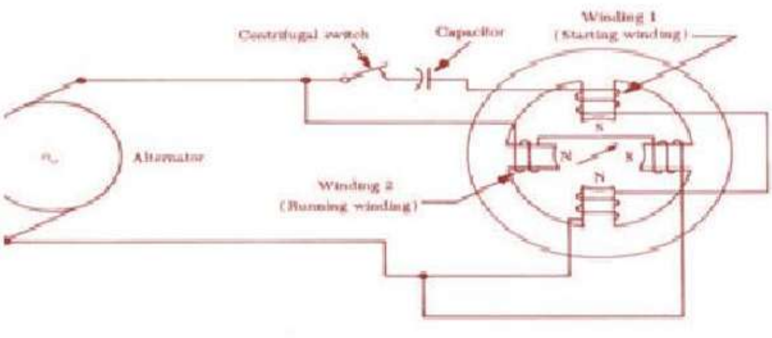



Fig. 18.5 Single – phase motor with capacitor starting winding

With the development of high capacity electrolytic capacitors, a variation of the split phase motor, known as the capacitor start motor, has been made. Nearly all fractional horsepower motors in use today on refrigerators, oil burners, and other similar appliances are of this type. (See figure 18.5) In this adaptation, the starting winding and running winding have the same size and resistance value. The phase shift between currents of the two windingsisobtainedbyusingcapacitorsconnectedinserieswith the starting winding.

Although some single phase induction motors are rated as high as 2 hp (horsepower), the major field of application is 1 hp, or less, at a voltage rating of 115 volts for the smaller sizes and 110 to 220 volts for one-fourth hp and up. For even larger power ratings, poly phase motors generally are used, since they have excellent starting torquecharacteristics.

## Direction of Rotation of Induction Motors

The direction of rotation of a three phase induction motor can be changed by simply reversing two of the leads to the motor. The same effect can be obtained in a two phase motor by reversing connections to one phase. In a single phase motor, reversing connections to the starting winding will reverse the direction of rotation. Most single phase motors designed for general application have provision for readily reversing connections to the starting winding. Nothing can be done to a shaded pole motor to reverse the direction of rotation because the direction is determined by the physical location of the copper shading ring.

## Synchronous Motor

The synchronous motor is one of the principal types of ac motors that rotate at the same speed as the supply frequency. Like the induction motor, the synchronous motor makes use of a rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction of currents in the rotor. Briefly, the principle of operation of the synchronous motor isasfollows:Amultiphasesourceofacisappliedtothestator windings, and a rotating magnetic field is produced. A direct current is applied to the rotor winding, and another magnetic field is produced. The synchronous motor is so designed and constructedthatthesetwofieldsreacttoeachotherinsucha manner that the rotor is dragged along and rotates at the same speed as the rotating magnetic field produced by the stator windings.

An understanding of the operation of the synchronous motor can be obtained by considering the simple motor of figure 18.6. Assume that poles A and B are being rotated clockwise by some mechanical means in order to produce a rotating magnetic field, they induce poles of opposite polarity in the soft iron rotor, and forces of attraction exist between corresponding north and south poles.

Consequently, as poles A and B rotate, the rotor is dragged along at the same speed. However, if a load is applied to the rotor shaft, the rotor axis will momentarily fall behind that of the rotating field but, thereafter, will continue to rotate with the field at the same speed, as long as the load remains constant. If the load is too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate with the field at the same speed. The motor is then said to beoverloaded.

Such a simple motor as that shown in figure 18.7 is never used. The idea of using some mechanical means of rotating the poles is impractical because another motor would be required to perform this work. Also, such an arrangement is unnecessary because a rotating magnetic field can be produced electrically by using phased ac voltages. In this respect, the synchronous motor is similar to the induction motor.

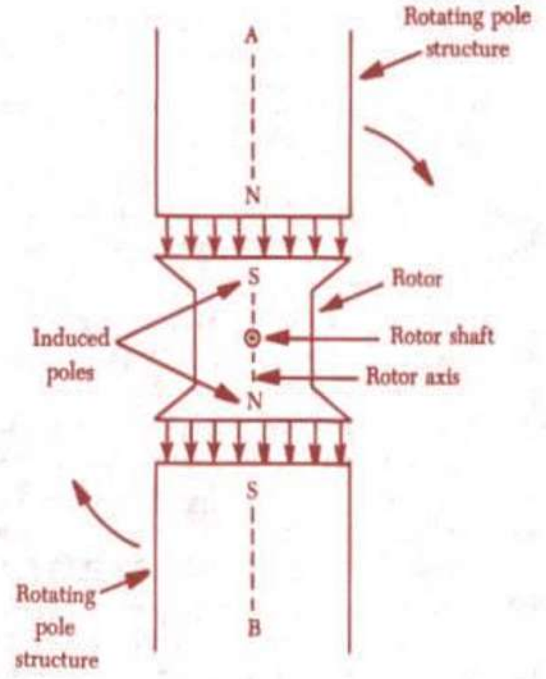



Fig. 18.6

The synchronous motor consists of a stator field winding similar to that of an induction motor. The stator winding produces a rotating magnetic field. The rotor may be a permanent magnet, as in small single phase synchronous motors used for clocks and other small precision equipment, or it may be an electromagnet, energized from a dc source of power and fed through slip rings into the rotor field coils, as in an alternator. In fact, an alternator may be operated either as an alternator or a synchronousmotor.

Sinceasynchronousmotorhaslittlestartingtorque,somemeans
must be provided to bring it up to synchronous speed. The most common method is to start the motor at no load, allow it to reach full speed, and then energize the magnetic field. The magnetic field of the rotor locks with the magnetic field of the stator andthe motor operates at synchronous speed.

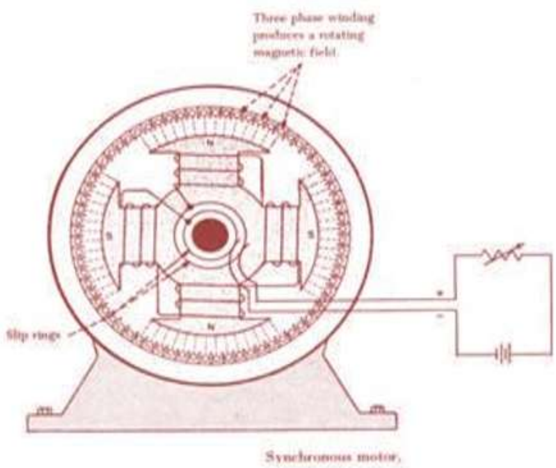



Fig. 18.7

The magnitude of the induced poles in the rotor shown in figure 18.7 is so small that sufficient torque cannot be developed for most practical loads. To avoid such a limitation on motoroperation, a winding is placed on the rotor and energized with dc. A rheostat placed in series with the dc source provides the operator of the machine with a means of varying the strength of the rotor poles, thus placing the motor under control for varying loads.

The synchronous motor is not a self starting motor. The rotor is heavy and, from a dead stop, it is impossible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all Synchronousmotorshavesomekindofstartingdevice.Onetype Of simple starter is another motor, either ac or dc, which brings the rotor up to approximately 90 percent of its synchronous speed. The starting motor is then disconnected, and the rotor locks in step with the rotating field. Another starting method is a second winding of the squirrel cage type on the rotor. This induction winding brings the rotor almost to synchronous speed, and when thedcisconnectedtotherotorwindings,therotorpullsintostep With the field. The latter method is the more commonly used.

AC Series Motor

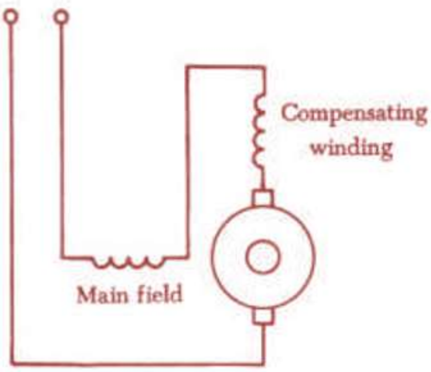



Fig. 18.8

An alternating current series motor is a single phase motor (fig 18.8), but is not an induction or synchronous motor. It resembles a dc motor in that it has brushes and a commutator. The ac series motor will operate on either ac or dc circuits. It will be recalled that the direction of rotation of a dc series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a dc series motor is connected to an ac source, a torque will be developed which tends to rotate the armature in one direction.

However, a dc series motor does not operate satisfactorily from an ac supply for the following reasons:

1. The alternating flux sets up large eddy current and hysteresis losses in the unlaminated portions of the magnetic circuit and causes excessive heating andreduced Efficiency.

1. The eddy current losses are reduced by laminating the field Poles, frame and armature.

Causes excessive sparking at the commutator.

To design a series motor for satisfactory operation on ac, the Following changes are made:

If the compensating winding is designed as shown in figure 18.10, the armature is inductively compensated. If the motor is designed for operation on both dc and ac circuits, the compensating winding is connected in series with thearmature.

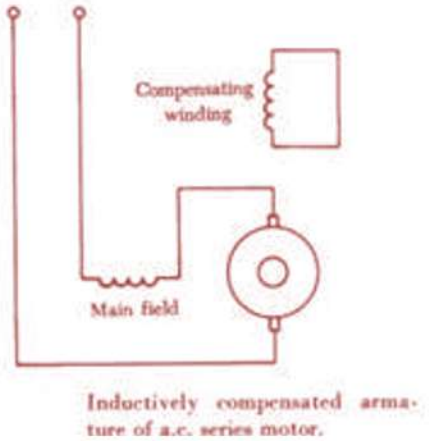



Fig. 18.9

The axis of the compensating winding is displaced from the main field axis by an angle of 90°. This arrangement is similar to the compensating winding used in some dc motors and generators to over come armature reaction.

The compensating winding establishes a counter magneto motive force, neutralizing the effect of the armature magneto motive force, preventing distortion of the main field flux, and reducing the armature reactance. The inductively compensated armature acts like the primary of a transformer, the secondary of which is the shorted compensatingwinding.

The shorted secondary receives an induced voltage by the action of the alternating armature flux, and the resulting current flowing through the turns of the compensating winding establishes the opposing magneto motive force, neutralizing the armature reactance.

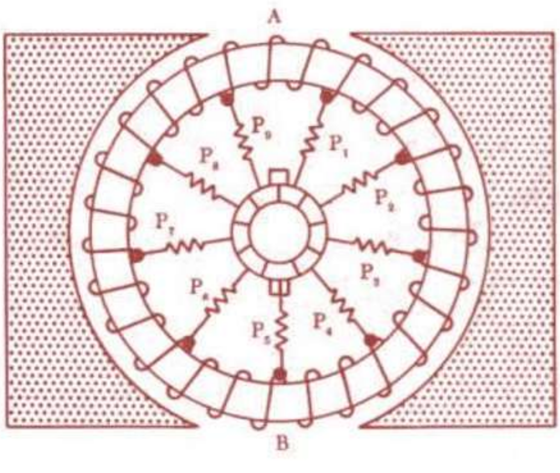



Fig. 18.10

SPEED CONTROLOF AC MOTOR

The speed of induction motors is dependent on motor design. The synchronous speed (the speed at which the stator field rotates) is determined by the frequency of the input ac power and the number of poles in the stator. The greater the number of poles, the slower the synchronous speed. The higher the frequency of applied voltage, the higher the synchronous speed. Remember, however, that neither

frequency nor number of poles are variables. They are both fixed by the manufacturer.
The relationship between poles, frequency, and synchronous Speed is as follows:

N = 120 f/p

Where n is the synchronous speed in rpm, f is the frequency of applied voltage in hertz, and p is the number of poles in the stator.

## DIRECTION REVERSAL OF INDUCTION MOTOR

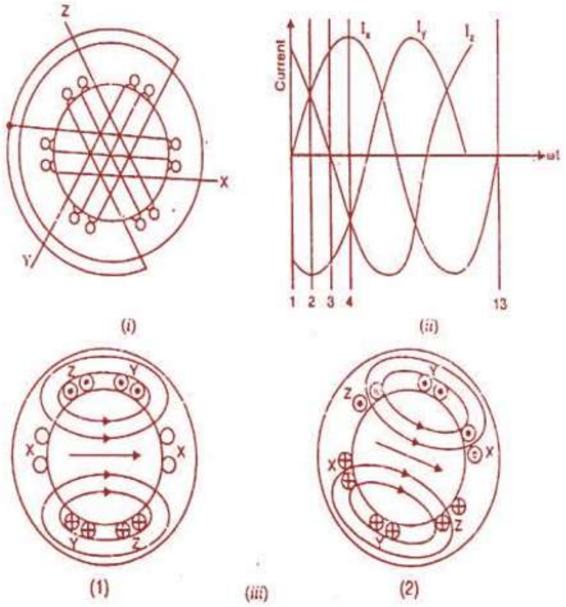



Fig. 18.11

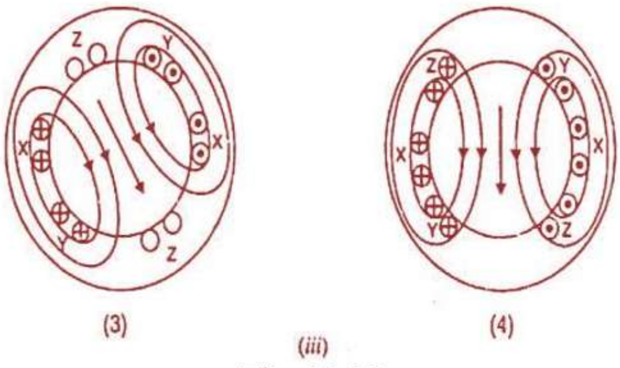



Fig. 18.12

The phase sequence of the three-phase voltage applied to the stator winding in Fig.18.12(ii)) is X-Y-Z. If this sequence is changed to X-Z-Y, it is observed that direction of rotation of the field is reversed i.e., the field rotates counterclockwise rather than clockwise. However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines. As we shall see, the rotor in a 3-phase induction motor runs in the same direction as the rotating magnetic field. Therefore, the direction of rotation of a 3-phase induction motor can be reversed by interchanging any two of the three motor supplylines.