N4 Electrotechnics

Gateways to Engineering Studies - John Dillon & Chris Brink

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Gateways to Engineering Studies

Electrotechnics N4

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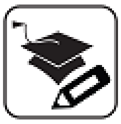
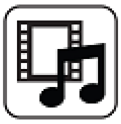
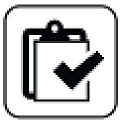
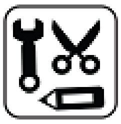
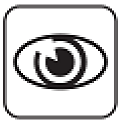
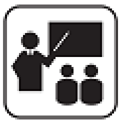
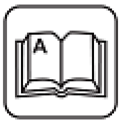
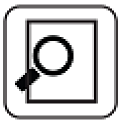
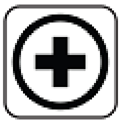
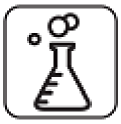
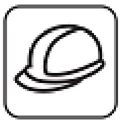
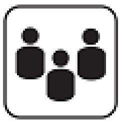
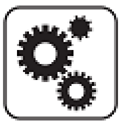
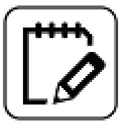
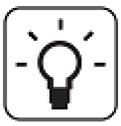
	Assessment / Activity		Multimedia
	Checklist		Practical
	Demonstration/ observation		Presentation/ Lecture
	Did you know?		Read
	Example		Safety
	Experiment		Site visit
	Group work/ discussions, role-play, etc.		Take note of
	In the workplace		Theoretical – questions, reports, case studies, etc.
	Keywords		Think about it

Module 1

Principles of electricity

Learning Outcomes
On the completion of this module the student must be able to:

- Describe the electric circuit and electromagnetism
- Describe the magnetic circuit and inductance in a DC circuit
- Describe electrostatics; electrolysis; Kirchhoff's law
- Calculate capacitor charge; inductance in a coil; magnetizing force
- Calculate voltage; current; resistance; power

1.1 Introduction

Electricity is the set of physical phenomena associated with the presence and flow of electric charge. In electricity, charges produce electromagnetic fields which act on other charges.

Electricity occurs due to several types of physical attributes:

1.1.1 Electric charge

A property of some subatomic particles, like electrons, which determine their electromagnetic interaction with other electrons.

Note:
Electrically charged matter is influenced by, and produces, electromagnetic fields.

1.1.2 Electric field

An electric field occurs when there is a potential difference even if there is no electric current. The electric field produces a force on other charges in its vicinity.

1.1.3 Electric potential

the capacity of an electric field to do work on an electrical charge, typically measured in volts.

1.1.4 Electric current

A movement or flow of electrically charged particles, typically measured in amperes.

1.1.5 Electromagnets

Moving charges produce a magnetic field. Electric currents generate magnetic fields, and changing magnetic fields generate electric currents.

In electrical engineering, electricity is used for:

- Electric power
- Electronics

Definition: Electric power
Where electric current is used to energise equipment.

Definition: Electronics
Electrical circuits that involve active electrical components such as vacuum tubes, transistors, diodes and integrated circuits, and associated passive interconnection technologies.

1.2 Electric circuits

1.2.1 Electromotive force EMF

The unit for EMF is the volt.

EMF can be generated by the following:

- Cells. Primary and secondary
- The relative movement between a conductor and a magnetic flux found in generators
- The difference in temperature between two dissimilar metals found in thermos-junctions

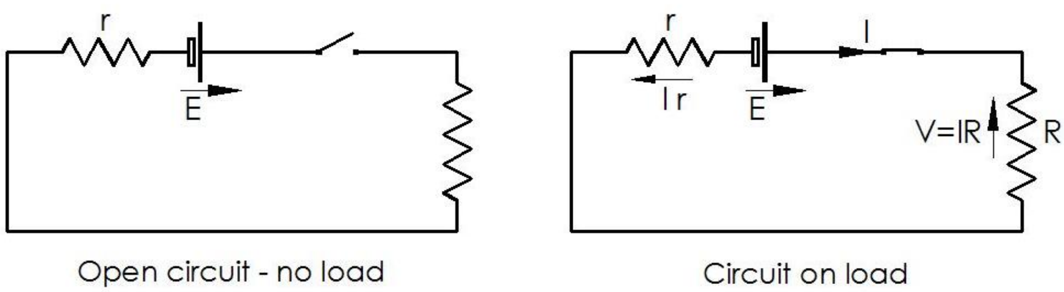


Figure 1.1 EMF and PD

Figure 1.1 shows an open circuit and EMF, indicated as E in the sketch is the no-load terminal voltage.

The potential difference or V as indicated in the sketch is the terminal voltage on load.

Kirchhoff's second law shows that:

$$E = V + I\,r$$

$$V = E - I\,r$$

An electric circuit is an interconnection of electric components such that electric charge is made to flow along a closed path (a circuit), usually to perform some useful task.

The components in an electric circuit can take many forms, which can include elements such as resistors, capacitors, switches, transformers.

The simplest electric components are those that are termed passive and linear … while they may temporarily store energy, they contain no sources of it, and exhibit linear responses to stimuli.

1.2.2 The resistor

The resistor is perhaps the simplest of passive circuit elements, as its name suggests, it resists the current through it, dissipating its energy as heat.

The resistance is a consequence of the motion of charge through a conductor: in metals, for example, resistance is primarily due to collisions between electrons and ions.

Definition: Ohm's Law
Ohm's law is a basic law of circuit theory, stating that the current passing through a resistance is directly proportional to the potential difference across it.

The resistance of most materials is relatively constant over a range of temperatures and currents; materials under these conditions are known as 'ohmic'.

The ohm, the unit of resistance, was named in honour of George Ohm, and is symbolized by the Greek letter Ω.

Note:
1 Ω is the resistance that will produce a potential difference of one volt in response to a current of one amp.

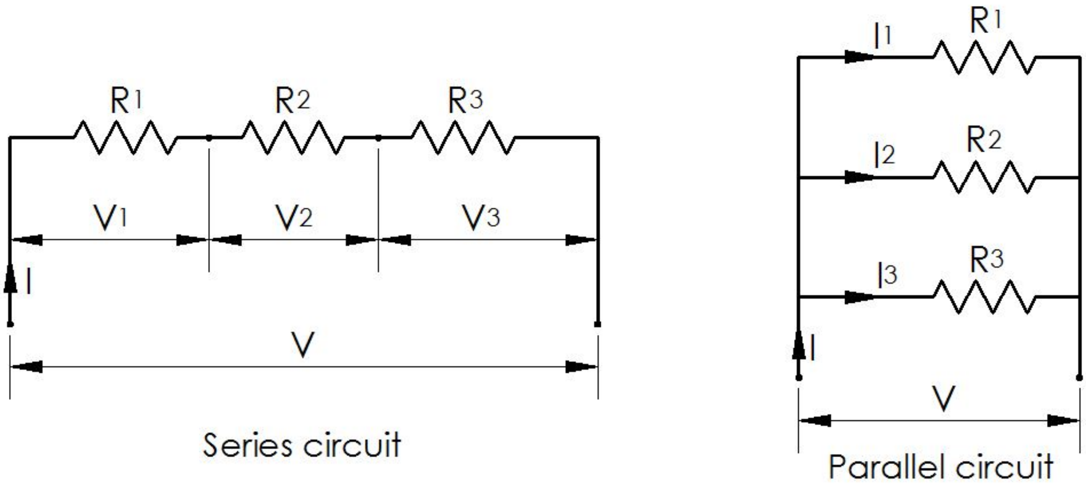


Figure 1.2 Resistors in series and parallel circuits

Looking at **Figure 1.2**, find the total resistance in the **series circuit**:

$$\text{Total voltage V} = V_1 + V_2 + V_3$$

$$\text{I } R_t = I\,R_1 + I\,R_2 + I\,R_3$$

$$R_t = R_1 + R_2 + R_3$$

Find the total resistance in the **parallel circuit**:

$$\text{Total current I} = I_1 + I_2 + I_3$$

$$\text{I} = \frac{V}{R_t}$$

$$\text{Therefore } \frac{V}{R_t} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\text{Divide through by V: } \frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\text{Total resistance for a parallel circuit } R_t = \frac{1}{\frac{1}{R_1}} + \frac{1}{\frac{1}{R_2}} + \frac{1}{\frac{1}{R_3}}$$

Resistivity:

The resistance of a material is proportionate to:

- The type of material… ρ

- Length of the material… L

And

- Inversely proportionate to its cross sectional area… A

$$R = \frac{L\,\rho}{A}$$

1.2.3 The capacitor

The capacitor is a development of the Leyden jar and is a device that can store charge, and thereby storing electrical energy in the resulting field.

It consists of two conducting plates separated by a thin insulating di-electric layer. in practice, thin metal foils are coiled together, increasing the surface area per unit volume and therefore the capacitance.

The unit of capacitance is the farad, named after Michael faraday, and given the symbol F.

Note:
One farad is the capacitance that develops a potential difference of one volt when it stores a charge of one coulomb.

A capacitor connected to a voltage supply initially causes a current as it accumulates charge; this current will however decay in time as the capacitor fills, eventually falling to zero.

A capacitor will therefore not permit a steady state current, but instead blocks it.

1.2.4 The coil

The inductor is a conductor, usually a coil of wire, that stores energy in a magnetic field in response to the current through it. When the current changes, the magnetic field does too, inducing a voltage between the ends of the conductor.

Did you know?
The induced voltage is proportional to the time rate of change of the current. The constant of proportionality is termed the inductance. The unit of inductance is the henry, named after Joseph Henry, a contemporary of Faraday.

Note:
One henry is the inductance that will induce a potential difference of one volt if the current through it changes at a rate of one

ampere per second. The inductor's behaviour is in some regards converse to that of the capacitor: it will freely allow an unchanging current, but opposes a rapidly changing one.

1.2.5 Electric charge

The presence of charge gives rise to an electrostatic force. charges exert a force on each other.

A lightweight ball suspended from a string can be charged by touching it with a glass rod that has itself been charged by rubbing with a cloth.

If a similar ball is charged by the same glass rod, it is found to repel the first. the charge acts to force the two balls apart. Two balls that are charged with a rubbed amber rod also repel each other.

However, if one ball is charged by the glass rod, and the other by an amber rod, the two balls are found to attract each other.

like-charged objects repel and opposite-charged objects attract.
The force acts on the charged particles themselves, hence charge has a tendency to spread itself as evenly as possible over a conducting surface.

Note:
The magnitude of the electromagnetic force, whether attractive or repulsive, is given by Coulomb's law, which relates the force to the product of the charges and has an inverse square relation to the distance between them.

1.2.6 Electric power

Electric power is the rate at which electrical energy is transferred by an electric circuit. The SI unit of power is the watt.

A watt is one joule per second.

Electric power, like mechanical power, is the rate of doing work, measured in watts, and represented by the letter P.

The term wattage is used colloquially to mean "electric power in watts."

The electric power in watts produced by an electric current… consisting of a charge of Q coulombs every *t* seconds passing through an electric potential difference of *V* is:

$$P = \text{work done per unit time} = \frac{QV}{t} = IV$$

where

Q is electric charge in coulombs
t is time in seconds
I is electric current in amperes
V is electric potential or voltage in volts

$$P = V I$$

$$I = \frac{V}{R}$$

$$P = I^2 R$$

$$P = \frac{V^2}{R}$$

From Joules experiments on heat generated in a circuit, he found that it was proportionate to:

- The square of the current
- The resistance of the wire
- The time the current flows

$$\text{Therefore the heat generated} = I^2 R t$$

1.2.7 The effect of temperature in a circuit

The resistivity of metals typically increases as temperature is increased, while the resistivity of semiconductors typically decreases as temperature is increased.

The resistivity of insulators and electrolytes may increase or decrease depending on the system.

As a consequence, the resistance of wires, resistors, and other components often change with temperature. This effect may be undesired, causing an electronic circuit to malfunction at extreme temperatures.

In some cases, however, the effect is put to good use.

When temperature-dependent resistance of a component is used purposefully, the component is called a resistance thermometer or thermistor.

A resistance thermometer is made of metal, usually platinum, while a thermistor is made of ceramic or polymer.

If the temperature … *T* does not vary too much, a linear approximation is typically used:

$$R_t = R_o (1 + \propto_o t)$$

Where:
α is called the temperature coefficient of resistance
t is a fixed reference temperature (usually room temperature)
R_0 is the resistance at temperature

Figure 1.3 shows this relationship:

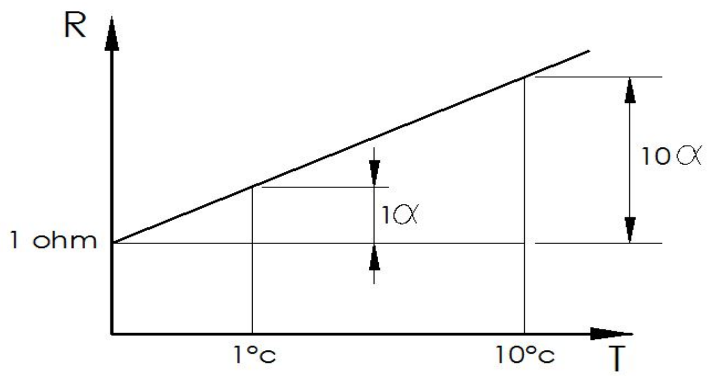


Figure 1.3 Resistance of a coil at various temperatures

If the resistance is R_1 at the temperature t_1 and the resistance is R_2 at the temperature t_2 then:

$$R_1 = R_o\,(1 + \propto_o t_1)$$

$$\text{and } R_2 = R_o\,(1 + \propto_o t_2)$$

Then by manipulating these two formula:

$$\frac{R_1}{R_2} = \frac{1 + \propto_o t_1}{1 + \propto_o t_2}$$

1.2.8 Kirchhoff's law

Kirchhoff's circuit laws are two equalities that deal with the current and potential difference (commonly known as voltage) in the lumped element mode of electrical circuits.

They are accurate for DC circuits, and for AC circuits at frequencies where the wavelengths of electromagnetic radiation are very large compared to the circuits.

Kirchhoff's current law:

This law is also called **Kirchhoff's first law**, Kirchhoff's point rule, or Kirchhoff's junction rule.

Definition: Kirschhoff's First Law

The principle of conservation of electric charge implies that:
At any junction in an electric circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.
Or:
The algebraic sum of currents in a network of conductors meeting at a point is zero.

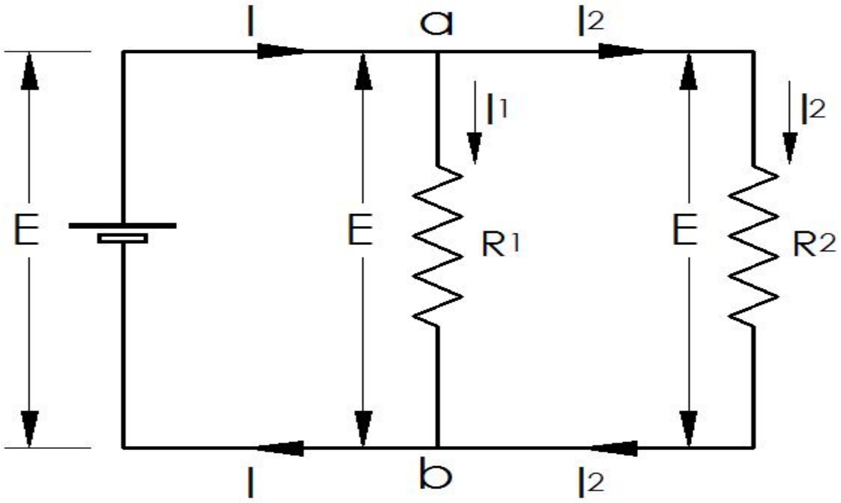


Figure 1.4 Applying Kirchhoff's law to a circuit

Worked Example 1.1

The parallel resistors shown in **Figure 1.4** have values R_1=12 ohms and R_2=15 ohms. The battery voltage is E=9 V.

Calculate the current that flows through each resistor and the total current drawn from the battery.

Solution:

$$I_1 = \frac{E}{R_1} = \frac{9}{12} = 0.75\,A$$

$$I_2 = \frac{E}{R_2} = \frac{9}{15} = 0.6\,A$$

$$\mathrm{I} = I_1 + I_2 = 0.75 + 0.6 = 1.35\,A$$

The law is based on the conservation of charge whereby the charge (measured in coulombs) is the product of the current (in amperes) and the time (in seconds).

Kirchhoff's voltage law:
This law is also called **Kirchhoff's second law**, Kirchhoff's loop (or mesh) rule, and Kirchhoff's second rule.

Definition: Kitchhoff's Second Law
The principle of conservation of energy implies that The directed sum of the electrical potential difference (voltage) around any closed network is zero.

More simply, the sum of the EMFs in any closed loop is equivalent to the sum of the potential drops in that loop, or:

The algebraic sum of the products of the resistances of the conductors and the currents in them in a closed loop is equal to the total EMF available in that loop.

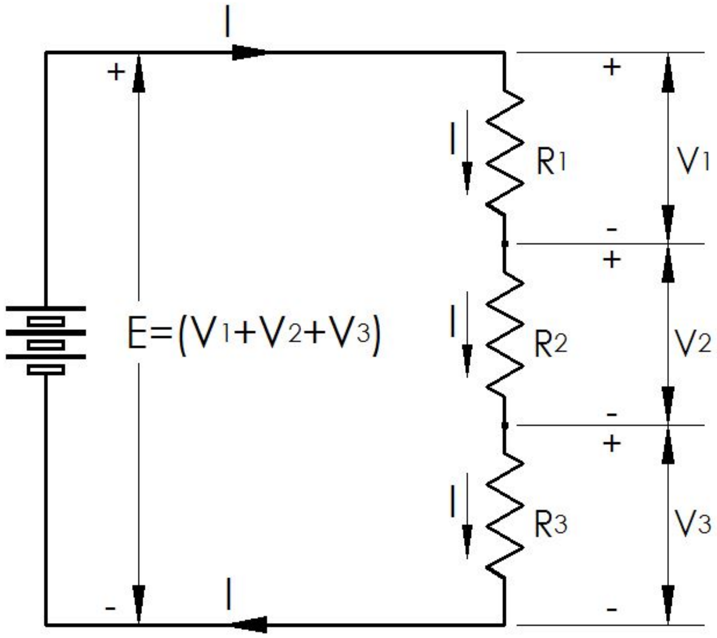


Figure 1.5 Applying Kirchhoff's law to a circuit

Worked Example 1.2

The values of the resistors shown in **Figure 1.5** are R_1=15 ohms R_2=25 ohms and R_3=5 ohms. The battery voltage is E=9 V. Calculate the voltage drop across each resistor.

Solution:

$$I = \frac{E}{R_1 + R_2 + R_3}$$

$$I = \frac{9}{15 + 25 + 5} = 0.2\,A$$

$$V_1 = I\,R_1 = 0.2 \times 15 = 3\,V$$

$$V_2 = I\,R_2 = 0.2 \times 25 = 5\,V$$

$$V_3 = I\,R_3 = 0.2 \times 5 = 1\,V$$

$$\boldsymbol{E = V_1 + V_2 + V_3 = 9\,V}$$

This law is based on the conservation of energy whereby voltage is defined as the energy per unit charge. The total amount of energy gained per unit charge must be equal to the amount of energy lost per unit charge, as energy and charge are both conserved.

1.2.9 Current divider

Figure 1.6 shows a two resistor parallel circuit. The supply current is divided between the two branches of the circuit.

$$I_1 = \frac{E}{R_1} \text{ and } I_2 = \frac{E}{R_2}$$

$$\mathrm{I} = I_1 + I_2$$

$$\text{Then I} = E\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\mathrm{I} = E\left(\frac{R_1 + R_2}{R_1 \times R_2}\right)$$

$$\mathrm{R} = \left(\frac{R_1 \times R_2}{R_1 + R_2}\right)$$

$$I_1 = I\left(\frac{R_2}{R_1 + R_2}\right)$$

$$I_2 = I\left(\frac{R_1}{R_1 + R_2}\right)$$

Worked Example 1.3

Calculate the equivalent resistance and the branch currents in **Figure 1.6** when R_1=12 ohms and R_2=15 ohms and E=9 V.

Solution:

$$\mathrm{R} = \left(\frac{R_1 \times R_2}{R_1 + R_2}\right) = \frac{12 \times 15}{12 + 15} = 6.67\ ohms$$

$$I = \frac{E}{R} = \frac{9}{6.67} = 1.35\ V$$

$$I_1 = I\left(\frac{R_2}{R_1 + R_2}\right) = 1.35\left(\frac{15}{12 + 15}\right) = 0.75\ A$$

$$I_2 = I\left(\frac{R_1}{R_1 + R_2}\right) = 1.35\left(\frac{12}{12 + 15}\right) = 0.6\ A$$

See how this compares with **worked example 1.1**

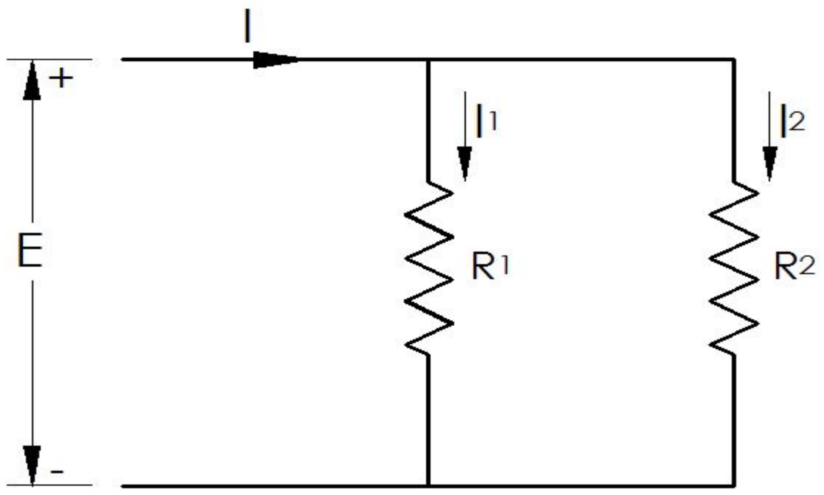


Figure 1.6 Applying Kirchhoff's law to a circuit

1.3 Magnetic circuits

1.3.1 Magnetism and electricity

Early on in his research, Faraday calls the patterns of apparently continuous curves traced out in metallic filings near a magnet magnetic curves. **Figure 1.7**.

Later on he refers to them as just an instance of magnetic lines of force or simply lines of force. Eventually Faraday would also begin to use the phrase "magnetic field".

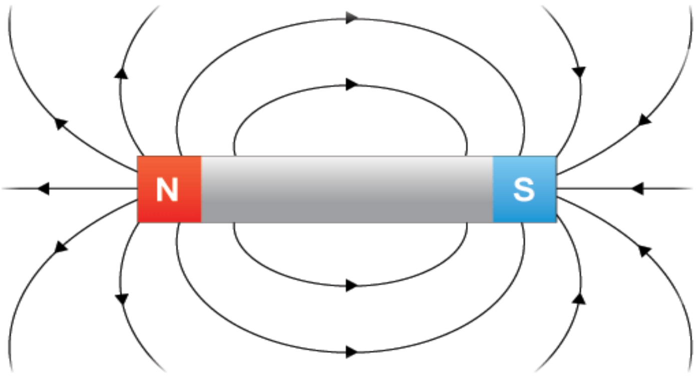


Figure 1.7 Lines of force around a magnet

The characteristics of these lines of force are:

- The direction of the lines of a magnetic flux at any point is North pointing.
- Each line of a magnetic flux is a closed loop.
- Lines of magnetic flux never intersect.
- Each line of magnetic flux is always trying to shorten itself.
- These parallel lines of magnetic flux are in the same direction and they repel each other.

1.3.2 Electromagnetic shielding

This is the practice of reducing the electromagnetic field in a space by blocking the field with barriers made of conductive or magnetic materials.

Shielding is typically applied to enclosures to isolate electrical devices from the 'outside world', and to cables to isolate wires from the environment through which the cable runs.

Definition: RF shieldig
Electromagnetic shielding that blocks radio frequency and electromagnetic radiation is also known as RF shielding.

One example is a shielded cable, which has electromagnetic shielding in the form of a wire mesh surrounding an inner core conductor.

The shielding impedes the escape of any signal from the core conductor, and also prevents signals from being added to the core conductor.

Some cables have two separate coaxial screens, one connected at both ends, the other at one end only, to maximize shielding of both electromagnetic and electrostatic fields.

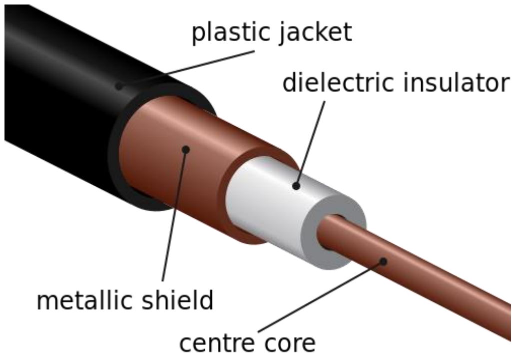


Figure 1.8 Coax cable

1.3.3 Electromagnetism

All moving charged particles produce magnetic fields. Moving point charges, such as electrons, produce complicated but well known magnetic fields that depend on the charge, velocity, and acceleration of the particles.

Magnetic field lines form in concentric circles around a cylindrical current-carrying conductor, such as a length of wire **Figure 1.9**.

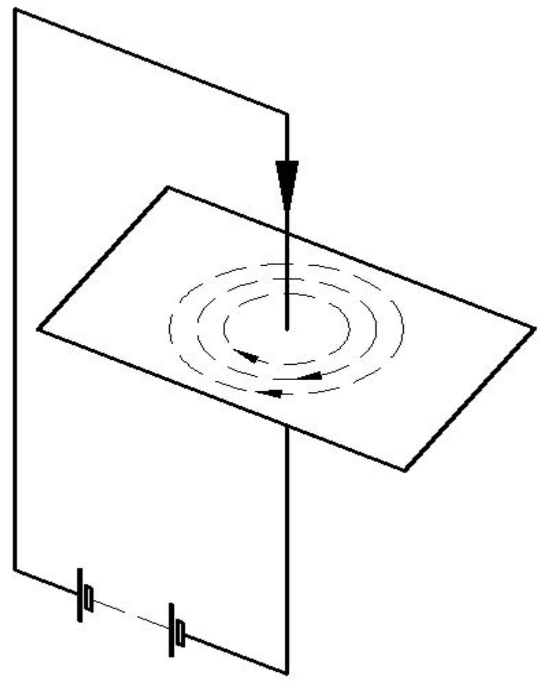


Figure 1.9 Magnetic field lines around a conductor

The direction of such a magnetic field can be determined by using the "right hand grip rule" see **Figure 1.10**. The strength of the magnetic field decreases with distance from the wire. (For an infinite length wire the strength is inversely proportional to the distance.)

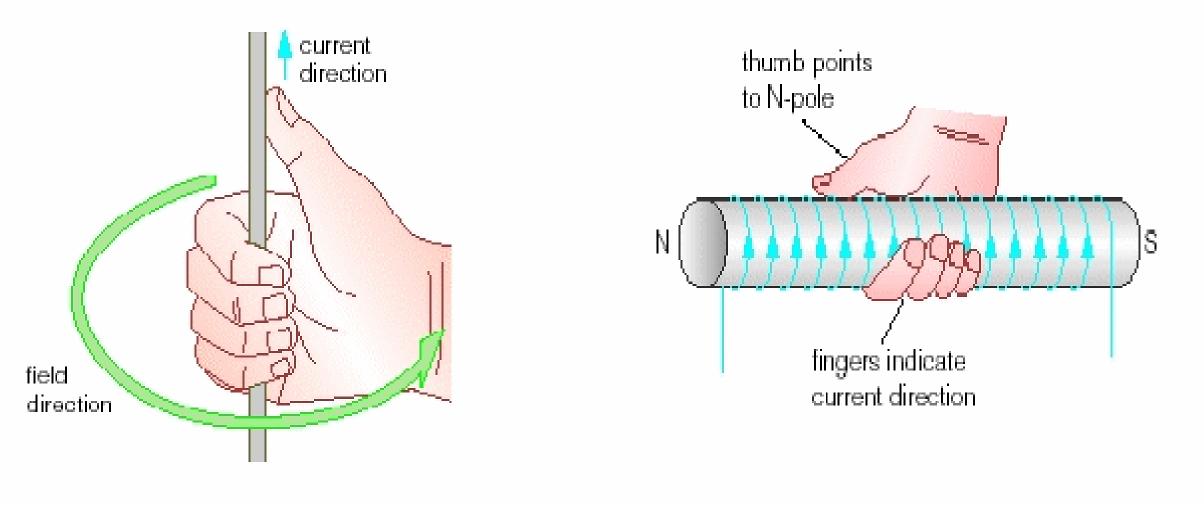


Figure 1.10 Right hand grip rule

Force on a current carrying conductor:
The force on a current carrying wire is similar to that of a moving charge as expected since a charge carrying wire is a collection of moving charges.

A current-carrying wire feels a force in the presence of a magnetic field. The Lorentz force on a macroscopic current is often referred to as the Laplace force.

Consider a conductor of length *L,* cross section *A*, and charge Q due to electric current I.

If this conductor is placed in a magnetic field of magnitude *B* that makes an angle θ with the velocity of charges in the conductor, the force exerted on a single charge Q is:

$$F = Q\,V\,B\,\sin\theta$$

so, for *N* charges where

$$N = n\,L\,A$$

the force exerted on the conductor is

$$f = FN = Q\,V\,B\,n\,L\,A\,\sin\theta = B\,I\,L\,\sin\theta$$

$$\text{or}\;\; F = B\,L\,I$$

Direction of force:
The direction of force on a charge or a current can be determined by the right-hand rule **Figure 1.10**. Using the right hand and pointing the thumb in the direction of the moving positive charge or positive current and the fingers

in the direction of the magnetic field the resulting force on the charge points outwards from the palm.

The force on a negatively charged particle is in the opposite direction. If both the speed and the charge are reversed, then the direction of the force remains the same.

For that reason, a magnetic field measurement (by itself) cannot distinguish whether there is a positive charge moving to the right or a negative charge moving to the left. (Both of these cases produce the same current.)

On the other hand, a magnetic field combined with an electric field *can* distinguish between these.

1.3.4 The solenoid

Figure 1.11 Bent conductor becomes a solenoid

	Note: Bending a current-carrying wire into a loop concentrates the magnetic field inside the loop while weakening it outside. **Figure 1.11**.

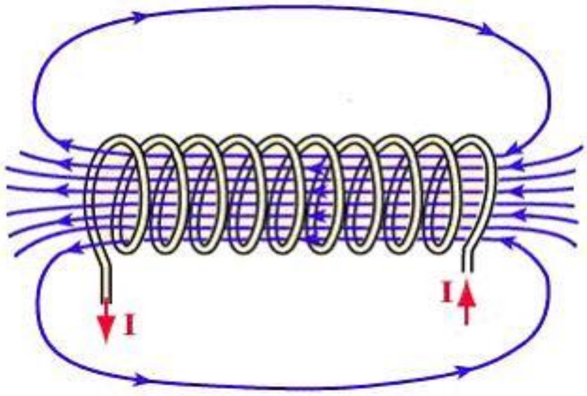


Figure 1.12 A solenoid without core

Bending a wire into multiple closely spaced loops to form a coil or solenoid enhances this effect. **Figure 1.12.**

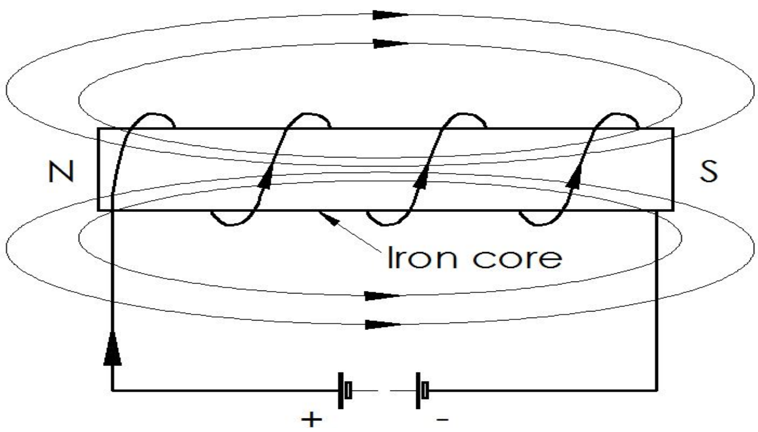


Figure 1.13 A solenoid with iron core

A device so formed around an iron core may act as an electromagnet, generating a strong, well-controlled magnetic field. **Figure 1.13**. An infinitely long cylindrical electromagnet has a uniform magnetic field inside, and no magnetic field outside.

A finite length electromagnet produces a magnetic field that looks similar to that produced by a uniform permanent magnet, with its strength and polarity determined by the current flowing through the coil.

1.3.5 The magnetic circuit

A magnetic circuit is made up of one or more closed loop paths containing a magnetic flux. The flux is usually generated by electromagnets and confined to the path by magnetic cores consisting of ferromagnetic materials like iron. although there may be air gaps or other materials in the path.

The concept of a "magnetic circuit" exploits a one-to-one correspondence between the equations of the magnetic field in an unsaturated ferromagnetic material to that of an electrical circuit.

Using this concept, the magnetic fields of complex devices such as transformers can be quickly solved using the methods and techniques developed for electrical circuits.

Some examples of magnetic circuits are:

- Horseshoe magnet with iron keeper (low-reluctance circuit)
- Horseshoe magnet with no keeper (high-reluctance circuit)
- Electric motor (variable-reluctance circuit)

Magnetic force:

Similar to the way that electromotive force, EMF drives a current of electrical charge in electrical circuits, magetomotive force, MMF 'drives' magnetic flux through magnetic circuits.

Note:
The term 'magnetomotive force', though, is a misnomer since it is not a force nor is anything moving. It is perhaps better to call it simply MMF. In analogy to the definition of EMF.

The MMF represents the potential that a hypothetical magnetic charge would gain by completing the loop. The magnetic flux that is driven is not a current of magnetic charge. it merely has the same relationship to MMF that electric current has to EMF.

$\mathrm{N\,I}$ is the amere-turns
H is the magnetizing force

$$\mathrm{H} = \frac{\mathrm{N\,I}}{L} \ in \ A/m$$

Magnetic flux:
An applied MMF 'drives' magnetic flux through the magnetic components of the system. The magnetic flux through a magnetic component is proportional to the number of magnetic field lines that pass through the cross sectional area of that component.

This is the net number, ie the number passing through in one direction, minus the number passing through in the other direction. The direction of the magnetic field vector ***B*** is by definition from the south to the north pole of a magnet inside the magnet; outside the field lines go from north to south.

The flux through an element of area perpendicular to the direction of magnetic field is given by the product of the magnetic field and the area element. More generally, magnetic flux Φ is defined by a scalar product of the magnetic field and the area element vector.

Φ is the magnetic flux measured in weber… Wb
B is the flux density measured in tesla… T (webers per square meter)
A is the cross-sectional area measured in m^2

$$B = \frac{\Phi}{A}$$

$$\text{Primary rms voltage } E_p = 4.44\,\Phi_m \ f\ N_p$$

$$\text{Secondary rms voltage } E_s = 4.44\,\Phi_m \ f\ N_s$$

Peak value of magnetic flux:

$$\Phi = \frac{E_p}{4.44\, f\, N_p}$$

Magnetic leakage and fringing:
There is an air gap between the rotor and stator of an electric machine. If the windings are not properly embedded and uniform, there may be flux leak into the air gap.

	Note: This flux cannot be used and leakage is a loss in power.

Magnetic fringing:
We already know that magnetic lines which flow parallel to each other, repel each other. While these lines are inside a magnetic material, they will remain close to each other. As soon as they are in free space or air, magnetic fringing takes place.

$$\textit{Leakage factor} = \frac{\textit{total flux produced in coil A}}{\textit{usable flux in the free space}}$$

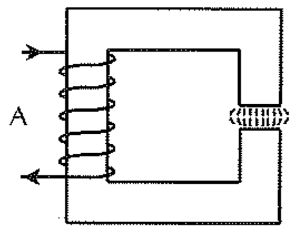


Figure 1.14

	Note: Reluctance calculations use the cross-sectional area. Since this area enlarges in free space, these calculations must be done carefully!

Toroidal inductors:
Toroidal inductors and transformers are passive electronic components, typically consisting of a circular ring-shaped magnetic core of high magnetic permeability material such as iron powder or ferrite, around which wire is coiled to make an inductor.

Toroidal coils are used in a broad range of applications in AC electronic circuits, such as high-frequency coils and transformers.

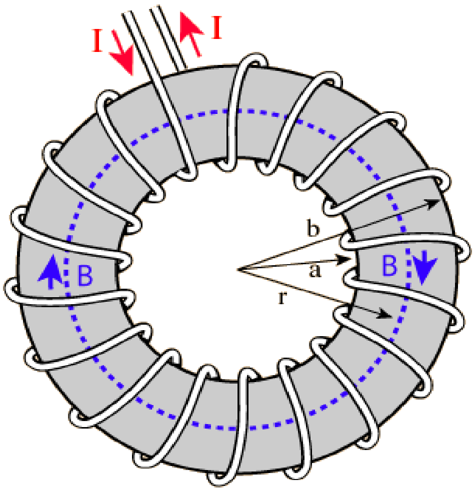


Figure 1.15 A toroidal solenoid

1.3.6 Hysteresis

Hysteresis is the time-based dependence of a system's output on present and past inputs. The dependence arises because the history affects the value of an internal state.

To predict its future outputs, either its internal state or its history must be known. If a given input alternately increases and decreases, a typical mark of hysteresis is that the output forms a loop as in the **Figure 1.16.**

Such loops may occur purely because of a dynamic lag between input and output. This effect disappears as the input changes more slowly.

This effect meets the description of hysteresis given above, but is often referred to as rate-dependent hysteresis to distinguish it from hysteresis with a more durable memory effect.

Hysteresis occurs in ferromagnetic materials and ferroelectric materials, as well as in the deformation of some materials (such as rubber bands and shape-memory alloys) in response to a varying force.

Note:
In natural systems hysteresis is often associated with irreversible thermodynamic change.

Many artificial systems are designed to have hysteresis: for example, in thermostats and Schmitt triggers, the principle of hysteresis is applied to avoid unwanted frequent switching.

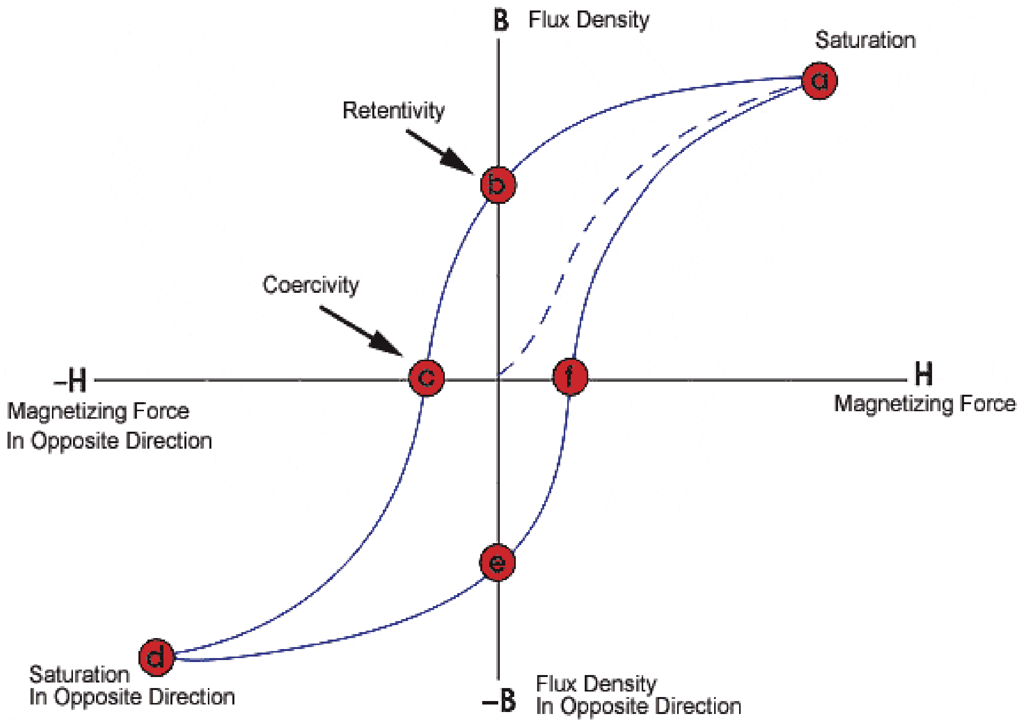


Figure 1.16 Hysteresis loop

A closer look at a magnetization curve generally reveals a series of small, random jumps in magnetization called Barkhausen jumps. This effect is due to crystallographic defects such as dislocations.

Magnetic hysteresis loops are not exclusive to materials with ferromagnetic ordering. Other magnetic orderings, such as spin glass ordering, also exhibit this phenomenon.

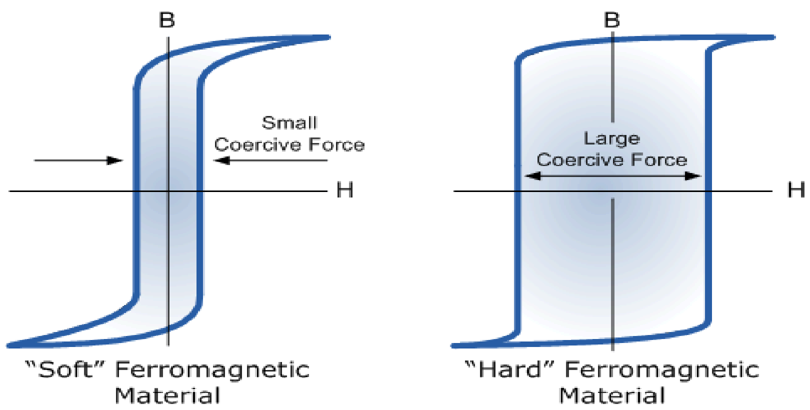


Figure 1.17 Hysteresis loops

1.3.7 Eddy currents

Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor, due to Faradays law of induction.

Eddy currents flow in closed loops within conductors, in planes perpendicular to the magnetic field.

They can be induced within nearby stationary conductors by a time-varying magnetic field created by an AC electromagnet or transformer, for example, or by relative motion between a magnet and a nearby conductor.

Note:
The magnitude of the current in a given loop is proportional to the strength of the magnetic field, the area of the loop, and the rate of change of flux, and inversely proportional to the resistivity of the material.

By Lenz' law, an eddy current creates a magnetic field that opposes the magnetic field that created it, and thus eddy currents react back on the source of the magnetic field.

For example, a nearby conductive surface will exert a drag force on a moving magnet that opposes its motion, due to eddy currents induced in the surface by the moving magnetic field.

This effect is employed in eddy current brakes which are used to stop rotating power tools quickly when they are turned off. The current flowing through the resistance of the conductor also dissipates energy as heat in the material.

Thus eddy currents are a source of energy loss in alternating current (AC) inductors, transformers, electric motors and generators, and other AC machinery, requiring special construction such as laminating magnetic cores to minimize them.

Eddy currents are also used to heat objects in induction heating furnaces and equipment, and to detect cracks and flaws in metal parts using eddy-current testing instruments.

$$\text{Power loss for one lamination} = I_a{}^2\, R_a$$

$$\text{Power loss for n laminations} = I_a{}^2\, R_a = \left(\frac{1}{25}\right)^2 \times I_a{}^2 \times n \times R_a$$

$$\text{Power loss for n laminations} = \frac{1}{25}\, I_a{}^2\, R_a$$

1.4 Electromagnetic induction

1.4.1 Fleming's left-hand rule

Fleming's left-hand rule (for motors) **Figure 1.18**, and Fleming's right hand rule (for generators) are a pair of visual memory aids. They were originated by John Fleming, in the late 19th century, as a simple way of working out the direction of motion in an electric motor, or the direction of electric current in an electric generator.

When current flows in a wire, and an external magnetic field is applied across that flow, the wire experiences a force perpendicular both to that field and to the direction of the current flow.

A left hand can be held, as shown in the illustration, so as to represent three mutually orthogonal axes on the thumb, first finger and middle finger. Each finger is then assigned to a quantity (mechanical force, magnetic field and electric current).

Note:
The right and left hand are used for generators and motors respectively.

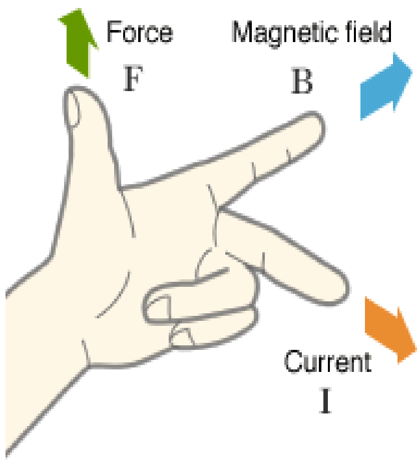


Figure 1.18 Fleming's right-hand rule

1.4.2 Electromagnetic induction

Michael Faraday who mathematically described Faradays law of induction, is generally credited with its discovery in 1831.

Note:
Induction is the process by which an electric potential (volts) in a circuit is created by a change in the magnetic field (flux).

1.4.3 Statically induced EMF

In statically induced EMF, conductor is stationary with respect to the magnetic field. Transformer is an example of statically induced EMF. Here the windings are stationary, magnetic field is moving around the conductor and produces the EMF.

⚠	**Note:** Meaning of a static is stationary. so there is no relative motion between field nor coil. The source should be alternating in nature. Then only EMF can be induced.

In **Figure 1.19**, a EMF is induced in the secondary coil, marked (S) only when the switch (K) is closed or opened. The ammeter (a) will show a momentary in one direction when the switch is closed and a momentary current in the opposite direction when the switch is opened.

Hence, for this to work, the current needs to alternate.

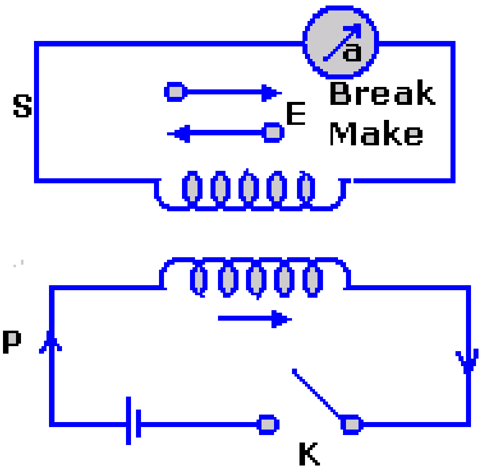


Figure 1.19 Static induction

Electrostatic induction is a redistribution of electrical charge in an object, caused by the influence of nearby charges. In the presence of a charged body, an insulated conductor develops a positive charge on one end and a negative charge on the other end.

Due to induction, the electrostatic potential is constant at any point throughout a conductor. Electrostatic Induction is also responsible for the attraction of light nonconductive objects, such as balloons, paper or Styrofoam scraps, to static electric charges.

When a charged object is brought near an uncharged, electrically conducting object, such as a piece of metal, the force of the nearby charge due to coulombs law causes a separation of these internal charges.

For example, if a positive charge is brought near the object, the electrons in the metal will be attracted toward it and move to the side of the object facing it. When the electrons move out of an area, they leave an unbalanced positive charge due to the nuclei.

This results in a region of negative charge on the object nearest to the external charge, and a region of positive charge on the part away from it.

These are called induced charges. If the external charge is negative, the polarity of the charged regions will be reversed.

Since this process is just a redistribution of the charges that were already in the object, it doesn't change the *total* charge on the object. it still has no net charge.

⚠	**Note:** This induction effect is reversible; if the nearby charge is removed, the attraction between the positive and negative internal charges causes them to intermingle again.

The unit of self-inductance is the henry (H). The average EMF is the relation between the change in flux and the time difference.

$$\text{Average EMF } E_{ave} = \frac{Increace\ or\ decreace\ if\ flux}{time\ taken} \times number\ turns$$

$$E_{ave} = \frac{\Delta\,\Phi \times \mathrm{N}}{\Delta\,t}$$

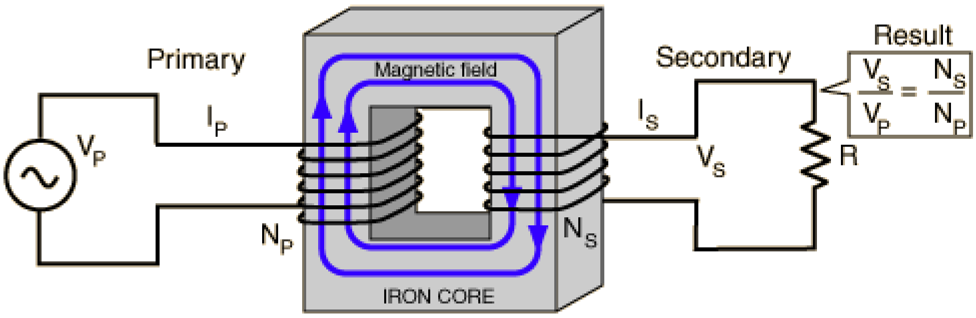


Figure 1.20 A transformer works with alternating current only

1.4.4 Dynamically induced EMF

An EMF is induced due to the physical movement of either the conductor or the magnet. **Figure 1.21** shows an iron bar passing to and fro inside a coil. Note how the current direction changes when the direction of movement changes.

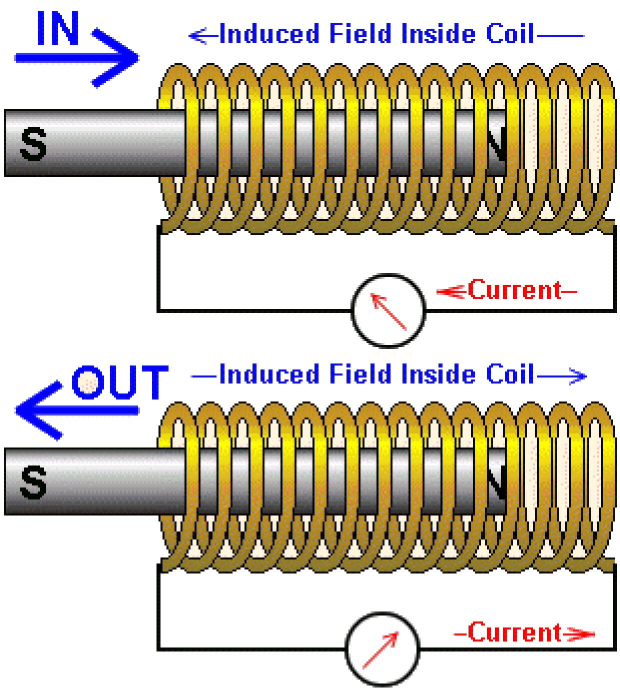


Figure 1.21 Dynamic induction

The principle of dynamically induced EMF is used in the operation of electric motors and generators. **Figure 1.22** shows how dynamically induced EMF is used to run a motor.

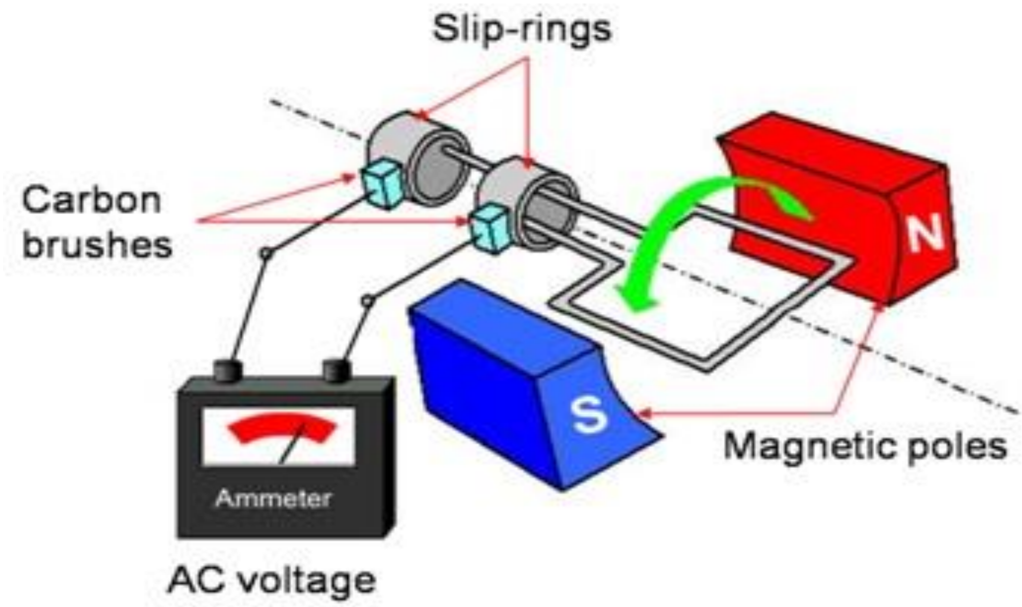


Figure 1.22 The principle of dynamic induction

A conductor with length (Le) moving at a velocity (v) at right angle to the magnetic field of density (B).

In one second, the conductor would have moved across an area of (L x v) m^2, and with the magnetic flux density of (B) we get:

$$The\ force\ \ f\ =\ FN =\ Q\ V\ B\ n\ Le\ A\ \sin\theta\ =\ B\ I\ Le\ \sin\theta$$

$$\text{or}\ \ F\ =\ B\ Le\ I$$

$$\text{and the EMF}\ \ \mathrm{E}\ =\ B\ Le \times the\ velocity\ \ v$$

1.4.5 Self-induction and the coil

Self-inductance in terms of Magnetic Flux

A coil carrying current has magnetic flux associated with it. The flux **Φ** is directly proportional to the current **I**

$$\Phi\ =\ L\,I$$

L is the constant of proportionality. ***L*** is called the self-inductance. Thus the ratio of the magnetic flux to the current is the **self-inductance**.

Self-inductance in terms of EMF

According to Faraday's laws of electromagnetic induction when the electric current flowing through a wire changes, magnetic flux associated with it changes, electromotive force (EMF) is induced that opposes the change in flux and current.

$$\text{The EMF}\ \ \mathrm{E}\ =\ -\,\frac{\Delta\,\Phi}{\Delta\,t}$$

The opposing induced EMF is called as "back EMF". EMF is due to a change in flux in that circuit (wire) itself, hence it is called as Self inductance. Suppose the current flowing in the circuit increases from 0 to 1. It changes by an amount *dI* in a time duration *dt* then the magnetic flux linking the circuit changes by an amount:

$$\mathrm{E}\ =\ -L\,\frac{\Delta\,I}{\Delta\,t}$$

Note:
If the current is increasing then the induced EMF always acts to reduce the current, and vice versa. Hence the self-inductance *L* of a circuit is necessarily a positive number. Self-inductance of A solenoid.

Consider a helically wound solenoid of length **Le** and cross-sectional area **A**. Length is much greater than its diameter. **n** is the number of turns per unit length. Current **I** is flowing through the solenoid. hence the field within the solenoid is approximately constant.

The magnetic flux across each turn of area A is = $A\mu_0 nI$

The total number of turns = n
The total magnetic flux is Φ

1.5 Capacitors

Note:
A capacitor is a passive two-terminal electronic component used to store electrical energy temporarily in an electrical field.

The forms of practical capacitors vary widely, but all contain at least two electrical conductors (plates) separated by a dielectric (i.e. an insulator that can store energy by becoming polarized).

The conductors can be thin films, foils or sintered beads of metal or conductive electrolyte, etc. The non-conducting dielectric acts to increase the capacitor's charge capacity. Materials commonly used as dielectrics include glass, plastic paper and mica.

Capacitors are widely used as parts of electrical circuits in many common electrical devices. Unlike a resistor, an ideal capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates.

When there is a potential difference across the conductors (e.g., when a capacitor is attached across a battery), an electric field develops across the dielectric, causing positive charge **+Q** to collect on one plate and negative charge **−Q** to collect on the other plate.

If a battery has been attached to a capacitor for a sufficient amount of time, no current can flow through the capacitor. However, if a time-varying voltage is applied across the leads of the capacitor, a displacement current can flow.

An ideal capacitor is characterized by a single constant value, its capacitance. Capacitance is defined as the ratio of the electric charge **Q** on each conductor to the potential difference ***V*** between them.

Note:
The SI unit of capacitance is the farad (**F**), which is equal to one coulomb per volt (1 **C/V**). Typical capacitance values range from about 1 pF (10^{-12} F) to about 1 mF (10^{-3} F).

The larger the surface area of the "plates" (conductors) and the narrower the gap between them, the greater the capacitance is. In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, known as the breakdown voltage. The conductors and leads introduce an undesired inductance and resistance.

1.5.1 Capacitors in series

Like in the case of resistors in parallel, the reciprocal of the circuit's total capacitance is equal to the sum of the reciprocals of the capacitance of each individual capacitor. **Figure 1.23**.

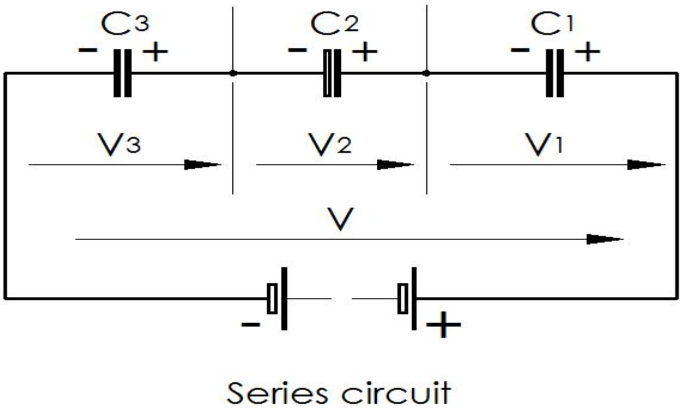


Figure 1.23

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\text{Total capacitance for a series circuit } C_t = \frac{1}{\frac{1}{C_1}} + \frac{1}{\frac{1}{C_2}} + \frac{1}{\frac{1}{C_3}}$$

1.5.2 Capacitors in parallel

Total capacitance for a circuit involving several capacitors in parallel (and none in series) can be found by simply summing the individual capacitances of each individual capacitor. **Figure 1.24.**

$$C_t = C_1 + C_2 + C_3$$

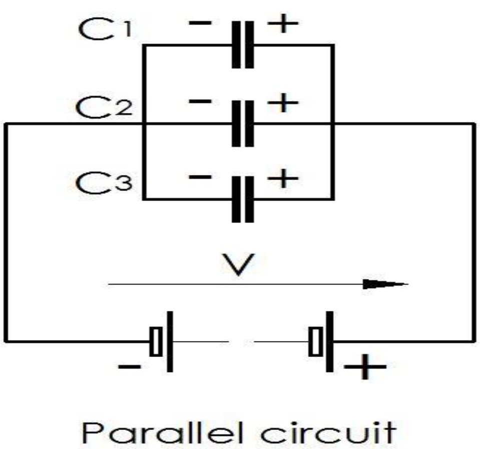


Figure 1.24

It is possible for a circuit to contain capacitors that are both in series and in parallel. To find total capacitance of the circuit, simply break it into segments and solve piece-wise.

Worked Example 1.4

Three capacitors have values of C_1=1 uF, C_2=2 uF and C_3=3 uF. Find the total capacitance and the charge on capacitor…C_1 when they are connected in parallel and with a 100 V supply.

Solution:

$$C_t = C_1 + C_2 + C_3$$

$$C_t = 1 + 2 + 3 = 6\, uF$$

$$Q_1 = C\ E$$

$$Q_1 = 1 \times 100 = 100\, uC$$

Worked Example 1.5

Three capacitors have values of C_1=1 uF, C_2=2 uF and C_3=3 uF. Find the total capacitance and the charge on capacitor…C_1 when they are connected in series and with a 100 V supply.

Solution:

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\frac{1}{C_t} = \frac{1}{1} + \frac{1}{2} + \frac{1}{3}$$

$$C_t = 0.545\ uF$$

For a parallel circuit $C_1 = C_2 = C_3 = C\ E = 0.545 \times 100 = 54.5\, uC$

Worked Example 1.6

Two capacitors of 16 microfarads and 4 microfarads respectively are connected in series across a 10-volt supply.

Calculate the following:

1. The total capacitance
2. The pd across each capacitor

Solution:

1. $C_s = \frac{1}{\frac{1}{16} - \frac{1}{4}} = 3{,}2\ \mu F$

2. $Q_T = Q_1 = Q_2 = VC = 10 \times 3{,}2\ \mu F = 32\ \mu C$

$V = \frac{Q}{C} = \frac{32}{16} \& \frac{32}{4}$

$= 2V \ \&\ 8V$

Worked Example 1.7

An aluminium conductor, 1 km long, is connected in parallel with a copper conductor, having the same length. When a current of 350 A is passed through the combination, it is found that the current through the copper conductor is 150 A. The diameter of the aluminium is 3 mm.

Calculate the following:

1. The diameter of the copper conductor if the resistivity of copper is 0,018 micro-ohm metres and that of the aluminium is 0,028 micro-ohm metres.
2. The voltage drop across the conductors.

Solution:

1. $A_a = \frac{nd_a^2}{4} = \frac{n(3 \times 10^{-3})^2}{4} = 7{,}0685834 \times 10^{-6} m^2$

$R_a = \frac{P_a \times L_a}{A_a}$

$= \frac{0{,}028 \times 10^{-3} \times 1000}{7{,}0685834 \times 10^{-6}}$

$$= 3{,}961189695\ \Omega$$

$$R_c = \frac{V_C}{I_C} = \frac{792{,}238}{150} = 5{,}282\ \Omega$$

but $I_a = I_T - I_c$

$$= 350 - 150$$

$$= 200\ A$$

2. $V_a = IaRa$

$$= 200 \times 3{,}9612 = 792{,}238$$

Worked Example 1.8

The field coil of a motor has a resistance of 300 ohms at 30 °C. By how much will the resistance increase if the motor reaches a temperature of 40 °C when running? Take the temperature coefficient of resistance to be 0,004 per °C at 30 °C.

Solution:

$$d = \sqrt{\frac{4P_C L_C}{nR_c}} = \sqrt{\frac{4 \times 0{,}01 \times 10^{-6} \times 1000}{n(5{,}282)}} = 2{,}0831\ mm$$

$$R_t = R_{30}[1 + \alpha_{30}(t - 30°)]$$

$$= 300\ [1 + 0{,}004(40° - 30°)]$$

$$= 300\ [1 + 0{,}004(10)]$$

$$= 312\ \Omega$$

$$= 312 - 300 = 12\ \Omega$$

Activity 1.1

1. Four parallel connected resistors are supplied from a 25 V battery. Three of the resistors have values of R_1=1 kΩ, R2=12 kΩ and R3=8.32 kΩ. If the battery current is measured as 36.5 mA. Find the value of the fourth resistor.
   [3.9]
2. Four 115 V lamps are connected in parallel to a 115 V supply. The lamp

ratings are L_1=100 W, L_2=40 W, L_3=60 W and L_4=25 W. Find the current that flows through each lamp and the total power delivered by the supply.
[870; 348; 522; 217; 225]

3. Two resistors connected in parallel take a total of 75 mA from the supply. R_1=620 Ω and R_2=880 Ω. Find I_1, I_2 and the level of the supply voltage. Also find the power dissipated in each resistor.
[44; 31; 27.28; 1.2; 0.85]

Activity 1.2

1. A capacitor with a plate area of 50 cm^2 and a dielectric thickness of 0.5 mm has a charge of $10X10^{-9}$ C when the applied voltage is 20 V. Find the electric field strength and the flux density.
[40000; $2x10^{-6}$]
2. A 100 uF capacitor is connected in parallel with a 50 uF capacitor, then the two are connected in series with a 25 uF capacitor. Find the total capacitance and if a 25 V supply is connected to the series combination, find the voltage across each capacitor.
[21.4; 21.4; 3.6]
3. A 100 uF capacitor is connected in parallel with a 50 uF capacitor, then the two are connected in series with a 25 uF capacitor. If a 25 V supply is connected to the series combination, find the energy stored in each capacitor.
[637; 319; 5.74]

Activity 1.3

1. Define the following:
   a) The ampere
   b) Resistance
   c) Impedance
   d) Self-inductance
   e) Capacitance.
2. What are the properties of hard and soft magnetic materials and where are these materials used?
3. What is meant by a negative coefficient of resistance.
4. Name the three EMF sources.
5. What is meant by the EMF of a battery.
6. How can the magnetic field of a solenoid be strengthened?

Activity 1.4

A resistor of 9 0hms is connected in parallel with a resistance of 3 ohms. This combination is connected in series with an unknown resistance. The circuit is then connected across a 160 V DC-supply.

Calculate the following:

1. The value of the unknown resistor when a 40 A current is drawn from the supply.
2. The power dissipated in the circuit.

[90; 1.75; 70; 2.25; 6.400]

Activity 1.5

The field coil of a motor has a resistance of 100 ohms at a certain temperature. The resistance increases with 25 ohms when the motor attains a temperature of 92,5 °C when running. Take the temperature coefficient of resistance as 0,004 per degree Celsius. Determine the unknown temperature.

[30]

Activity 1.6

A resistance of 20 ohms is connected in parallel with an unknown resistance. The combination is connected in series with a third resistance of 10 ohms that draws a current of 15 A. If the whole circuit is connected across a battery having a pd of 300 V, calculate the following:

1. Current through the unknown resistor.
2. Value of the unknown resistor.
3. EMF of the battery with an internal resistance of 1 ohm.

[20; 150; 7.5; 20; 315]

Activity 1.7

An aluminium conductor of unknown length with a voltage of 30 V, is connected in parallel with a copper conductor with the same length. When a current of 40 A is passed through the combination, it is found that the current through the copper conductor is 10 A. The diameter of the aluminium conductor is 2 mm.

Determine the following:

1. Length of the copper conductor if the resistivity of copper is 0,017 micro-ohm metres and that of aluminium 0,027 micro-ohm metres.
2. Resistance and the diameter of the copper conductor.

[1; 30; 116.355; 3; 0.916]

Activity 1.8

The field coils of a motor has a resistance of 200 ohms at 80 °C. After a run at full load, the resistance increases to 280 ohms and the temperature of the coils to 180 °C. Calculate the temperature coefficient of resistance at 80 °C.

[0.004]

Activity 1.9

An aluminium conductor 500 m long is connected in parallel with a copper conductor of the same length. When a current of 150 A is passed through the combination, it is found that the current through the copper conductor is 50 A. The diameter of the aluminium conductor is 25 mm.

Determine the following:

1. The diameter of the copper conductor, if the resistivity of copper is 0,017 micro-ohm metre and that of aluminium is 0,027 micro-ohm metre.
2. The voltage drop across the conductors.

[4.9×10^{-4}; 10075; 0.055; 14.027]

Activity 1.10

A resistance of 6 ohms is connected in parallel with a resistance of 30 ohms. The combination is connected in series with a third resistance of 3 ohms. If the whole circuit is connected across a battery having an EMF of 27 V and an internal resistance of 1 ohm,

Determine the following:

1. The terminal voltage of the battery.
2. The current through each resistor.

[3; 3; 24; 15; 2.5; 0.5]

Activity 1.11

Two capacitors each having a potential difference (PD) of 200 V and 50 V respectively are connected in series across a DC supply.

Determine the total capacitance and the capacitance across each capacitor if a charge of 800 micro coulomb is measured across the capacitors.

[3.2; 16; 4]

Self-Check

I am able to:	Yes	No
• Describe the electric circuit and electromagnetism		
• Describe the magnetic circuit and inductance in a DC circuit		
• Describe electrostatics; electrolysis; Kirchhoff's law		
• Calculate capacitor charge; inductance in a coil; magnetizing force		
• Calculate voltage; current; resistance; power		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 2

DC Machines

Learning Outcomes
On the completion of this module the student must be able to:

- Describe the uses of and characteristics of shunt, series and compound motors
- Describe the purpose of the armature, brushes and the commutator
- Calculate speed and starting torque

2.1 Introduction

The DC motor was the mainstay of electric traction drives on both electric and diesel-electric for many years. It consists of two parts, a rotating armature and a fixed field.

The fixed field consists of tightly wound coils of wire fitted inside the motor case. The armature is another set of coils wound round a central shaft.

It is connected to the field through "brushes" which are spring loaded contacts pressing against an extension of the armature called the commutator. The commutator collects all the terminations of the armature coils and distributes them in a circular pattern to allow the correct sequence of current flow.

The motor works because, simply put, when a current is passed through the motor circuit, there is a reaction between the current in the field and the current in the armature which causes the armature to turn. The armature and the field are connected in series and the whole motor is referred to as "series wound".

Note:
A series wound DC motor has a low resistance field and armature circuit. Because of this, when voltage is applied to it, the current is high. (Ohms Law: current = voltage/resistance).

The advantage of high current is that the magnetic fields inside the motor are strong, producing high torque (turning force), so it is ideal for starting a train.

The disadvantage is that the current flowing into the motor has to be limited somehow, otherwise the supply could be overloaded and/or the motor and its cabling could be damaged. At best, the torque would exceed the adhesion and the driving wheels would slip. Traditionally, resistors were used to limit the initial current.

In accordance with SANS 10142 (SABS 0142) Regulation 7.20 and 10.2 joints and terminations shall not:

In electromagnetism there are two basic principles which ultimately mean exactly the same thing:

- One is the motor principle — *a current flowing in a wire though a magnetic field produces movement.*
- The other is the generator or dynamo principle — *when a wire moves through a magnetic field a current is produced in the wire.*

Important Note!

Motor principle: current + field = movement

Generator principle: movement + field = current

A simplified model of a direct-current motor is shown in **Figure 2.1**. Its essential elements are the armature, the magnetic *field*, the *commutator*, and the brushes. The armature is usually a cylinder of soft steel about which a number of turns of copper wire are wound constituting the *armature winding*.

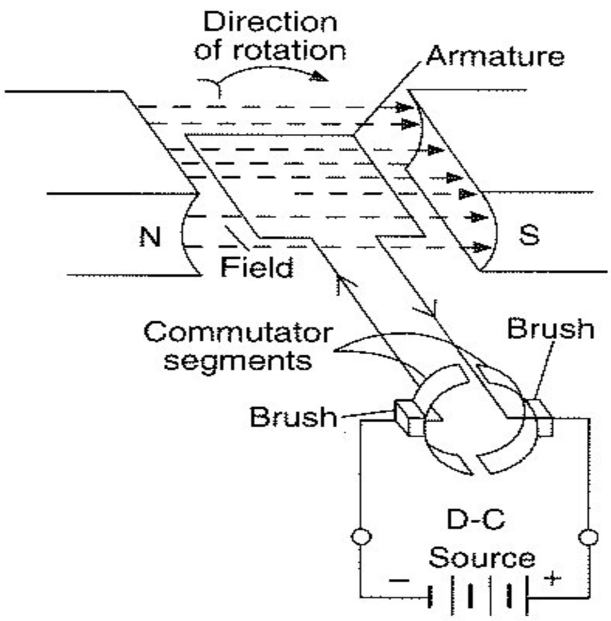


Figure 2.1 (a) Direct Current (DC) motor operation

For simplicity, **Figure 2.1** shows only a single loop of wire serving as armature. The external field in which the armature rotates is usually provided by a *multi-pole electromagnet*, but the basic action is the same for the field of a two-pole permanent magnet, shown in **Figure 2.1**.

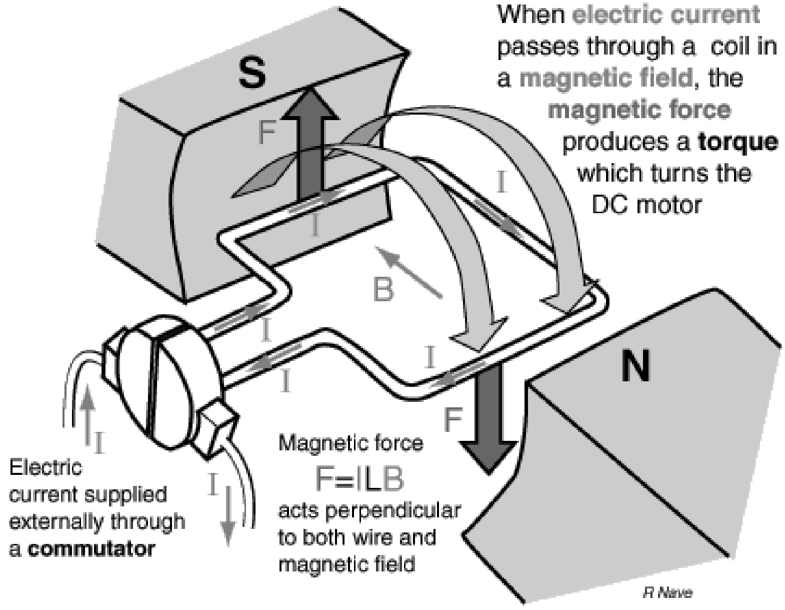


Figure 2.1 (b) Direct Current (DC) motor operation

The commutator is attached to the shaft of the armature and is essentially a *reversing switch*. It consists of as many ring-shaped segments as there are poles in the magnet (in this case two).

Current is passed to and from the armature though graphite (carbon) *brushes*, which slide on the cylindrical commutator segments. A battery or generator serves as direct-current source.

2.1.1 Component identification of a DC motor

Figure 2.2 shows the general arrangement of a four-pole DC generator or motor. The fixed part consists of four iron cores, referred to as pole cores, attached to the iron or steel ring, and called the yoke.

The pole cores are usually made of steel plates riveted together and bolted to the yoke, which may be of cast steel or fabricated rolled steel.

Each pole core has pole tips, called pole shoes, partly to support the field winding and partly to increase the cross-sectional area and thus reduce the reluctance of the air gap.

Each pole core carries a winding so connected as to excite the poles alternately N and S. The armature core consists of iron laminations, insulated from one another.

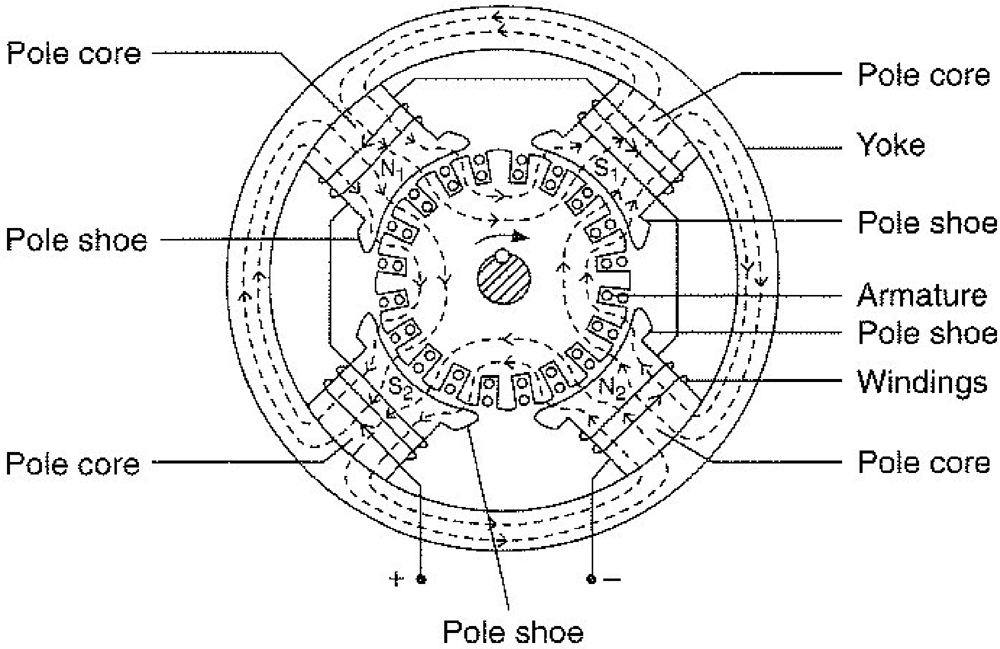


Figure 2.2 A four-pole DC motor

A cross-sectional view of a DC motor is shown in **Figure 2.3**.

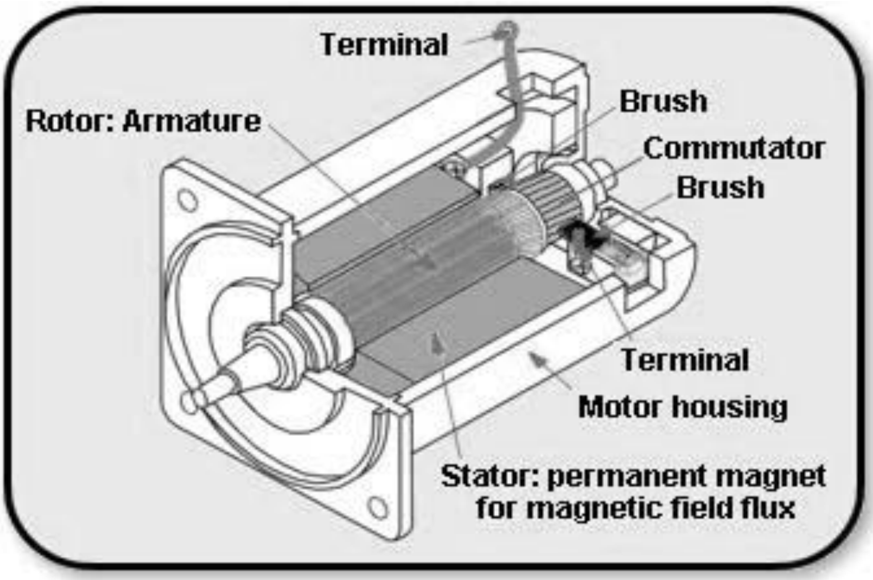


Figure 2.3 A cross-sectional view of a DC motor

2.1.2 Comparison of different DC motors

Direct current motors are named according to their field arrangement. There are three common types: series-wound, shunt-wound, and compound-wound.

2.1.2.1 The series-wound motor

A DC series motor has all the 6 fundamental components-axle, rotor (armature), stator, commutator, field magnet(s) and brushes-that are present in a generic DC motor.

Note:
The motor casing where two or more electromagnet pole pieces are housed forms the stationary part of the motor, the stator.

The armature, windings on a core, electrically connected to the commutator comprise the rotor. Rotor has a central axle about which the rotor rotates in relation to the stator. Power is supplied to the armature windings through the stationary brushes touching the rotating commutator.

Figure 2.4 shows that when the motor is running, the supply current passes through both the armature windings and the field windings in series. The series winding is normally of relatively few turns of suitably large-gauge wire. The curves of torque and speed against current are shown in **Figure 2.5**.

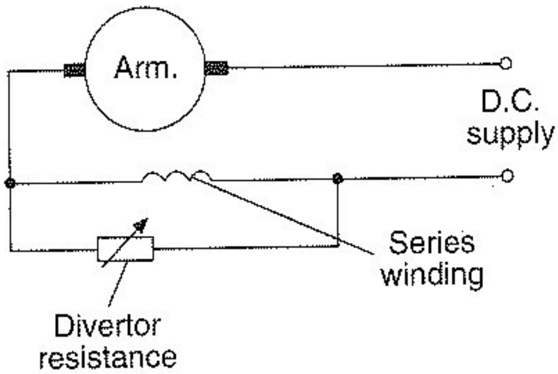


Figure 2.4 A series-wound motor

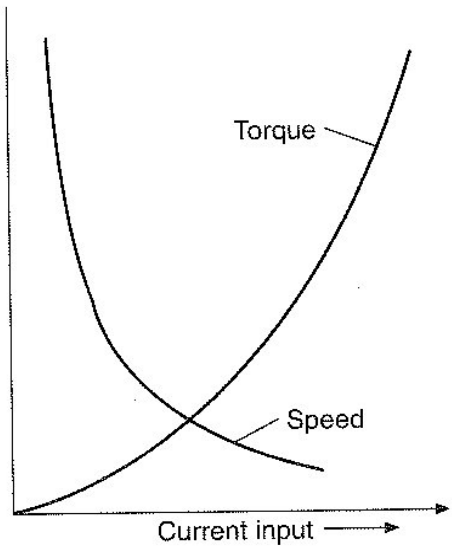


Figure 2.5 Characteristic curve of a series-sound motor

At low speeds the current is heavy and the turning effort is proportionately great. Thus, when starting under load, the torque and current are both large.

At no-load conditions the speed tends to increase beyond the safe speed of the motor.

From this it can be seen that a series motor must not run unloaded. Series-wound motors are suitable for such purposes as traction, where the motor is permanently mechanically connected to the load.

2.1.2.2 The shunt-wound motor

Figure 2.6 shows that the field winding is connected in parallel to the armature hence the name shunt winding.

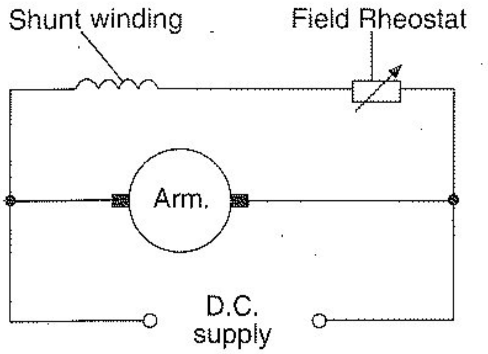


Figure 2.6 A shunt-wound motor

Figure 2.7 shows that the current through the field winding is approximately constant in value, from no-load to full load. Hence the speed will be fairly constant throughout the range of load. The torque is proportional to the current, is weak at low loads, and increases with increasing load.

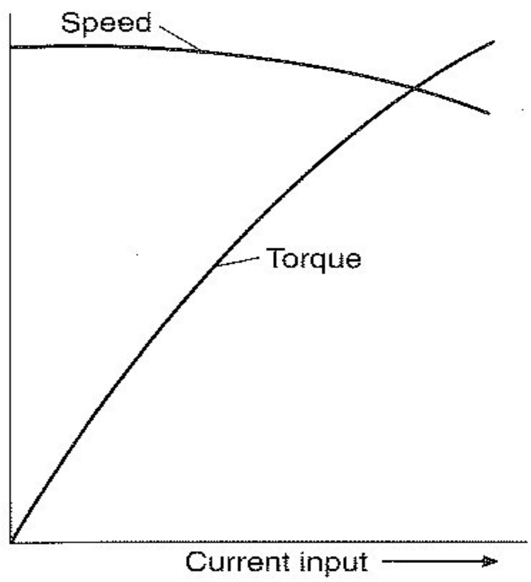


Figure 2.7 Characteristic curve of a shunt-wound motor

The shunt-wound motor is used for most general purposes owing to the constancy of speed. It has a good starting torque, and is used to drive machinery requiring a fairly constant speed at all loads up to full load.

2.1.2.3 The compound-wound motor

The compound-wound motor has both shunt and series field windings (**Figure 2.8**) The effect of the series winding is relatively weak compared with the shunt winding.

The series winding may be connected so as to assist the shunt winding ("cumulative compound") or to oppose the shunt winding ("*differential* compound").

Note:
The cumulative compound machine is used in cases where there are sudden heavy overloads as in rolling mills.

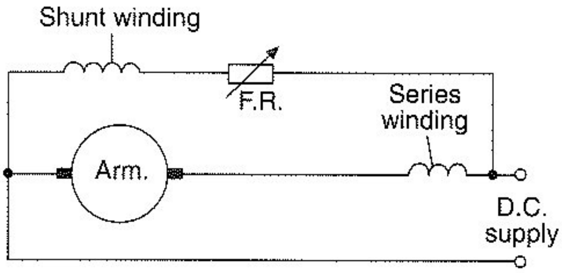


Figure 2.8 A compound-wound motor

The compound-wound motor is fitted with a heavy flywheel so that when a sudden heavy load comes on the machine, the speed of the motor decreases and the heavy power demand is supplied by the flywheel slowing down, reducing the sudden power demand on the main power supply.

The differential compound motor will give almost constant speed at all normal loads.

As the load increases and the speed of the motor as a shunt motor tends to drop, the series winding weakens the field, tending to increase the speed, thus giving a steady speed throughout the range of the load.

Figure 2.9 shows typical torque and speed curves for this motor. This type of motor is rarely used.

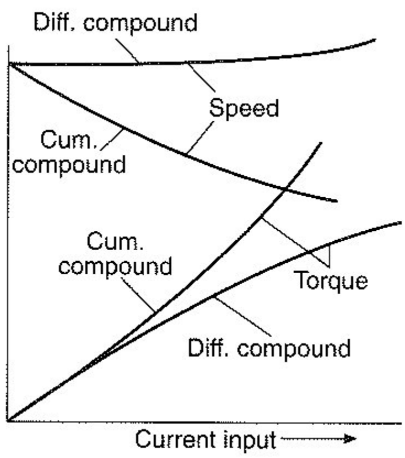


Figure 2.9 Characteristic curves of a direct current motor

Important: Compound machines may also be classified as long-shunt and short-shunt.

2.1.2.4 The short-shunt compound-wound motor

The shunt field winding is connected across the armature terminals. The voltage impressed on the shunt field is the line voltage less the RI drop.

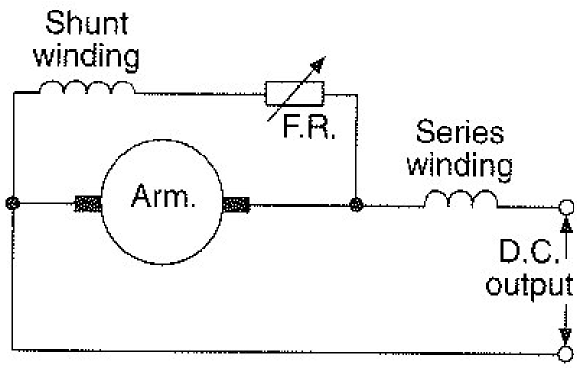


Figure 2.10 The short-shunt compound-wound motor

2.1.2.5 The long-shunt compound-wound motor

The shunt field winding is connected across the armature terminals and the series winding.

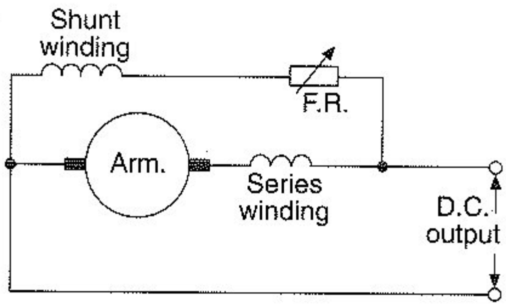


Figure 2.11 The long-shunt compound-wound motor

The voltage impressed on the shunt field in this case is the line voltage. The speed of the machine is affected by using this method.

2.3 Starters for DC motors

For all direct current motors a starting resistance is required. Since the resistance of a motor armature is very low, a large and damaging current will flow when the motor is first switched on.

This high starting current could blow the protection fuses, trip the circuit breakers and/or damage the starting equipment or motor.

To limit this starting current to a safe value, a starting resistor must be added in series to the armature circuit. This resistance is of sufficient ohmic value to cut down the starting current to a safe value.

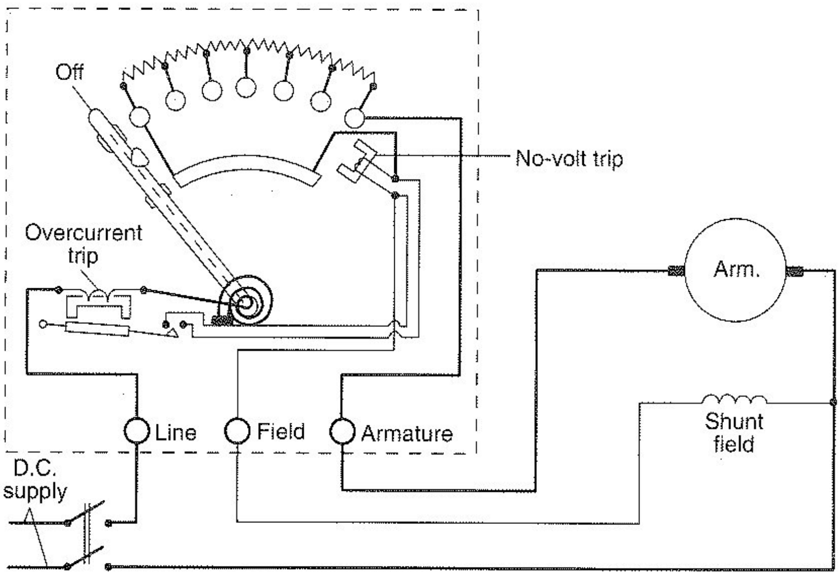


Figure 2.12 Face-place motor start for direct shunt motor

The resistance is divided into a number of sections, which may be cut out one by one as the motor speed rises and the back emf takes its part in reducing the armature current.

⚠	**Note:** Most starters include safety devices, an overload trip, and a no-volt trip.

A face-plate starter for a shunt or a compound motor is shown in **Figure 2.12**.

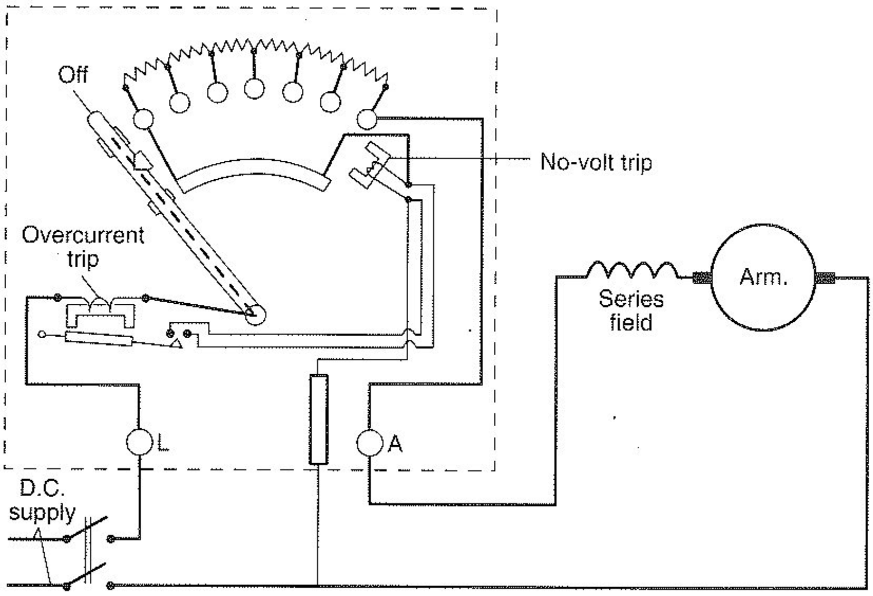


Figure 2.13 Face-plate motor starter for a series motor

The starter used for a series motor, **Figure 2.13**, is similar in construction and operation to that of a shunt motor, except that the no-volt trip is connected in series with a suitable resistor across the supply.

Very often, however, series motor starters are of the controller type and continuously rated so that they may be left in position and used for speed.

To comply with SANS 10142 (SABS 0142) Regulation 6.6.5 a no-voltage trip is supplied. The no- voltage trip coil is a small electromagnet connected in series with the motor shunt winding. The coil is energized when the starter handle is brought up to the first resistance stud, and remains energized unless the supply fails.

When the starter handle is at the end of its travel with all the starting resistances cut out of the armature circuit, the electromagnet holds firm a small soft iron armature which is pivoted loosely to the starter arm.

In the event of the supply failing by being purposely switched off or otherwise, the electromagnet is de-energized and the starter arm returns to its original position by the action of a spring. This cuts off the current to the motor, and prevents the motor from restarting automatically.

Note:
To comply with SANS 10142(SABS 0142) Regulation 6.6.2 an overcurrent protection device has to be installed.

The overcurrent trip (see **Figure 2.13**) is a small electromagnet consisting of a coil of few turns of heavy wire connected in series with the armature winding.

If the current passing through it is too great, the electromagnet attracts to its poles a soft iron adjustable armature, pivoted at one end. This movement of the iron armature is arranged to short-circuit the no-voltage trip, which in turn releases the starter handle, thus cutting off the supply to the motor.

2.3.1 Methods of inverting the rotational direction of a DC motor

The need for inverting the rotational direction of a DC motor may become clear in the following practical example:

When using a DC motor to drive a lift or escalator, it is necessary to invert the rotational direction of operation in order to ensure that the lift may operate in both directions, ie up and down.

The following methods may be used to invert the rotational direction of a DC motor:

- interchanging field winding connections
- reversing the armature connection

2.3.2 Interchanging the rotational direction of a series motor by word picture

Figure 2.14 illustrates the process of changing the rotational direction of a motor.

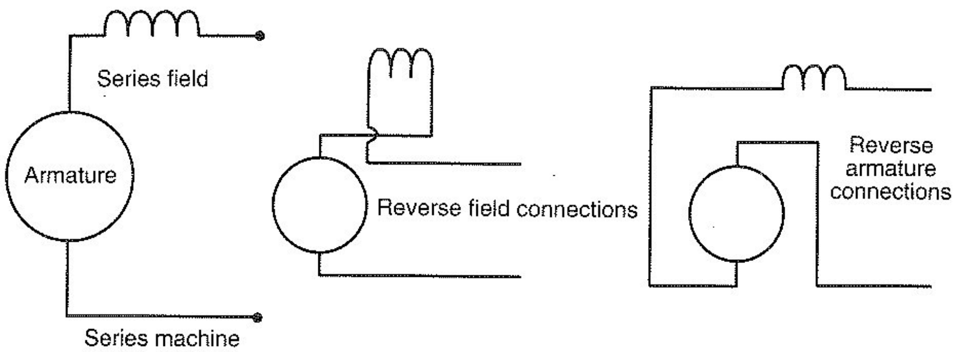


Figure 2.14 Reversing the direction of a rotation of a series motor

2.3.3 Interchanging the rotational direction of a shunt motor by word picture

By reversing the connections to either the shunt field or the armature, the excitation will also be reversed with the result that the machine may be rotated in the opposite direction. (See **Figure 2.15**)

Note:
It must be remembered that either the field or the armature connections must be reversed, depending on which is the easiest. Never reverse both.

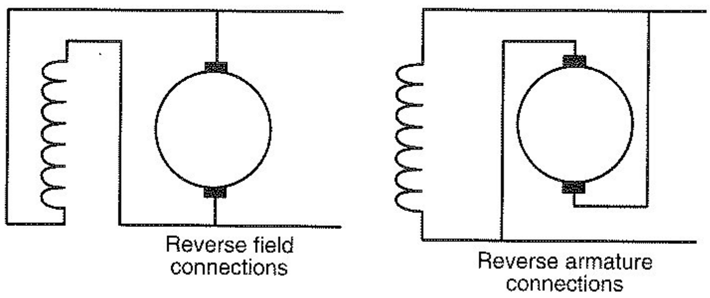
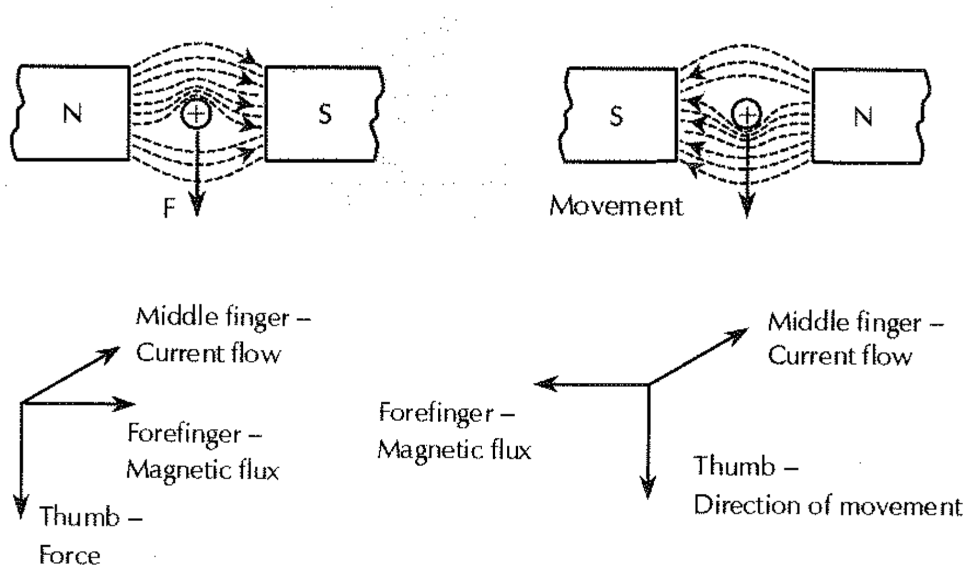


Figure 2.15 Reversing the direction of rotation of a shunt motor



(a) Motor - Fleming's left hand rule (b) Generator - Fleming's right hand rule

Figure 2.16

2.4 The working of a direct current motor

The current that flows in creates a clock-wise magnetic field, according to the corkscrew rule - see **Figure 2.17(a)**. Thus, the magnetic lines above the conductor are pressed together, causing the conductor to be pushed down - see **Figure 2.17(b).**

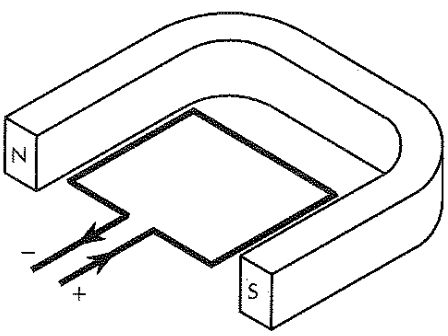


Figure 2.17 (a) Current that flows in creates a clock-wise magnetic field

Similarly, the other conductor is pushed up. This rotates the armature through 90°, where the commentator-segments change the direction of the current flow and the armature rotates through another 180°. This process continues.

Figure 2.18 (b)

The reason for the movement could also be explained with reference to Fleming's left hand rule.

2.4.1 Magnetic flux

One weber is the magnetic flux that, when cut by a conductor at a constant rate, induces an emf of 1 V in the conductor.

The flux can be spread over a wide area, thus it is necessary to determine the flux per unit area. The flux density (B) is measured in tesla (T). Flux density means the webers per square metre.

Symbol: phi, Φ
Unit: weber, Wb

$$\Phi = BA$$

Φ = flux in webers
B = flux density in tesla
A= area in m^2

	Note: We only use the area that is perpendicular to the flux. A magnetic flux will have no flux density in an area that is not perpendicular to the flux.

This formula can also be derived in the following manner:

One tesla (T) is that magnetic flux which will produce a force of 1 newton per metre of length (1N/m) on a conductor, carrying a current of 1 A, if the conductor moves perpendicularly through the flux.

$$F = BIl$$

We already know that force times distance is equal to work done.

Work done $= F.b$

$= BIlb$

We also know that electrical energy can be expressed as:

Electrical energy = $I\ E\ t$

Due to the conservation of energy statement, we can do the following:

Electrical energy = Mechanical energy

$$IEt = BIlb$$

$$B = \frac{IEt}{Ilb} \qquad l.b = A$$

$$\therefore B = \frac{\Phi t}{tA} \qquad E = \Phi/t$$

$$\text{thus } B = \frac{\Phi}{A}$$

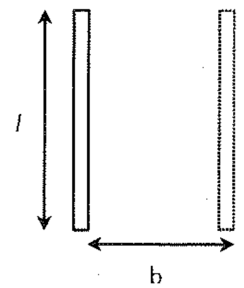


Figure 2.19

2.4.2 Field strength
Symbol: **H** Unit: **Nm**
Until now, we have only looked at the magnetic flux. This flux is caused by the magneto motive force (**m.m.f.**) which is created when a current flows through one or more of the windings. The unit of **m.m.f.** is amperes (A).

m.m.f. =IN

I = current through the windings
N = number of windings

The magneto motive force per metre length of the magnetic circuit is the field strength. The symbol for field strength is H and its unit is A/m.

$$H = \frac{IN}{l}$$

l = length of the *magnetic circuit*

M.m.f. can also be found as follows:

m.m.f. = H l

It is possible to determine both the field strength around a single conductor and the field strength in a magnetic circuit, for example a transformer core.

2.5 Armature windings

Armature windings are mainly of two types – **lap winding** and wave winding. Here we are going to discuss about **lap winding**.

2.4.1 Wave winding

Wave winding is one type of armature winding. In this winding the end of one coil is connected to the starting of another coil of the same polarity as that of the first coil.

In this type of winding the coil side(A-B) progress forward around the armature to another coil side and goes on successively passing through N and S pole till it returns to a conductor (A1-B1) lying under the starting pole.

This winding forms a wave with its coil, that's why it is named as wave winding. It is also called series winding because its coils are connected in series.

2.4.2 Lap winding

Lap winding is the winding in which successive coils overlap each other. It is named "Lap" winding because it doubles or laps back with its succeeding coils.

In this winding the finishing end of one coil is connected to one commutator segment and the starting end of the next coil situated under the same pole and connected with same commutator segment.

Here we can see in picture, the finishing end of coil - 1 and starting end of coil - 2 are both connected to the commutator segment - 2 and both coils are under the same magnetic pole that is N pole here.

Definition: Simplex lap winding
A winding in which the number of parallel path between the brushes is equal to the number of poles is called simplex lap winding.

Definition: Duplex lap winding
A winding in which the number of parallel path between the brushes is twice the number of poles is called duplex lap winding.

2.5 EMF generated in armature windings

Φ is the useful flux per pole

P is number of pole pairs

N is the speed

Z is the number of armature conductors

c is number of parallel paths between positive and negative brushes

$$\text{Number of conductors per path} = \frac{Z}{c}$$

$$\text{For a wave winding } c = 2$$

$$\text{For a lap winding } c = 2P$$

$$\text{Time taken to move past one pole pitch} = \frac{60}{2NP}$$

$$E = \frac{\Phi}{t}$$

$$\text{For one conductor } E = \frac{2NP\Phi}{60}$$

$$\text{Total } E = \frac{2ZNP\Phi}{60 \, . \, c}$$

2.6 Armature reaction

In a DC machine, the main field is produced by field coils. In both the generating and motoring modes, the armature carries current and a magnetic field is established, which is called the armature flux. The effect of armature flux on the main field is called the armature reaction.

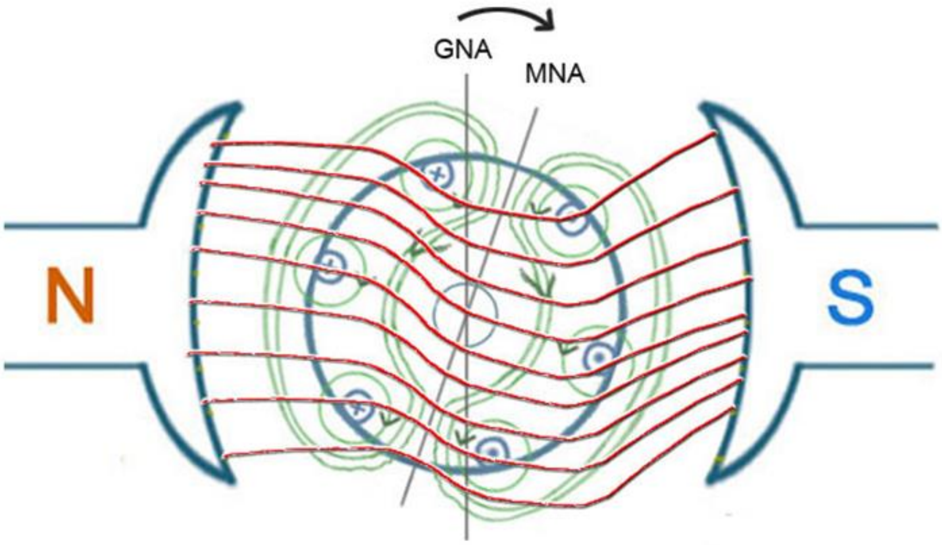


Figure 2.20 Distortion of main field flux due to armature flux – Armature reaction

The armature reaction:

- demagnetizes the main field, and
- cross magnetizes the main field.

The demagnetizing effect can be overcome by adding extra ampere turns on the main field winding. The cross magnetizing effect can be reduced by having common poles.

> **Note:**
> Armature reaction is essential in amplidine rotating amplifiers.

Armature reaction drop is the effect of a magnetic field on the distribution of the flux under main poles of a generator.

Since an armature is wound with coils of wire, a magnetic field is set up in the armature whenever a current flows in the coils. This field is at right angles to the generator field, and is called cross magnetization of the armature.

The effect of the armature field is to distort the generator field and shift the neutral plane. The neutral plane is the position where the armature windings are moving parallel to the magnetic flux lines, that is why an axis lying in this plane is called as magnetic neutral axis (MNA).

> **Note:**
> This effect is known as armature reaction and is proportional to the current flowing in the armature coils.

The brushes of a generator must be set in the neutral plane; that is, they must contact segments of the commutator that are connected to armature coils having no induced EMF. If the brushes were contacting commutator segments outside the neutral plane, they would short-circuit "live" coils and cause arcing and loss of power.

Without armature reaction, the magnetic neutral axis (MNA) would coincide with geometrical neutral axis (GNA). Armature reaction causes the neutral plane to shift in the direction of rotation, and if the brushes are in the neutral plane at no load, that is, when no armature current is flowing, they will not be in the neutral plane when armature current is flowing.

For this reason it is desirable to incorporate a corrective system into the generator design.

These are two principal methods by which the effect of armature reaction is overcome. The first method is to shift the position of the brushes so that they are in the neutral plane when the generator is producing its normal load current. In the other method, special field poles, called interpoles, are installed in the generator to counteract the effect of armature reaction.

The brush-setting method is satisfactory in installations in which the generator operates under a fairly constant load. If the load varies to a marked degree, the neutral plane will shift proportionately, and the brushes will not be the correct position at all times.

The brush-setting method is the most common means of correcting for armature reaction in small generators (those producing approximately 1000 W or less). Larger generators require the use of interpoles.

2.7 DC generators

2.7.1 Open circuit characteristic (OCC)

Open circuit characteristic is also known as magnetic characteristic or no-load saturation characteristic. This characteristic shows the relation between generated EMF at no load (E_0) and the field current (I_f) at a given fixed speed.

The OCC curve is just the magnetization curve and it is practically similar for all type of generators. The data for OCC curve is obtained by operating the generator at no load and keeping a constant speed.

Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain OCC curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.

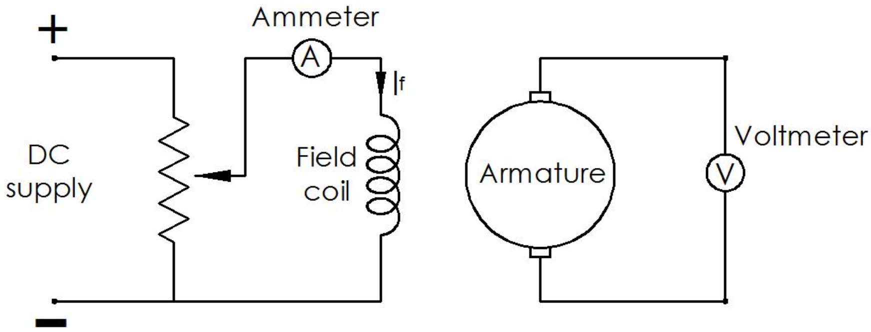


Figure 2.21

Now, from the EMF equation of DC generators, we know that $E_g = k\phi$. Hence, the generated EMF should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of EMF is generated (represented by OA in the figure below).

This initially induced EMF is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial EMF is induced in the armature. This initially induced EMF aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced EMF.

Thus, OCC follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the I_f further, ϕ remains constant and hence, E_g also remains constant. Hence, the OCC curve looks like the B-H characteristic.

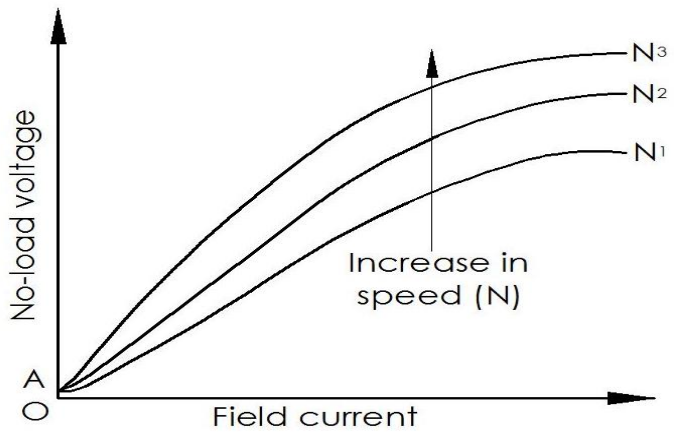


Figure 2.22 Open circuit characteristics (OCC)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

2.7.2 Internal or total characteristic

An internal characteristic curve shows the relation between the on-load generated EMF (Eg) and the armature current (I_a). The on-load generated EMF Eg is always less than E_0 due to the armature reaction.

Note:
Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0. Therefore, internal characteristic curve lies below the OCC curve.

2.7.3 External characteristic

An external characteristic curve shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated EMF Eg due to voltage drop in the armature circuit.

Therefore, external characteristic curve lies below the internal characteristic curve.

External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as performance characteristic or load characteristic.

Internal and external characteristic curves are shown below for each type of generator.

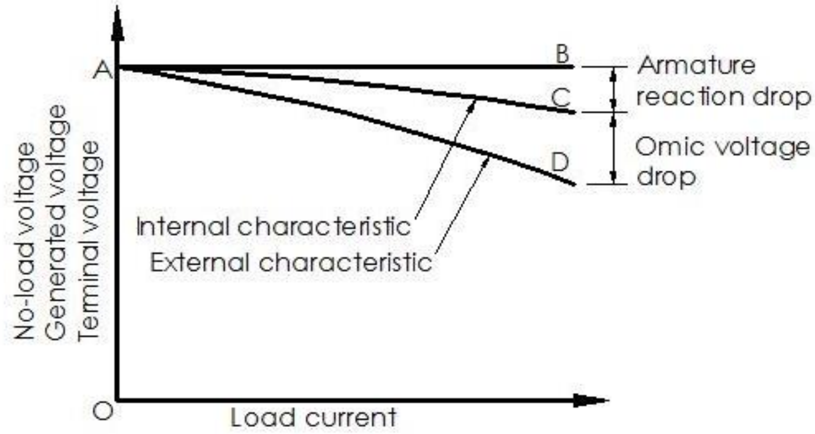


Figure 2.23 Characteristics of separately exited DC generator

If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs load current I_L.

Due to the demagnetizing effect of armature reaction, the on-load generated EMF is less than the no-load voltage. The curve AC represents the on-load generated EMF Eg vs. load current I_L, ie internal characteristic (as $I_a = I_L$ for a separately excited dc generator).

Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

2.7.4 Characteristics of DC shunt generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover.

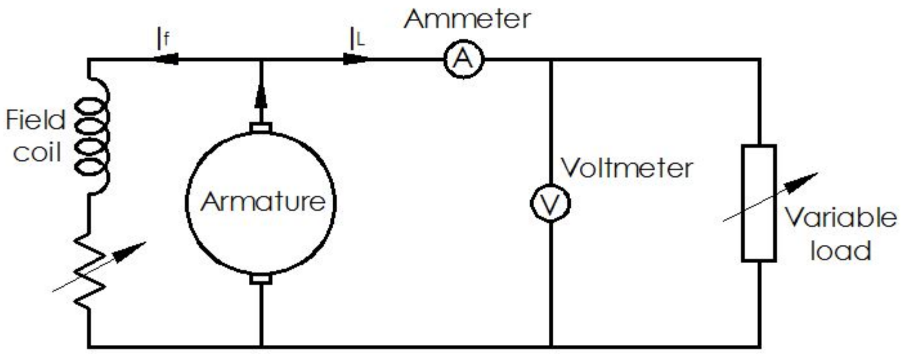


Figure 2.24

Initial voltage is induced due to residual magnetism in the field poles. The generator builds up its voltage as explained by the OCC curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals. Connection arrangement is as shown in **Figure 2.24**.

Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of I_f from I_a.

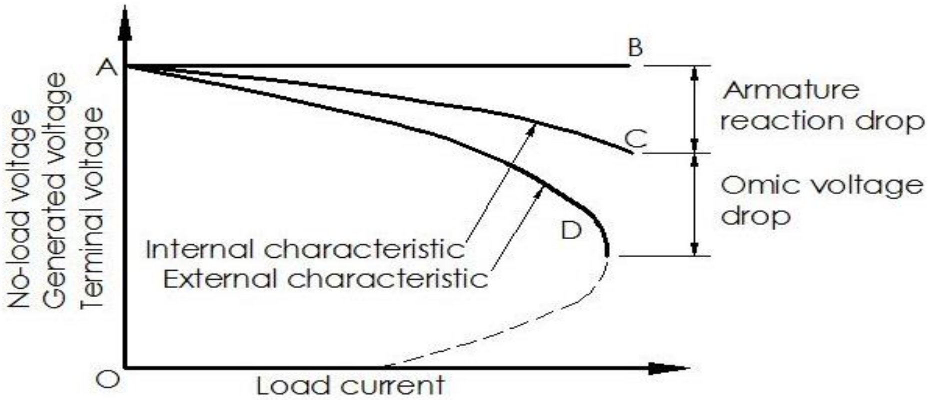


Figure 2.25 Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls.

So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses.

Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the above figure.

2.7.5 Characteristics of DC series generator

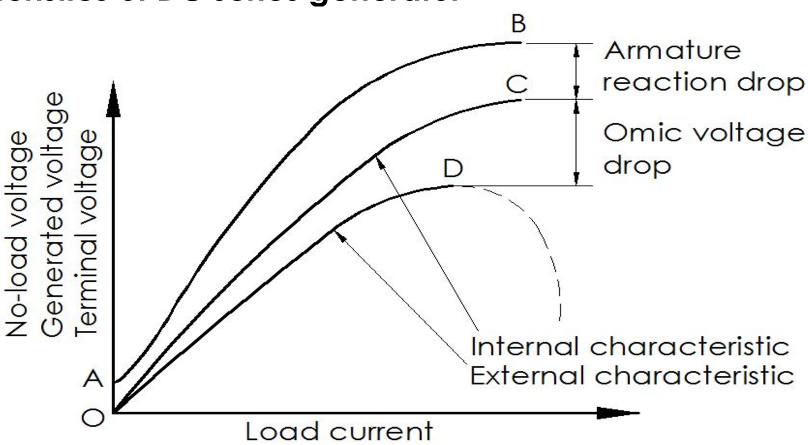


Figure 2.26 Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. $I_L=I_f$).

The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases.

However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

2.7.6 Characteristics of DC compound generator

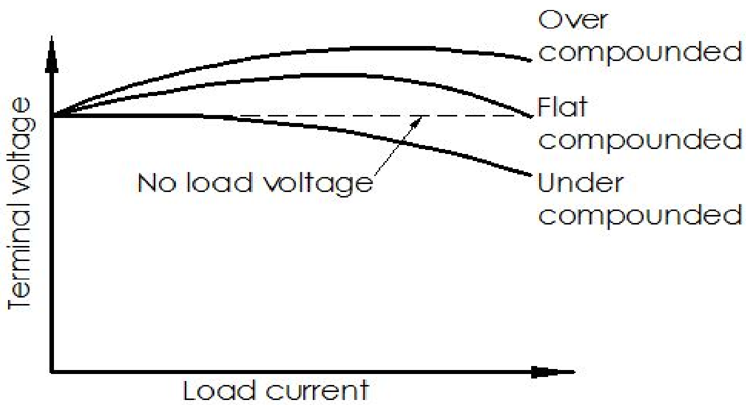


Figure 2.27 External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded.

The external characteristic for over compounded generator is shown by the curve AB in **Figure 2.27**.

Definition: Flat compounded
If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called flat compounded.

The external characteristic for a flat compounded generator is shown by the curve AC.

If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

Worked Example 2.1

A DC generator of EMF 75 V and an internal resistance of 0,5 ohms are connected in parallel with a battery of EMF of 41 V and internal resistance of 0,3 ohms. The combination is used to supply a load having a resistance of 2,5 ohms.

Use Kirchoff's laws to determine the following:

1. The value and direction of the current through the generator.
2. The value and direction of the current through the battery.
3. The terminal voltage across the load.

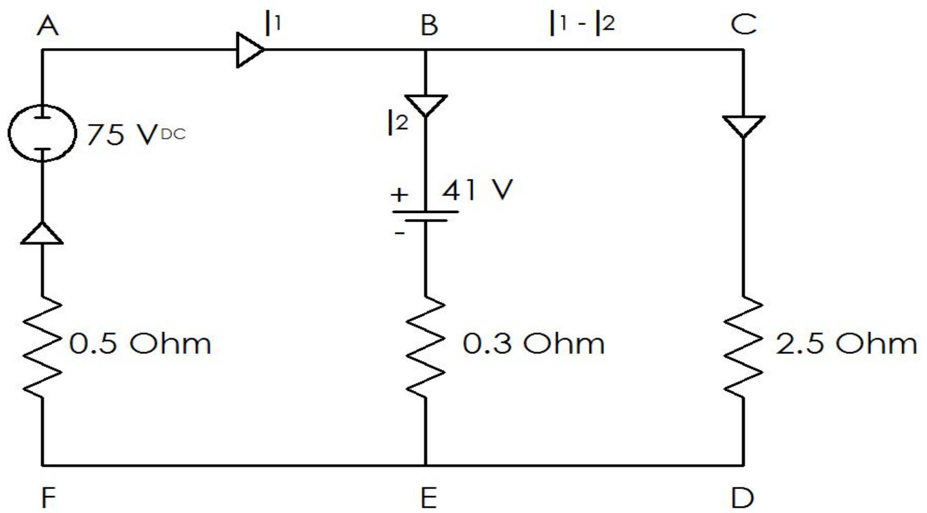


Figure 2.28

Solution:

$$\Sigma E = \Sigma IR = 0$$

$$(E_1 - E_2) - (I_1 R_1 - I_2 R_2) = 0$$

$$(75 - 41) - (0{,}5I_1 + 0{,}3I_2) = 0$$

$$34 - 0{,}5I_1 - 0{,}3I_2 = 0 \quad .... (1)$$

$$\Sigma E = \Sigma IR = 0$$

$$E - [I_1 R_1 + R_2(I_1 - I_2)] = 0$$

$$75 - 0{,}5I_1 - 2{,}5I_1 + 2{,}5I_2 = 0$$

$$75 - 3I_1 + 2{,}5I_2 = 0 \quad .... (2)$$

Eq $(1) \times 8{,}333$ $\quad 283{,}33 - 4{,}166I_1 - 2{,}5I_2 = 0$ .... (3)

Eq $(2) + (3)$ $\quad 358{,}333 - 7{,}166I_1 = 0$

Thus: $I_1 = \frac{358,333}{7,166} = 50\ A$

Substitute $I_1 = 50\ A\ into\ Eq\ (1)$

$$34 - 0,5(50) = \frac{9}{0,3} = 30\ A$$

$$I_1 - I_2 = 50 - 30 = 20A$$

1. $I_1 = 50\ A\ from\ positive\ to\ negative$
2. $I_2 = 30\ A\ from\ positive\ to\ negative$
3. $PD = IR = 20 \times 2,5 = 50\ V$

Worked Example 2.2

The open circuit characteristics of a separately excited generator is as follows:

Field cu rent (A)	10	20	30	40	85	100	120
EMF (V)	200	400	500	600	775	800	825

Table 2.1

Plot a graph and determine the following:

1. The voltage to which the machine will excite on no-load when shunt connected if the total field resistance is 8 ohms.
2. The value of the critical resistance.

Solution:

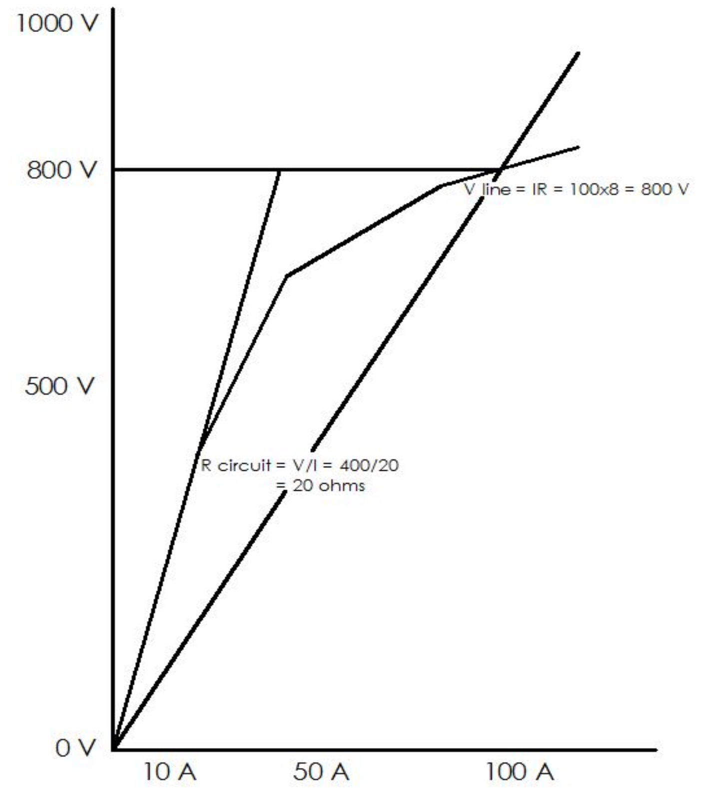


Figure 2.29

Worked Example 2.3

A short shunt compound generator supplies a load current of 80 A. It has a shunt field resistance of 40 ohms, an armature resistance of 0,2 ohms and a field resistance of 0,5 ohms.

Calculate the armature EMF if the terminal voltage is 360 V.

Solution:

$I_{SH} = \frac{V - I_1 R_{SF}}{R_{SH}}$

$= 360 + \frac{(80 \times 0{,}5)}{40}$

$= \frac{400}{40}$

$= 10\ A$

$I_a = I_L - I_{SH}$

$= 80 - 10$

$= 90\ A$

$E = V + I_a R_a + I_L R_{SE}$

$= 360 + (90 \times 0{,}2) + (80 \times 0{,}5)$

$= 418\ V$

Worked Example 2.4

A long-shunt compound-wound DC machine has an armature resistance of 0,2 ohms, a series field resistance of 0,3 ohms and a shunt field resistance of 50 ohms. The machine draws a current of 110 A from a 500 V DC supply when run as a motor.

Calculate the EMF generated in the armature.

Solution:

$$I_{SH} = \frac{V}{R_{SH}}$$

$$= \frac{500}{50}$$

$$= 10\ A$$

$$I_a = I_L - I_{SH}$$

$$= 110 - 10$$

$$= 100\ A$$

$$E = V + I_aR_a + I_LR_{SE}$$

$$= 500 - [(100 \times 0{,}2) + (100 \times 0{,}3)]$$

$$= 450\ V$$

Worked Example 2.5

A 4 pole, 316 shunt motor has its armature lap wound with 150 conductors. The armature draws a current of 80 A when the motor rotates at 1 200 r/min.

Calculate the useful flux per pole in Wb if the resistance of the armature is 0,2 ohm.

Solution:

$$\text{Flux} = X\text{Wb P} = 2$$

$$E = V - IR$$
$$= 316 - (80 \times 0{,}2)$$
$$= 300\ V$$
$$C = 2p = 2 \times 2 = 4 \quad Z = 150$$
$$E \times C \times 60/2.Z.N.P = \phi_m$$
$$\phi_m = 300 \times 4 \times 60/2 \times 150 \times 1200 \times 2$$
$$= 0{,}1\ Wb$$

Worked Example 2.6

Calculate the speed of a four-pole series generator having a wave-wound armature with 315 conductors and resistance of 0,6 ohm supplying a load of 50 kW at 1 000 V. The resistance of the field-winding brush contact resistance is 0,4 ohm. The field sets up a flux per pole of 0,1 Wb.

Solution:

$$\text{Flux} = 0{,}1\text{ Wb} \quad \text{P} = 2 \quad C = 2 \quad Z = 315$$
$$I_a = I_L = P/V = 50 \times 10^3/1000 = 50A$$
$$E = V + I_a(R_a + R_{SC})$$
$$= 1000 + 50(0{,}6 + 0{,}4)$$
$$= 1050\ V$$
$$E = (\frac{27}{C})(\frac{NP}{60}) \times \phi_m$$
$$1050 = \left(2 \times \frac{315}{2}\right)\frac{N2}{60} \times 0{,}1$$
$$N = 0{,}105\ N$$
$$= 1\ 000\ RPM$$

Activity 2.1

1. Identify the components of a direct current motor by means of a labelled freehand drawing, indicating clearly:
   a) the yoke
   b) the field windings
   c) the pole shoes
   d) the armature core
   e) the brushes
   f) the commutator
2. Compare different motors (shunt, series, long-shunt and short-shunt) in terms of:
   a) field windings
   b) full load speed
   c) no load speed
   d) starting torque
3. Draw circuit diagrams of:
   a) a shunt motor
   b) a series motor
   c) a compound wound motor
   d) a long-shunt motor
   e) a short-shunt motor
4. 4.Describe, with the aid of circuit diagrams, the operations of a face-plate-starter, related to:
   a) series motors
   b) shunt motors
5. Describe, with the aid of a diagram, methods of obtaining the reversal of direction of rotation or a series and shunt motor.

Activity 2.2

The open-circuit characteristics of a shunt-excited DC machine is as follows:

Terminal voltage (V)	10	20	25	28	30	30,5	31
Field current (A)	1,0	2,0	3,0	5,0	6,0	6,5	7,5

Table 2.2

Plot a graph and determine the following:
1. The voltage to which the machine will excite on no-load when shunt connected, if the total field resistance is 5 ohms.
2. The critical resistance.

[30; 10]

Activity 2.3

A short-shunt compound generator supplies a load current of 80 A. It has a shunt field resistance of 10 ohms, an armature resistance of 0,25 ohm and a field resistance of 0,1 ohm.

Calculate the armature EMF if the terminal voltage is 192 V.

[20; 225; 100]

Activity 2.4

The open-circuit characteristics of a shunt-excited DC machine is as follows:

Terminal voltage (V)	200	400	600	800	850	850
Field current (A)	2	4	6	10	12	15

Table 2.3

[900]

Activity 2.5

The open-circuit characteristics of a shunt-excited DC machine are as follows:

Terminal voltage (V)	80	160	240	320	340	360
Field current (A)	4	8	12	20	24	30

Table 2.4

Plot a graph and determine the open-circuit voltage if the field circuit resistance is 12 ohms.

[360]

Activity 2.6

A short-stunt compound generator supplies a load current of 100 A. It has a shunt-field resistance of 20 ohms, an armature resistance of 0,3 oh and a field resistance of 0,2 ohm.

Determine the armature EMF if the terminal voltage is 180 V.

[10; 233; 110]

Activity 2.7

The open-circuit characteristics of a separately excited DC-generator is as follows:

Terminal voltage (V)	40	80	130	155	160	165
Field current (A)	2	4	9	17	20	24

Table 2.5

Plot a graph and determine:

1. The voltage to which the machine will excite on no-load when shunt-connected, if the total field resistance is 8 ohms.
2. The value of the critical resistance.

[300; 200]

Activity 2.8

A short stunt compound generator supplies a load current of 100 A. It has a shunt field resistance of 50 ohms, an armature resistance of 0,1 ohms and a series field resistance of 0,5 ohms.

Calculate the armature EMF if the terminal voltage is 250 V.

[10; 100; 300]

Activity 2.9

The open-circuit characteristics of a shunt-excited DC machine a re as follows:

Terminal voltage (V)	200	400	500	580	610	620
Field current (A)	1	2	3	5	6,5	7,5

Table 2.6

Plot a graph and determine:

1. The voltage to which the machine will excite on no-load when shunt connected if the total field resistance is 100 ohms.

2. The critical resistance.

[600; 20]

Activity 2.10

A long-shunt compound-wound DC-machine has an armature resistance of 0,5 ohms, a series field resistance of 0,02 ohms, and a shunt field resistance of 35,2 ohms. The machine draws a current of 110 A from a 352 V DC-supply when run as a motor.

Calculate the EMF generated in the armature.

[10; 200; 400]

Self-Check

I am able to:	Yes	No
• Describe the uses of and characteristics of shunt, series and compound motors		
• Describe the purpose of the armature, brushes and the commutator		
• Calculate speed and starting torque		

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

Module 3

AC Circuit Theory

Learning Outcomes
On the completion of this module the student must be able to:

- Describe the generation of alternating EMF
- Describe reactance, inductance, capacitance, impedance
- Describe phasors and leading lagging power factors
- Calculate currents, RLC, frequency, rms value
- Calculate instantaneous values of waves and wave forms

3.1 Introduction

AC generators or alternators operate on the same fundamental principles of electromagnetic induction.

Alternating voltage may be generated by rotating a coil in the magnetic field or by rotating a magnetic field within a stationary coil. The value of the voltage generated depends on:

- the number of turns in the coil
- strength of the field
- the speed at which the coil or magnetic field rotates

Note:
An AC generator uses the principal of Faraday's electromagnetic induction to convert a mechanical energy such as rotation, into electrical energy, a Sinusoidal Waveform.

A simple generator consists of a pair of permanent magnets producing a fixed magnetic field between a north and a south pole. Inside this magnetic field is a single rectangular loop of wire that can be rotated around a fixed axis allowing it to cut the magnetic flux at various angles as shown in **Figure 3.1.**

As the coil rotates anticlockwise around the central axis which is perpendicular to the magnetic field, the wire loop cuts the lines of force set up between the north and south poles at different angles as the loop rotates.

The amount of induced EMF in the loop at any instant of time is proportional to the angle of rotation of the wire loop. As the loop rotates, electrons in the wire loop flow in one direction around the loop.

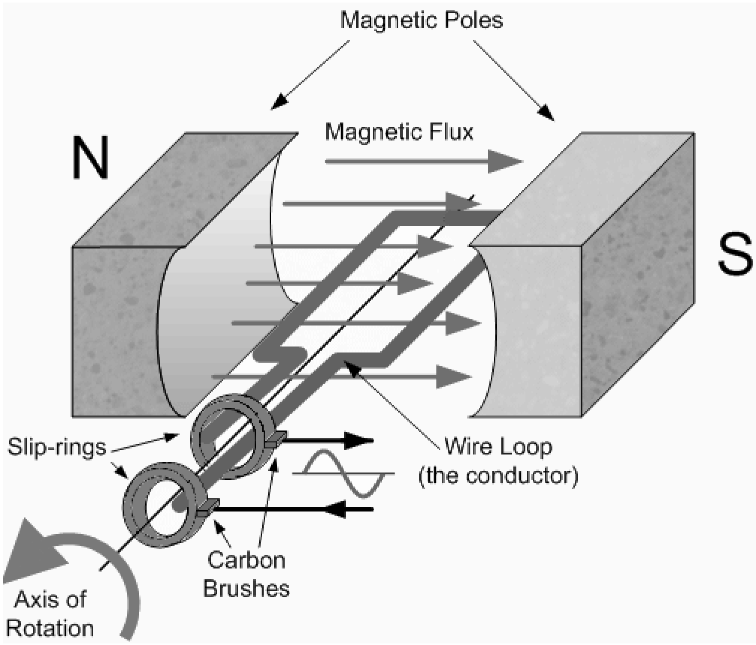


Figure 3.1 A simple generator

When the wire loop moves across the magnetic lines of force in the opposite direction, the electrons in the wire loop flow in the opposite direction.

Then the direction of the electron movement determines the polarity of the induced voltage. When the loop or coil rotates one complete revolution, or 360°, one full sinusoidal waveform is produced with one cycle of the waveform being produced for each revolution of the coil.

As the coil rotates within the magnetic field, the electrical connections are made to the coil by means of carbon brushes and slip-rings which are used to transfer the electrical current induced in the coil.

The amount of EMF induced into a coil cutting the magnetic lines of force is determined by the following three factors:

- Speed - the speed at which the coil rotates inside the magnetic field
- Strength - the strength of the magnetic field
- Length - the length of the coil or conductor passing through the magnetic field

Note:
Whenever there is a relative movement between a magnet and a nearby electrical coil, an electromotive force (EMF) is generated in the coil.

The value and other characteristics of the induced (EMF) depend on factors such as the magnetic field strength, the effective length of the coil and the angular velocity of the relative movement.

Definition: Dynamic and static induced EMF
When this relative movement is of a dynamical nature (physical), the generated voltage is known as dynamically induced EMF and when the relative movement is of a static (non-physical) nature, the generated voltage is known as statically induced EMF.

Electro-magnetic induction Generators (alternators) and electric motors work because forces act on current -carrying wires that are placed in magnetic fields. A motor converts electrical energy into mechanical energy.

The process can be put into reverse. If you turn a small motor by hand you produce a current. Then mechanical energy has been turned into electrical energy. This is called electromagnetic induction.

Figure 3.2 shows an experiment to find out what affects the making of a current.

Direction of movement. To get a current the wire must cut across lines of magnetic field. The wire must be moved up and down along the direction XX'. There is no current if the wire moves along ZZ' or YY'.

Reversing the direction of movement reverses the current. If moving the wire up makes the meter move to the right, moving the wire down will make the meter go to the left.

Size of current. You can make a larger current flow in the following ways:

- Moving the wire more quickly. When the wire is stationary
- between the poles of the magnet, there is no current.
- Using stronger and bigger magnets.
- Looping the wire so that several turns of wire pass through the poles.

Note:
These facts about electro-magnetic induction were first discovered by Faraday.

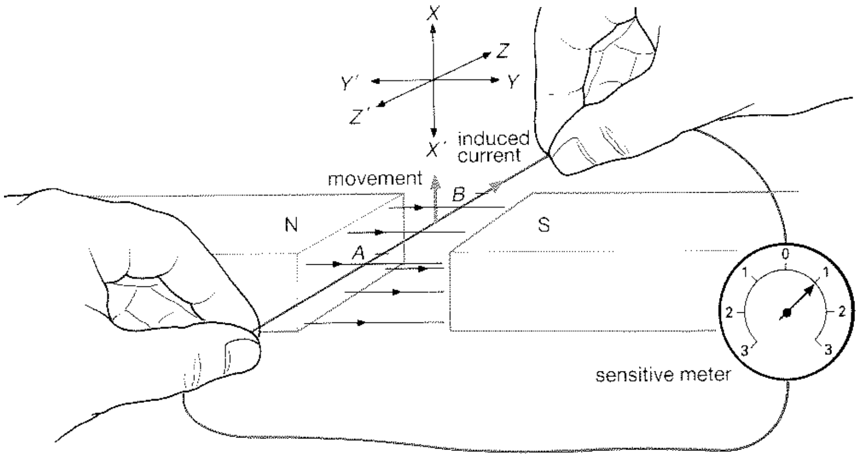


Figure 3.2 An experiment to find out what affects the making of a current.

Note:
Lenz's law of electromagnetic induction says: When a current is induced it always opposes the change in magnetic field that caused it. 'The end X of the solenoid is a north pole. So the effect of the induced current is to push the magnet back. This opposes the motion of the magnet, and agrees with Lenz 's law.

Angle and instantaneous value The angle measured along the base line is called the phase angle. This may be measured either in degrees or radius, and the two scales are shown in **Figure 2.92**. The instantaneous value is the value of current or voltage at any instant during the generation of a wave.

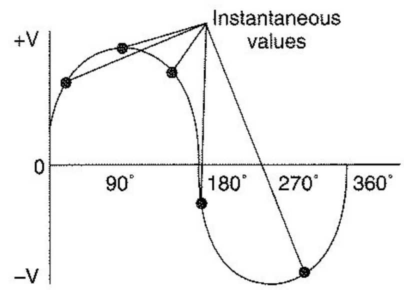


Figure 3.3 Phase angle

For maximum EMF:
$\theta = 90^{\circ}$ is the angle at maximum EMF
b is the breadth of the loop
n is the speed of rotation
V is the peripheral velocity

$$Maximum\ EMF = E_m = 2\,B\,L \times \pi\,b\,n$$

$$E_m = 2\,\pi\,B\,A\,n$$

$$Where\ A = \ L\ b$$

If this one loop is replaced by a coil of N turns each having an area A, then:

$$E_m = \ 2\ \pi\, B\ A\ N\ n$$

The instantaneous EMF (e) is:

$$Inatantaneous\ EMF\ \ \ e\ = \ E_m \sin\theta = \ 2\,\pi\ B\ A\ N\ n\ \ \sin\theta$$

The instantaneous value of the current (i) is:

$$Inatantaneous\ current\ \ i = \ \ I_m \sin\theta\ = \ I_m \sin(\omega\ t) = I_m \sin(2\ \pi\ f\ t)$$

$$e\ = \ E_m \sin(2\ \pi\ f\ t) =$$

Waveforms Alternating current (AC) and its associated voltage reverse between positive and negative polarities and varies in amplitude with time.

One complete waveform or cycle includes a complete set of variations, with two alternations in polarity. Many sources of voltage change direction with time and produce a resultant waveform.

Note:
The most common AC waveform is the sine wave.

Sine wave generation To understand how the alternating current sine wave is generated, some of the basic principles learned in magnetism should be reviewed.

Two principles form the basis of all electromagnetic phenomena:

- An electric current in a conductor creates a magnetic field that surrounds the conductor.
- Relative motion between a conductor and a magnetic field, when at least one component of that relative motion is in a direction that is perpendicular to the direction of the field, creates a voltage in the conductor.

Figure 3.4 shows how these principles are applied to generate an AC waveform in a simple one loop rotary generator. The conductor loop rotates through the magnetic field to generate the induced AC voltage across its open terminals. The magnetic flux shown here is vertical.

There are several factors affecting the magnitude of voltage developed by a conductor through a magnetic field.

They are the strength of the magnetic field, the length of the conductor, and the rate at which the conductor cuts directly across or perpendicular to the magnetic field.

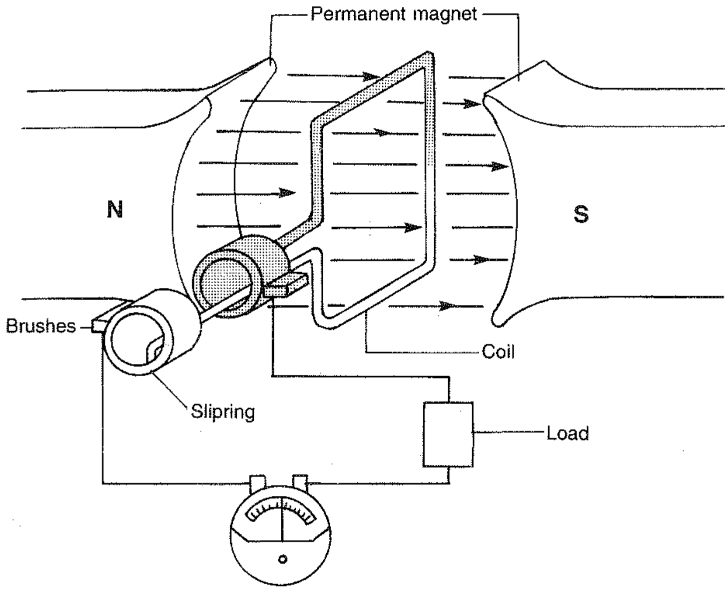


Figure 3.4 Conductor Moving Across A Magnetic Field

Characteristics of a Sine Wave A waveform 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 **Figure 3.5**).

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

- The PEAK TO PEAK value
- The AMPLITUDE
- The PEAK value
- The PERIODIC TIME
- The AVERAGE value
- The RMS value

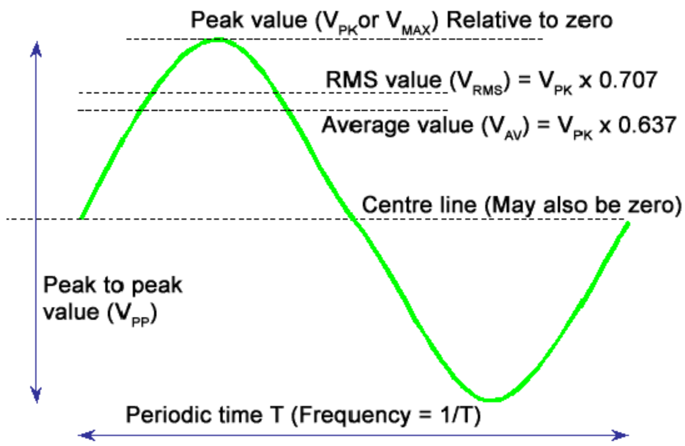


Figure 3.5 Characteristics of a sine wave

3.1.1 Frequency and speed

Both the sinus and the cosine waveforms have the same form and a cycle of 360°.

The big difference between the two is that one of the waves is moved in time with 90° before the sinus wave. This means that the cosine wave reaches its maximum value 90° before the sinus wave does.

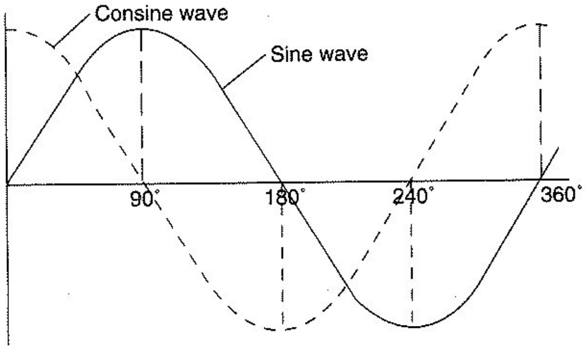


Figure 3.6 A waveform diagram of sinus and cosine waveforms

The sinus wave begins with the value 0 at 0°, 180° and 360° and reaches a peak value at 90° and minimum value at 270°. The cosines wave begins with a peak value at 0° and has the peak at 360°. The wave crosses the zero line at angles of 90° and 270° with a minimum at 180°.

Cycle A cycle can be seen as that part of the waveform before it starts to repeat itself. In the case of the sinus wave this is the part of the signal oscillating to a maximum on the positive side of the time axis, then back to zero on to the maximum negative and back to the zero line.

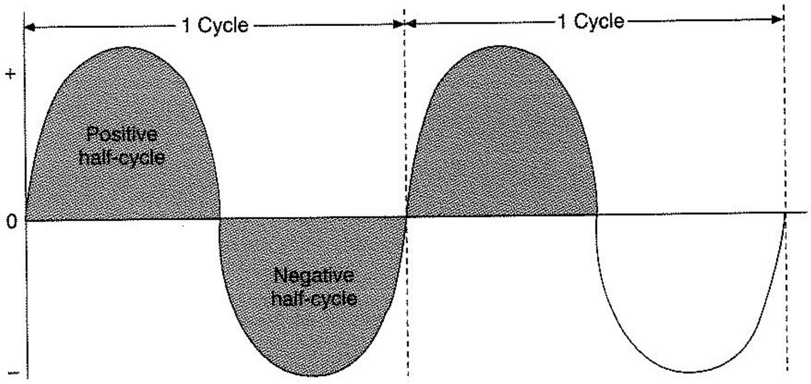


Figure 3.7 Cycle used in sinus wave

A cycle can be measured from any two corresponding points between which the waveform has gone through all its changes.

Period and frequency A period is the time taken to complete one cycle. The number of cycles executed in one second is called the frequency of the waveform.

Where f = frequency and t = time

A waveform of 50 Hz (cycles per second) will take 1/50 of a second (0,02 seconds) to go through one complete cycle (**Figure 3.8**).

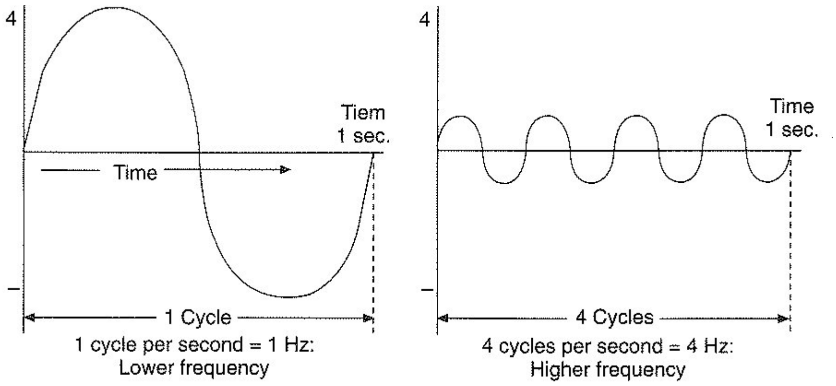


Figure 3.8 The period and frequency of a wave

Peak and peak-to-peak values With reference to **Figure 3.9**, the peak value of the wave is the maximum value (positive or negative), this can also be referred to as the amplitude. Peak-to-peak value is the sum of the positive peak and negative peak values of the wave, and may be calculated as follows:

peak-to-peak value = 2 x peak value

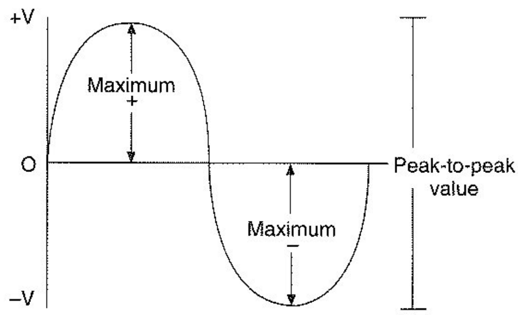


Figure 3.9 Peak and peak-to-peak values of the waveforms

p is the pairs of poles, so if a two pole machine generates an EMF at 50 Hz, then:

$$f = \frac{p\,N}{60}$$

$$and\ N = \frac{f \times 60}{p}$$

Terminology used in waveforms One cycle which is when an alternating current or voltage wave completes 360° electrical degrees ie when the wave rises from zero to positive maximum (Peak value), falls to zero, rises to negative maximum (peak value) and then falls back to zero again.

Definitions:

The **period time**, is the time taken for a wave to complete one cycle.

The **peak value** of the wave is the maximum value.

An **instantaneous value** of the wave (i, v or e) is the value of the waveform at a specific instant.

The ***peak to peak value*** of the waveform (vertical).

The **average value** is the average value of the wave taken over half a cycle. For a sine wave the average value = 0,637 x the maximum value. The average values of voltage and current are of little practical value.

The RMS value (**root mean square value**) which is the effective value of the current or voltage or that value of voltage or current which is equivalent to direct current when compared on an energy basis. The RMS value of a sine wave = 0,707 x the maximum value.

The **frequency** of an alternating current wave is the number of cycles which the wave completes in one second and is measured in hertz (Hz). In this country the standard frequency is so Hz (50 cycles per second).

3.1.2 Phasor representation

Phase angle: (The angle with which the current leads or lags the voltage.) In practice the current leads or lags the voltage by a much smaller angle.

This angle is referred to as the phase angle Φ (phi). In most cases the current lags the voltage as shown in **Figure 3.6**. In a purely resistive circuit the current is in phase with the voltage.

A phasor, is a complex number representing a sinusoidal function whose amplitude (A), angular frequency (ω), and initial phase (θ) are time invariant.

It decomposes a sinusoid into the product of a complex constant and a factor that encapsulates the frequency and time dependence. The complex constant, which encapsulates amplitude and phase dependence, is known as phasor, complex amplitude.

> **Note:**
> A common situation in electrical networks is the existence of multiple sinusoids all with the same frequency, but different amplitudes and phases. The only difference in their analytic representations is the complex amplitude (phasor).

A linear combination of such functions can be factored into the product of a linear combination of phasors (known as phasor arithmetic) and the time/frequency dependent factor that they all have in common.

The origin of the term phasor rightfully suggests that a (diagrammatic) calculus somewhat similar to that possible for vectors is possible for phasors as well.

An important additional feature of the phasor transform is that differentiation and integration of sinusoidal signals (having constant amplitude, period and phase) corresponds to simple algebraic operations on the phasors; the phasor transform thus allows the analysis (calculation) of the AC steady state of RLC circuits by solving simple algebraic equations.

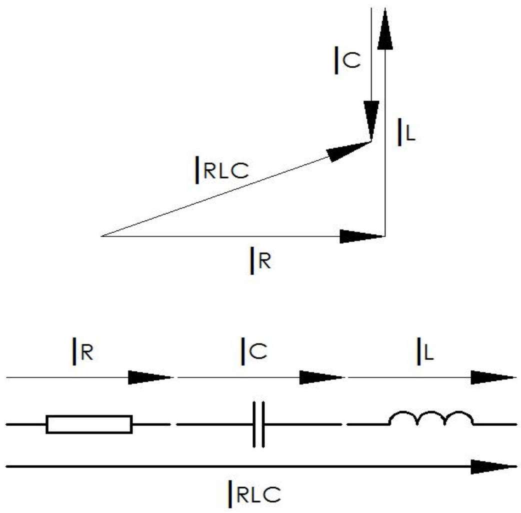


Figure 3.10 The RLC diagram for a specific speed

After the phasors have moved through θ, they occupy positions OA1 and OA1 respectively with OB1 leading OB1 with the angle Ø.

$$Inatantaneous\ EMF\quad e\ =\ E_m \sin(\theta + \emptyset)$$

$$Inatantaneous\ current\ \ i =\ I_m \sin\theta =$$

3.1.3 Phasor addition

Sometimes it is necessary when studying sinusoids to add together two alternating waveforms, for example in an AC series circuit, that are not in-phase with each other.

If they are in-phase that is, there is no phase shift then they can be added together in the same way as DC values to find the algebraic sum of the two vectors. For example, if two voltages of say 50 volts and 25 volts respectively are together "in-phase", they will add or sum together to form one voltage of 75 volts.

If however, they are not in-phase that is, they do not have identical directions or starting point then the phase angle between them needs to be taken into account so they are added together using phasor diagrams to determine their **Resultant Phasor** or **Vector Sum** by using the *parallelogram law*.

Consider two AC voltages, V_1 having a peak voltage of 20 volts, and V_2 having a peak voltage of 30 volts where V_1 leads V_2 by 60º. The total voltage, V_T of the two voltages can be found by firstly drawing a phasor diagram representing the two vectors and then constructing a parallelogram in which two of the sides are the voltages, V_1 and V_2 as shown below.

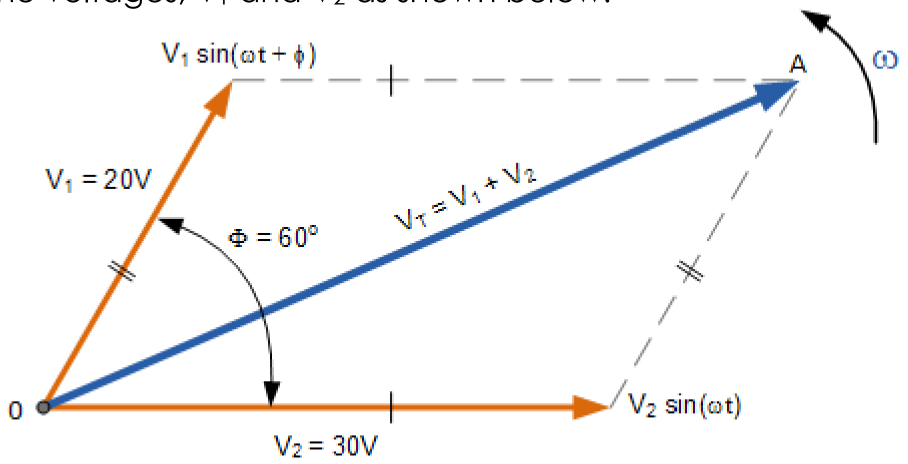


Figure 3.11 Phasor addition of two phases

By drawing out the two phasors to scale onto graph paper, their phasor sum $V_1 + V_2$ can be easily found by measuring the length of the diagonal line, known as the "resultant r-vector", from the zero point to the intersection of the construction lines 0-A.

⚠	**Note:** The downside of this graphical method is that it is time consuming when drawing the phasors to scale.

Also, while this graphical method gives an answer which is accurate enough for most purposes, it may produce an error if not drawn accurately or correctly to scale. Then one way to ensure that the correct answer is always obtained is by an analytical method.

Mathematically we can add the two voltages together by firstly finding their "vertical" and "horizontal" directions, and from this we can then calculate both the "vertical" and "horizontal" components for the resultant "r vector", V_T.

This analytical method which uses the cosine and sine rule to find this resultant value is commonly called the Rectangular Form.

In the rectangular form, the phasor is divided up into a real part, x and an imaginary part, y forming the generalized expression $Z = x \pm jy$. (we will discuss this in more detail in the next tutorial). This then gives us a mathematical expression that represents both the magnitude and the phase of the sinusoidal voltage.

3.1.4 RMS value

Root mean square (RMS) values: The RMS values of a wave refer to the effective D.C. value which will produce the same amount of energy and may be calculated as follows:

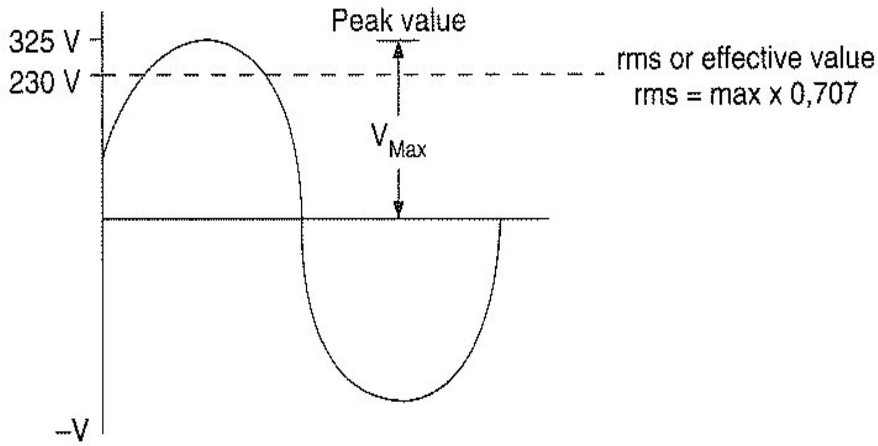


Figure 3.12 RMS value

Important Note!
A multimeter only measures RMS values whereas the peak values are measured using an oscilloscope.

3.1.5 Mean value

Average value

The average value is measured over a period of the wave. For a sinus the average value is zero because the charge transferred during the negative half-cycle is just equal and opposite to that transferred during the positive half-cycle.

In certain practical problems we are interested in the half-cycle average given by:

$$V_{half\ cycle\ average} = 0{,}637 \times V_{peak}$$

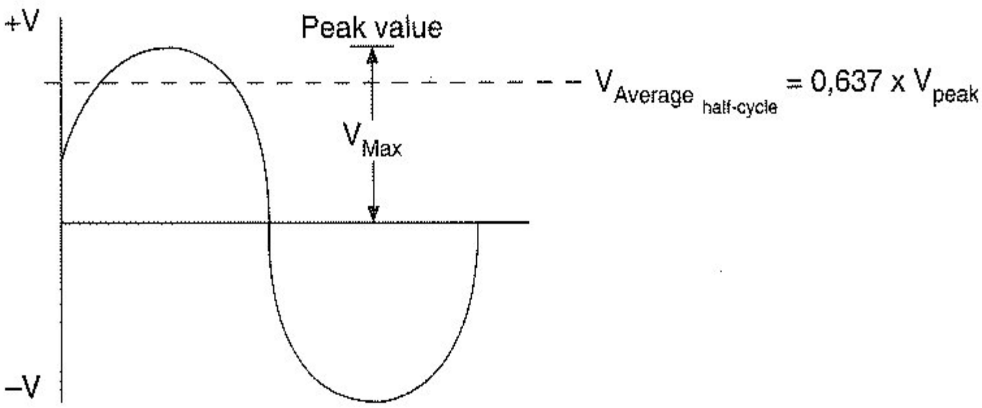


Figure 3.13 Average value of a sinus wave

3.2 Resistance

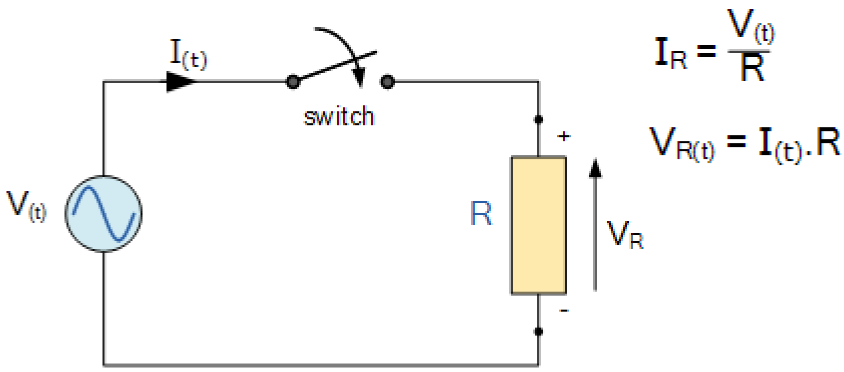


Figure 3.14 Pure resistance in an AC circuit

When the switch is closed, an AC voltage, V will be applied to resistor, R. This voltage will cause a current to flow which in turn will rise and fall as the applied voltage rises and falls sinusoidally.

As the load is a resistance, the current and voltage will both reach their maximum or peak values and fall through zero at exactly the same time, ie they rise and fall simultaneously and are therefore said to be "*in-phase*".

Then the electrical current that flows through an AC resistance varies sinusoidally with time and is represented by the expression, $I(t) = Im \times \sin(\omega t + \theta)$, where Im is the maximum amplitude of the current and θ is its phase angle.

In addition we can also say that for any given current, i flowing through the resistor the maximum or peak voltage across the terminals of R will be given by Ohm's Law as:

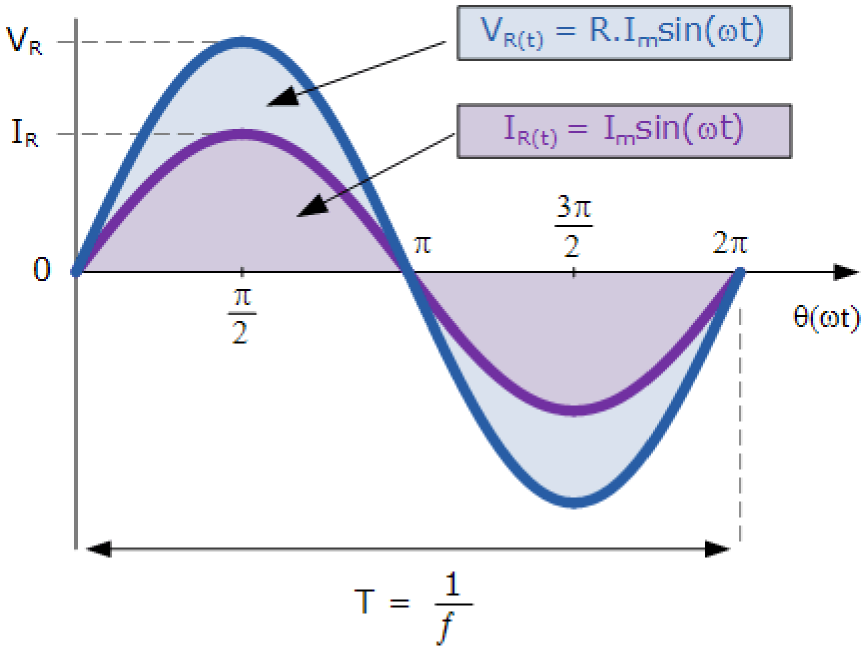


Figure 3.15 Sinusoidal waveforms of an AC circuit

3.3 Inductance

Inductors do not behave the same as resistors. Whereas resistors simply oppose the flow of electrons through them (by dropping a voltage directly proportional to the current), inductors oppose *changes* in current through them, by dropping a voltage directly proportional to the *rate of change* of current.

In accordance with *Lenz's Law*, this induced voltage is always of such a polarity as to try to maintain current at its present value. That is, if current is increasing in magnitude, the induced voltage will "push against" the electron flow; if current is decreasing, the polarity will reverse and "push with" the electron flow to oppose the decrease.

⚠	**Note:** This opposition to current change is called *reactance*, rather than resistance.

Expressed mathematically, the relationship between the voltage dropped across the inductor and rate of current change through the inductor is as such:

$$e = L\frac{di}{dt}$$

The expression *di/dt* is one from calculus, meaning the rate of change of instantaneous current (i) over time, in amps per second. The inductance (L) is in Henrys, and the instantaneous voltage (e), of course, is in volts.

Sometimes you will find the rate of instantaneous voltage expressed as "v" instead of "e" (v = L di/dt), but it means the exact same thing. To show what happens with alternating current, let's analyze a simple inductor circuit: **Figure 3.16.**

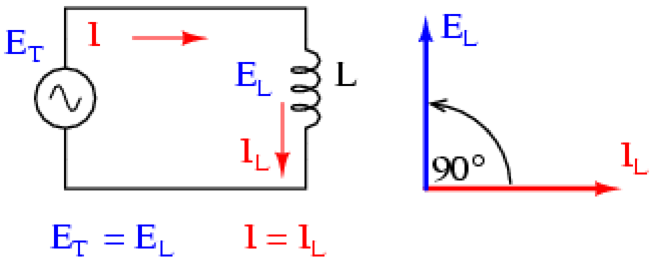


Figure 3.16 Simple inductor circuit

Pure inductive circuit: Inductor current lags inductor voltage by 90°.
If we were to plot the current and voltage for this very simple circuit, it would look something like this: **Figure 3.17.**

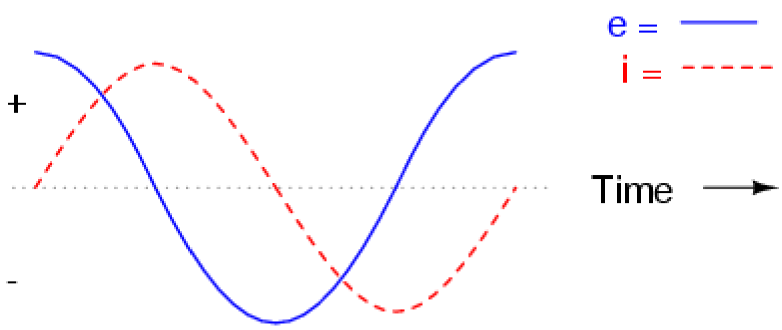


Figure 3.17 Pure inductive circuit, waveforms.

Remember, the voltage dropped across an inductor is a reaction against the *change* in current through it.

Therefore, the instantaneous voltage is zero whenever the instantaneous current is at a peak (zero change, or level slope, on the current sine wave), and the instantaneous voltage is at a peak wherever the instantaneous current is at maximum change (the points of steepest slope on the current wave, where it crosses the zero line).

This results in a voltage wave that is 90° out of phase with the current wave. Looking at the graph, the voltage wave seems to have a "head start" on the current wave; the voltage "leads" the current, and the current "lags" behind the voltage. **Figure 3.18.**

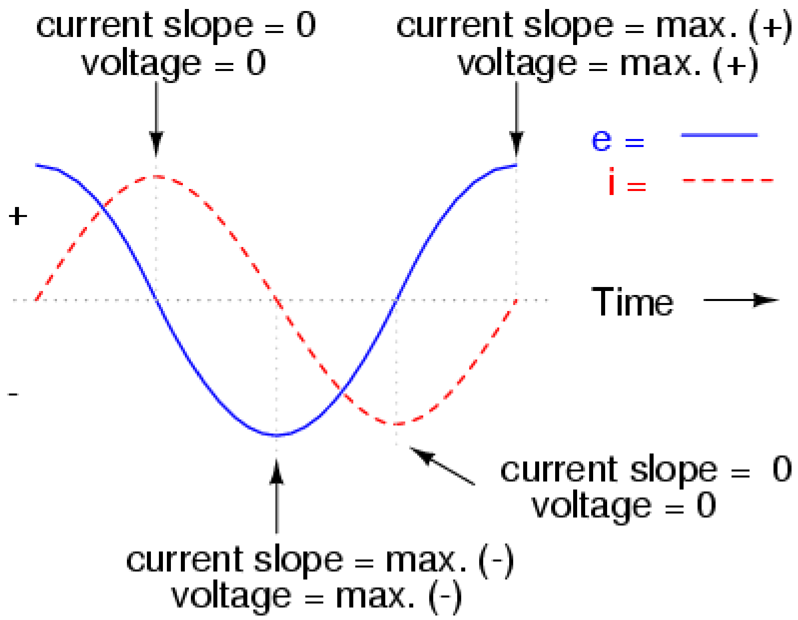


Figure 3.18 Current lags voltage by 90° in a pure inductive circuit.

The power for this circuit: **Figure 3.19**

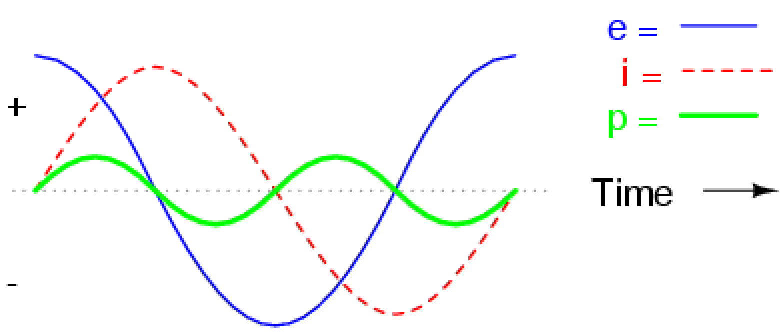


Figure 3.19 In a pure inductive circuit, instantaneous power may be positive or negative

Because instantaneous power is the product of the instantaneous voltage and the instantaneous current (p=ie), the power equals zero whenever the instantaneous current *or* voltage is zero. Whenever the instantaneous current and voltage are both positive (above the line), the power is positive.

As with the resistor example, the power is also positive when the instantaneous current and voltage are both negative (below the line). However, because the current and voltage waves are 90° out of phase, there are times when one is positive while the other is negative, resulting in equally frequent occurrences of *negative instantaneous power*.

3.4 Capacitance

Capacitors do not behave the same as resistors. Whereas resistors allow a flow of electrons through them directly proportional to the voltage drop, capacitors oppose *changes* in voltage by drawing or supplying current as they charge or discharge to the new voltage level.

The flow of electrons "through" a capacitor is directly proportional to the *rate of change* of voltage across the capacitor. This opposition to voltage change is another form of *reactance*, but one that is precisely opposite to the kind exhibited by inductors.

Expressed mathematically, the relationship between the current "through" the capacitor and rate of voltage change across the capacitor is as such:

$$i = C\frac{de}{dt}$$

The expression *de/dt* is one from calculus, meaning the rate of change of instantaneous voltage (e) over time, in volts per second. The capacitance (C) is in Farads, and the instantaneous current (i), of course, is in amps.

Sometimes you will find the rate of instantaneous voltage change over time expressed as dv/dt instead of de/dt: using the lower-case letter "v" instead or "e" to represent voltage, but it means the exact same thing.

To show what happens with alternating current, let's analyze a simple capacitor circuit: **Figure 3.20.**

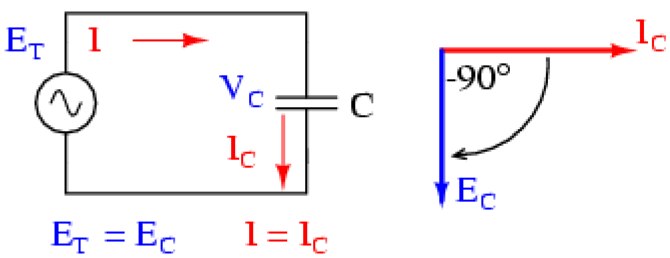


Figure 3.20 In a pure capacitor circuit

Pure capacitive circuit: capacitor voltage lags capacitor current by 90°.

If we were to plot the current and voltage for this very simple circuit, it would look something like this: **Figure 3.21.**

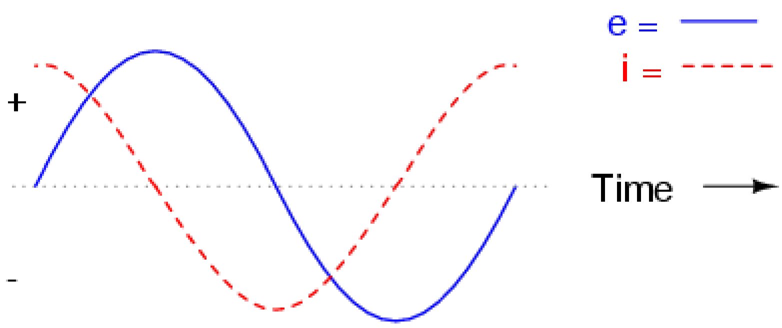


Figure 3.21 Pure capacitive circuit waveforms.

Remember, the current through a capacitor is a reaction against the *change* in voltage across it.

Therefore, the instantaneous current is zero whenever the instantaneous voltage is at a peak (zero change, or level slope, on the voltage sine wave), and the instantaneous current is at a peak wherever the instantaneous voltage is at maximum change (the points of steepest slope on the voltage wave, where it crosses the zero line).

Note:
This results in a voltage wave that is -90° out of phase with the current wave.

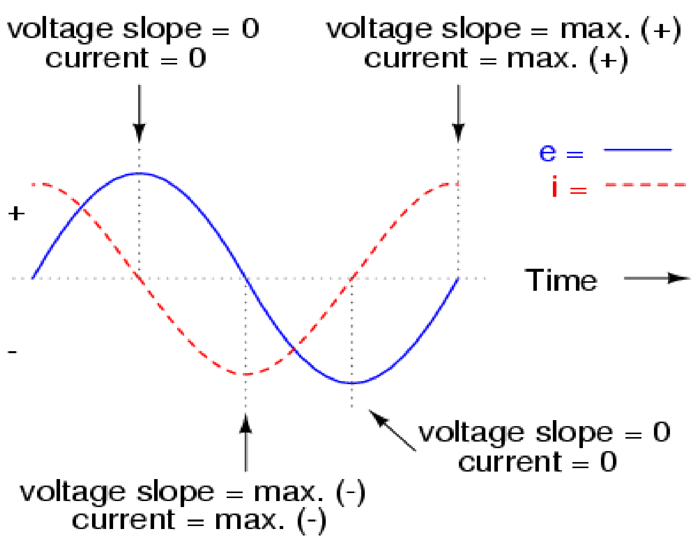


Figure 3.22 Voltage lags current by 90° in a pure capacitive circuit.

Looking at the graph, the current wave seems to have a "head start" on the voltage wave; the current "leads" the voltage, and the voltage "lags" behind the current. **Figure 3.22.**

The same unusual power wave that we saw with the simple inductor circuit is present in the simple capacitor circuit, too: **Figure 3.23**

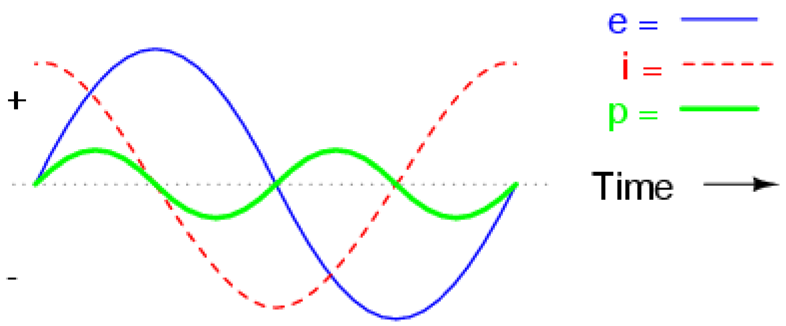


Figure 3.23 In a pure capacitive circuit, the instantaneous power may be positive or negative.

As with the simple inductor circuit, the 90 degree phase shift between voltage and current results in a power wave that alternates equally between positive and negative. This means that a capacitor does not dissipate power as it reacts against changes in voltage; it merely absorbs and releases power, alternately.

3.5 Series circuit

Thus far we have seen that the three basic passive components, R, L and C have very different phase relationships to each other when connected to a sinusoidal AC supply.

In a pure ohmic resistor the voltage waveforms are "in-phase" with the current. In a pure inductance the voltage waveform "leads" the current by 90°, giving us the expression of ELI. In a pure capacitance the voltage waveform "lags" the current by 90°, giving us the expression of ICE.

This Phase Difference, Φ depends upon the reactive value of the components being used and hopefully by now we know that reactance, (X) is zero if the circuit element is resistive, positive if the circuit element is inductive and negative if it is capacitive thus giving their resulting impedances as:

Instead of analyzing each passive element separately, we can combine all three together into a series RLC circuit.

The analysis of a **series RLC circuit** is the same as that for the dual series R_L and R_C circuits we looked at previously, except this time we need to take into account the magnitudes of both X_L and X_C to find the overall circuit reactance.

Series RLC circuits are classed as second-order circuits because they contain two energy storage elements, an inductance L and a capacitance C. Consider the RLC circuit **Figure 3.24**.

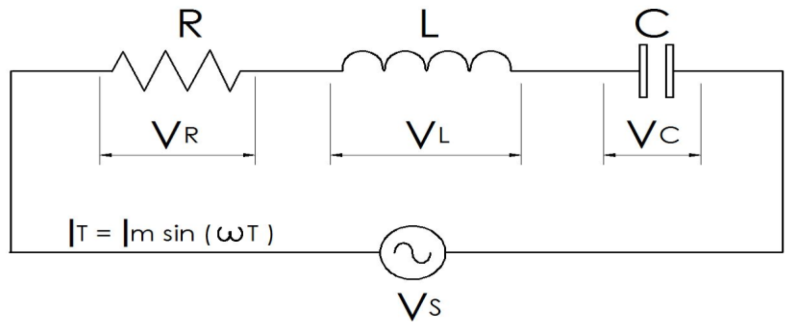


Figure 3.24 RLC circuit.

The series RLC circuit above has a single loop with the instantaneous current flowing through the loop being the same for each circuit element.

Since the inductive and capacitive reactance's X_L and X_C are a function of the supply frequency, the sinusoidal response of a series RLC circuit will therefore vary with frequency, f.

Then the individual voltage drops across each circuit element of R,L and C element will be "out-of-phase" with each other as defined by:

- $i_{(t)} = I_{max} \sin(\omega t)$
- The instantaneous voltage across a pure resistor, V_R is "in-phase" with the current.
- The instantaneous voltage across a pure inductor, V_L "leads" the current by 90^o
- The instantaneous voltage across a pure capacitor, V_C "lags" the current by 90^o
- Therefore, V_L and V_C are 180^o "out-of-phase" and in opposition to each other.

For the series RLC circuit **Figure 3.25**, this can be shown as:

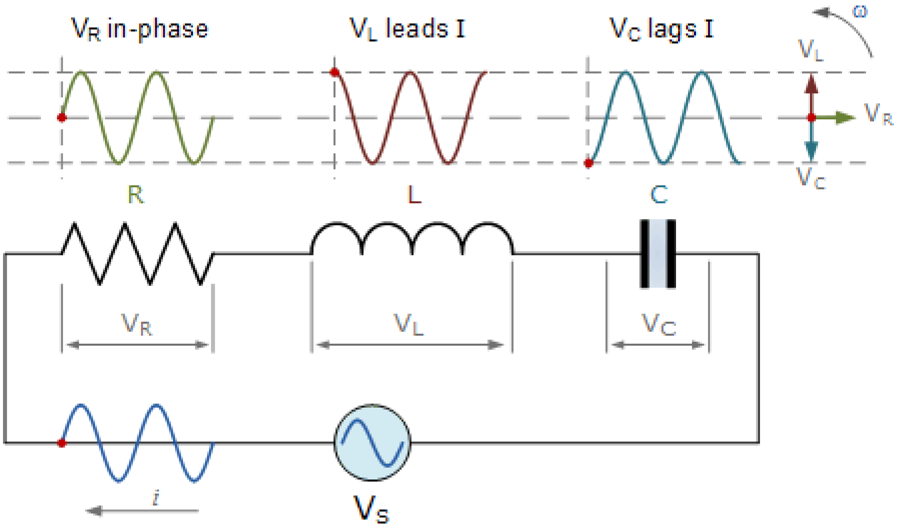


Figure 3.25 Series RLC circuit.

The amplitude of the source voltage across all three components in a series RLC circuit is made up of the three individual component voltages, V_R, V_L and V_C with the current common to all three components.

The vector diagrams will therefore have the current vector as their reference with the three voltage vectors being plotted with respect to this reference as shown **Figure 3.26**.

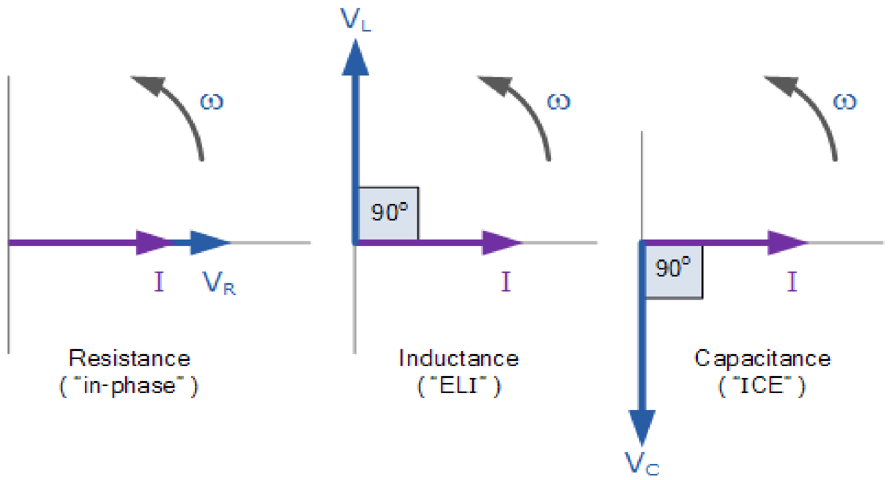


Figure 3.26 Series RLC circuit.

This means then that we cannot simply add together V_R, V_L and V_C to find the supply voltage, V_S across all three components as all three voltage vectors point in different directions with regards to the current vector.

Therefore, we will have to find the supply voltage, V_S as the **Phasor Sum** of the three component voltages combined together vectorially.

Kirchhoff's voltage law (KVL) for both loop and nodal circuits states that around any closed loop the sum of voltage drops around the loop equals the sum of the EMF's. Then applying this law to these three voltages will give us the amplitude of the source voltage, V_S as:

Instantaneous Voltages for a Series RLC Circuit

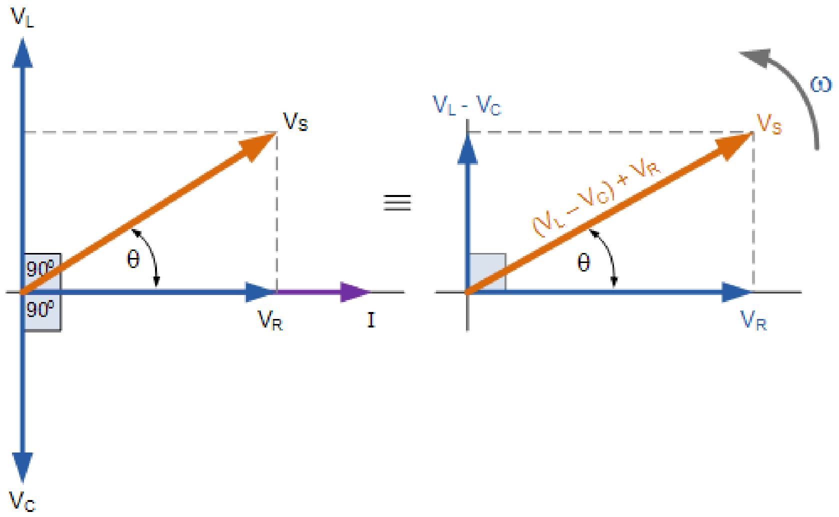


Figure 3.27

3.6 Impedance

Electrical impedance is the measure of the opposition that a circuit presents to a current when a voltage is applied.

In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit. Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude.

The induction of voltages in conductors self-induced by the magnetic fields of currents (inductance), and the electrostatic storage of charge induced by voltages between conductors (capacitance).

The impedance caused by these two effects is collectively referred to as reactance and forms the imaginary part of complex impedance whereas resistance forms the real part.

The symbol for impedance is usually Z and it may be represented by writing its magnitude and phase in the form $|Z|\angle\theta$. However, Cartesian complex number representation is often more powerful for circuit analysis purposes.

Definition: Impedance
The frequency domain ratio of the voltage to the current. In other words, it is the voltage–current ratio for a single complex exponential at a particular frequency ω.

In general, impedance will be a complex number, with the same unit as resistance, for which the SI unit is the ohm (Ω). For a sinusoidal current or voltage input, the polar form of the complex impedance relates the amplitude and phase of the voltage and current. In particular:

- The magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude.
- The phase of the complex impedance is the phase shift by which the current lags the voltage.

The reciprocal of impedance is admittance (i.e., admittance is the current-to-voltage ratio, and it conventionally carries units of Siemens, formerly called mhos).

X is the difference between X_L and X_C
If X_L is greater, the power factor will be lagging
If X_C is greater, the power factor will be leading.

$$Z = \sqrt{R^2 \ (X_L - X_C)^2}$$

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

3.7 Phase angle

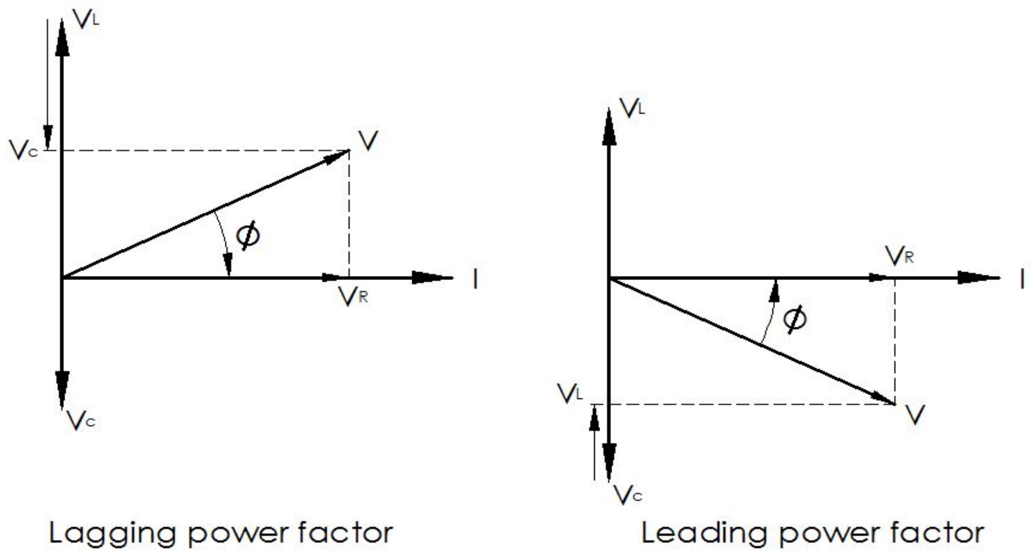


Figure 3.28 Phase angle with lagging and leading power factor

$$Lagging\ PF\ \tan\emptyset = \frac{V_L - V_C}{V_R} \qquad Leading\ PF\ \tan\emptyset = \frac{V_C - V_L}{V_R}$$

$$Lagging\ PF\ \tan\emptyset = \frac{X_L - X_C}{R} \qquad Leading\ PF\ \tan\emptyset = \frac{X_C - X_L}{R}$$

$$\tan\emptyset = \frac{X}{R}$$

3.8 Power

When there is a phase difference between the voltage and current, the actual power is not equal to *VI*. It is lower.

$$\text{Power} = PD \times \text{The inphase component}$$

$$\text{True or Actual Power P} = V\,I\,\cos\emptyset$$

I is the in-phase component of the current

$$\text{True Power P} = I^2\,R$$

$$\text{Apparent Power S} = V\,I$$

Power factor:

The power factor is a ratio between the true power and the apparent power:

$$\text{Power factor} = \frac{True\ power}{Apparent\ power}$$

$$\text{Power factor} = \frac{V\,I\,\cos\emptyset}{V\,I}$$

$$\therefore\ \text{Power factor} = \cos\emptyset$$

3.8.1 Low power factor

The power factor should be kept as high as possible because this will provide an efficient system.

To keep it high, the current should be brought as near into phase with the voltage as possible.

If the current is far out of phase with the voltage, the following negative effects will manifest themselves:

- An increase in resistance losses that will lessen the efficient of the equipment and supply.
- The output of generators and transformers are limited.

- Causes a greater fall in terminal voltage across power lines and equipment.

3.9 Parallel circuit

The Parallel RLC Circuit is the exact opposite to the series circuit we looked at in the previous tutorial although some of the previous concepts and equations still apply.

However, the analysis of *parallel RLC circuits* can be a little more mathematically difficult than for series RLC circuits so in this tutorial about parallel RLC circuits only pure components are assumed in this tutorial to keep things simple.

This time instead of the current being common to the circuit components, the applied voltage is now common to all so we need to find the individual branch currents through each element.

The total impedance, Z of a parallel RLC circuit is calculated using the current of the circuit similar to that for a DC parallel circuit, the difference this time is that admittance is used instead of impedance. Consider the parallel RLC circuit **Figure 3.29**.

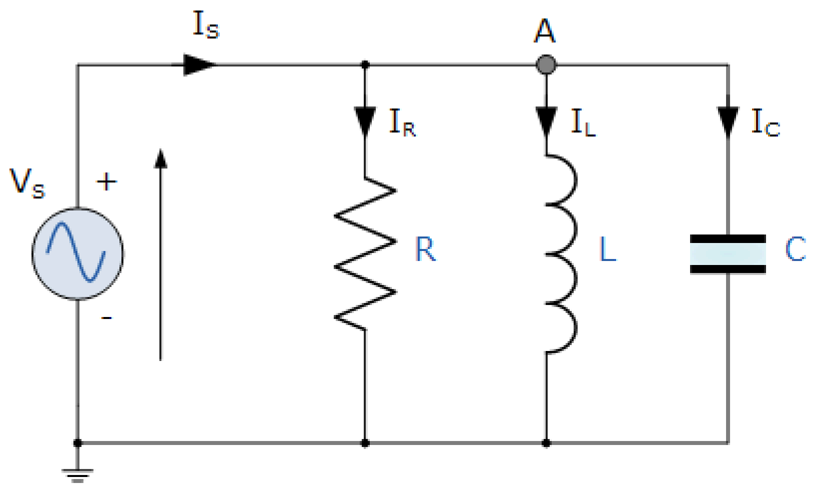


Figure 3.29 Parallel RLC circuit

In the above parallel RLC circuit, we can see that the supply voltage, V_S is common to all three components whilst the supply current I_S consists of three parts. The current flowing through the resistor, I_R, the current flowing through the inductor, I_L and the current through the capacitor, I_C.

But the current flowing through each branch and therefore each component will be different to each other and to the supply current, I_S. The total current drawn from the supply will not be the mathematical sum of the three individual branch currents but their vector sum.

Like the series RLC circuit, we can solve this circuit using the phasor or vector method but this time the vector diagram will have the voltage as its reference with the three current vectors plotted with respect to the voltage.

The phasor diagram for a parallel RLC circuit is produced by combining together the three individual phasors for each component and adding the currents vectorially.

Since the voltage across the circuit is common to all three circuit elements we can use this as the reference vector with the three current vectors drawn relative to this at their corresponding angles.

The resulting vector I_S is obtained by adding together two of the vectors, I_L and I_C and then adding this sum to the remaining vector I_R. The resulting angle obtained between V and I_S will be the circuits phase angle as shown **Figure 3.30**.

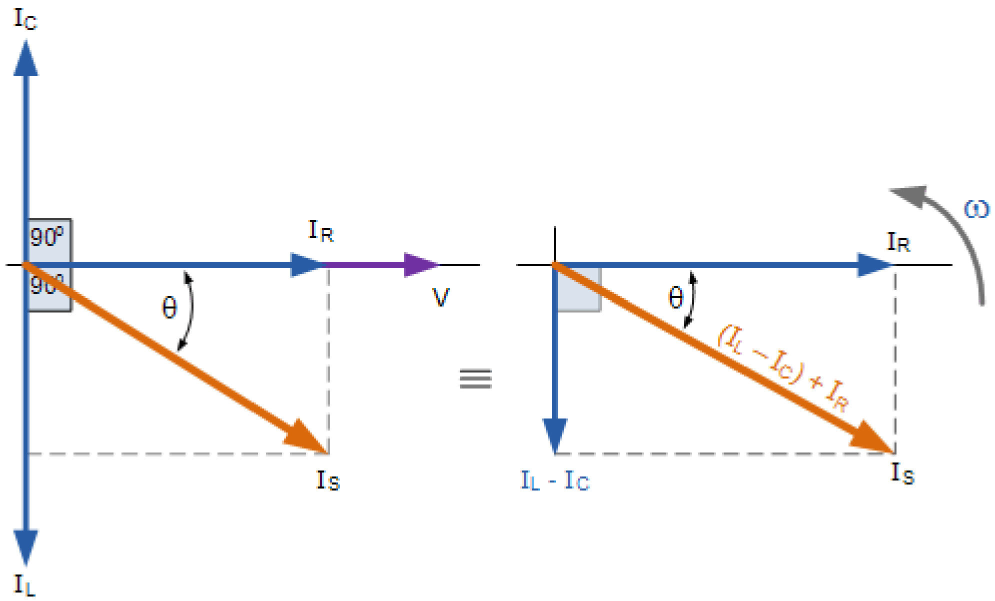


Figure 3.30 Circuits phase angle

We can see from the phasor diagram on the right hand side above that the current vectors produce a rectangular triangle, comprising of hypotenuse I_S, horizontal axis I_R and vertical axis $I_L - I_C$.

Hopefully you will notice then, that this forms a Current Triangle and we can therefore use Pythagoras's theorem on this current triangle to mathematically obtain the magnitude of the branch currents along the x-axis and y-axis and then determine the total current I_S of these components as shown.

Impedance of a parallel RLC circuit
You will notice that the final equation for a parallel RLC circuit produces complex impedance's for each parallel branch as each element becomes

the reciprocal of impedance, (1/Z) with the reciprocal of impedance being called Admittance.

In parallel AC circuits it is more convenient to use admittance, symbol (Y) to solve complex branch impedance's especially when two or more parallel branch impedance's are involved (helps with the math's).

The total admittance of the circuit can simply be found by the addition of the parallel admittances. Then the total impedance, Z_T of the circuit will therefore be $1/Y_T$ Siemens as shown.

Worked Example 3.1

A single phase 222/2 220 V, 50 Hz transformer has a net area of 100 cm^2 and 200 turns on the primary windings. Calculate the maximum flux density in Tesla and the number of turns in the secondary windings.

Solution:

$$E_1 = 4{,}44\phi_m f N_1$$

$$\phi_m = E_1/4{,}44 f N_1 = 222/4{,}44 \times 50 \times 200 \times 100 \times 10^{-4} = 0{,}5\ Tesla$$

$$N_2 = \frac{V_2 \times N_2}{V_1} = \frac{2220 \times 200}{222} = 2\ 000\ Turns$$

Worked Example 3.2

In a certain circuit of two parallel branches, the instantaneous branch currents are represented by the following:

$$i_1 = 50Sin\left(wt + \frac{\pi}{4}\right)A$$

$$i_2 = 60Sin\left(wt - \frac{\pi}{4}\right)A$$

Calculate the magnitude of the supply current and write it in the form:

$$i = I_{max} sin(wt + 0)A$$

Solution:

$$i_1 = 50D45° = 35{,}36 + j35{,}36$$

$$i_1 = 60D - 45° = 42{,}43 - j42{,}43$$

$$Total\ current = 77{,}782 - \mathrm{j}7{,}07 = 78{,}102 < -5{,}194°$$

$$i_T = 78{,}102\ Sin(wt - 5{,}194°)A$$

Worked Example 3.3

A sinusoidal AC supply has a RMS value of 197,96 V and a periodic time of 30 milliseconds.

Calculate the following:

1. The maximum value of the voltage
2. The frequency of the supply

Solution:

$$E_1 = 4{,}44\phi_m f N_1$$

$$\phi_m = E_1/4{,}44fN_1 = 222/4{,}44 \times 50 \times 200 \times 100 \times 10^{-4} = 0{,}5\ Tesla$$

$$N_2 = \frac{V_2 \times N_2}{V_1} = \frac{2220 \times 200}{222} = 2\ 000\ Turns$$

Worked Example 3.4

An impedance of 15+J10 ohms and an impedance of 15-j10 ohms are connected in parallel across a 270,825 V 50-Hz supply.

Calculate the following:

1. The total impedance of the circuit
2. The total current
3. The current in each branch
4. The total power
5. The power factor of the circuit

Solution:

1. $Z_1 = 15 - j10 = 18{,}03D33{,}69°$

   $Z_2 = 15 - j10 = 18{,}03D33{,}69°$

$Z_1 + Z_2 \ = \frac{Z_1 \times Z_2}{Z_1 + Z_2} = \frac{18{,}03D33{,}69° \times 18{,}03D - 33{,}69°}{30D0°} = 10{,}833D0° = 10{,}833$

2. $V \ = IZ \ \therefore I_T = \frac{V}{Z_T} = \frac{270{,}825D0°}{10{,}833D0°} = 25 < 0°A$

3. $I_1 \ = \frac{V}{Z_1} = 270{,}825D0°/18{,}03D33{,}69 = 15{,}023D - 33{,}69°A$

$I_2 \ = \frac{V}{Z_2} = 270{,}825D0°/18{,}03D33{,}69 = 15{,}023D - 33{,}69°A$

4. $P \ = \frac{V^2}{R} = 270{,}825^2/10{,}833 = 6{,}77\ Kw$ or

$P \ = I^2R = 25^2 \times 10{,}833 = 6{,}77\ Kw$ or

$P \ = VI = 270{,}825 \times 25 = 6{,}77\ Kw$

Worked Example 3.5

A 25 Hz sinusoidal voltage has an RMS value of 282,8 V. If the initial instantaneous voltage is zero and rising positively, how long will it take the voltage to reach a value of 200 V from zero for the first time?

Draw a phasor diagram and show the wave form of this voltage.

Solution:

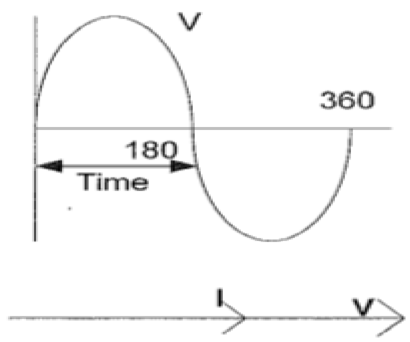


Figure 3.31

$V_{rms/wgk} \ = 0{,}707V_m$

$282{,}8 \ = 0{,}707V_m$

$V_m \ = \frac{282{,}8}{0{,}707}$

$$= 400\ V$$

$$v = V_m Sin2Pft$$

$$200 = 400\ Sin2P25t\,\frac{180}{n}$$

$$\frac{200}{400} = Sin9000t$$

$$9000t = Sin^{-1}0{,}5$$

$$t = \frac{30}{9000} = 3{,}33\ ms$$

Worked Example 3.6

A coil with a resistance of 30 ohms and an inductance of 100 millihenry is connected in series with a 25-microfarad capacitor. This circuit is connected across a 480 V, 50 Hz supply.

Calculate the voltage drop across the following:

1. The coil
2. The capacitor
3. Draw a phasor diagram to represent the distribution of the voltage and the current in the circuit

What an be done to improve the power factor?

Solution:

$$X_L = 2\pi fL = 2\pi 50 \times 100 \times 10^{-3} = 31{,}416\ \Omega$$

$$Z_{COIL} = \sqrt{R^2 + X^2} = \sqrt{30^2 + (31{,}416)^2} = \sqrt{1886{,}965} = 43{,}439\ \Omega$$

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\pi 50 \times 25 \times 10^{-6}} = 127{,}324\ \Omega$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{30^2 + (127{,}324 - 31{,}416)^2} = \sqrt{10098{,}336} = 100{,}490\ \Omega$$

$$I = V/Z = 480/100{,}490 = 4{,}777A$$

$$\Theta = Cos^{-1}\frac{R}{Z} = Cos^{-1}\frac{30}{100{,}490} = 72{,}63°$$

$$V_{COIL} = IZ_{COIL} = 4{,}777 \times 43{,}439 = 207{,}508\ V$$

$$V_C = IX_C = 4{,}777 \times 127{,}324 = 608{,}227\ V$$

Worked Example 3.7

An impedance of 15 + j 15 ohms and an impedance of 10 – j 10 ohms are connected in parallel to a 212,13 V, 50 Hz supply.

Determine the following:

1. The current flowing in each branch
2. The current flowing in the circuit
3. The overall power factor and draw the phasor diagram

Solution:

$Z_1 = 15 - j15 = 21{,}213 < 45°$

$Z_2 = 10 - j10 = 14{,}142 < -45°$

1. $I_1 = \frac{V}{Z_1} = \frac{212{,}13<0°}{212{,}13<45°} = 10 < -45° = 7{,}071 - j7{,}071\ A$

$I_2 = \frac{V}{Z_2} = \frac{212{,}13<0°}{14{,}142<45°} = 15 < -45° = 10{,}607 + j10{,}607\ A$

2. $I_T = I_1 + I_2 = 7{,}071 - j7{,}071 + 10{,}607 + j10{,}607$
$= 17{,}678 + j3{,}536 = 18{,}028 < 11{,}311°A$

3. $pf = Cos\ 11{,}308 = 0{,}981\ leading$

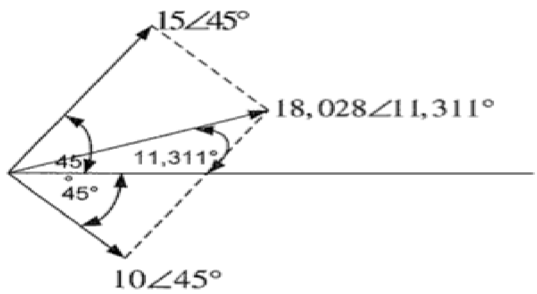


Figure 3.32

Activity 3.1

1. Alternating voltage may be generated by rotating a coil in the magnetic field or by rotating a magnetic field within a stationary coil. The value of the voltage generated depends on THREE aspects. Name them.
2. Generators (alternators) and electric motors work because of what?
3. The amount of EMF induced into a coil cutting the magnetic lines of force is determined by what three factors?

4. What is statically induced EMF?
5. What is dynamically induced EMF?
6. Lenz's law of electromagnetic induction says what?
7. Make a neat, fully labelled freehand drawing to show the construction of a basic AC single-phase generator. The following aspects must be shown in the drawing:
   a) TWO poles (N-S)
   b) Magnetic field between poles
   c) Armature windings
   d) TWO slip rings and TWO brushes
   e) Direction of rotation
   f) Conventional flow of current
   g) Any suitable type of load

Activity 3.2

In a certain circuit having three parallel branches, the instantaneous branch circuits are represented as follows:

$$i_1 = 60Sin\left(wt - \frac{\pi}{4}\right)$$

$$i_2 = 60Sin\left(wt + \frac{\pi}{4}\right)$$

$$i_3 = 60Sin\left(wt + \frac{\pi}{3}\right)$$

Calculate the total current and write it in the form

$$i = I_{max} sin(wt + \theta)$$

Represent these currents by drawing a phasor diagram.

[42.426+j42.426; 30+j51.926; 126.060 sin(wt+24.343)]

Activity 3.3

At what speed must a six-pole alternator be driven to produce an EMF having a frequency of 50 Hz?

[1000]

Activity 3.4

A sinusoidal AC-supply has a RMS value of 212,1 V and a frequency of 60 Hz.

Calculate:
1. The maximum value of the voltage
2. The periodic time in milliseconds

[300; 16.67]

Activity 3.5

In a certain circuit of three parallel branches, the instantaneous branch currents are represented by:

$$i_1 = 45Sin\left(wt - \frac{180}{4}\right)A$$
$$i_2 = 60Sin\left(wt + \frac{180}{3}\right)A$$
$$i_3 = 30Sin\left(wt + \frac{180}{4}\right)A$$

1. Calculate the magnitude of the supply current and write it in the form: $i = I_{max}sin(wt + \theta)$
2. Represent these currents by drawing a phasor diagram

[92.762 sin(wt+j26.476)A]

Activity 3.6

An impedance of 9 + j9 ohms and an impedance of 3 – j6 ohms are connected in series across a 371,08 V, 50 Hz supply.

Calculate:
1. The current flowing in the circuit
2. The power factor of the circuit

[30; 0.97]

Activity 3.7

A sinusoidal alternating current supply has a maximum value of 396,04 V and a periodic time of 50 milliseconds.

Determine the following:

1. The RMS value of the voltage
2. The average value of the voltage
3. The frequency
4. The instantaneous value two milliseconds after the commencement of the cycle

[280; 252.28; 20; 98.49]

Activity 3.8

In a certain circuit having two parallel branches the instantaneous branch circuits are represented by:

$$i_1 = 15Sin\left(wt - \frac{\pi}{4}\right)$$

$$i_2 = 45Sin\left(wt + \frac{\pi}{4}\right)$$

1. Determine the total current and write it in this form:
   $i = I_{max}sin(wt + \theta)$
2. Represent these currents by drawing a phasor diagram

[47.434 sin(wt-26.565)

Activity 3.9

An impedance of 15 <45 ohms and an impedance of 15 < -45 ohms are connected in parallel to a 150 volt, 50 Hz supply.

Determine the following:

1. The total impedance
2. The current in each branch
3. The current flowing in the circuit
4. The overall power factor and
5. Draw the phasor diagram to present the current in the circuit

[10.607; 7.071-j7.071A; 14.142A; 1]

Self-Check		
I am able to:	**Yes**	**No**
• Describe the generation of alternating EMF		
• Describe reactance, inductance, capacitance, impedance		
• Describe phasors and leading lagging power factors		
• Calculate currents, RLC, frequency, rms value		
• Calculate instantaneous values of waves and wave forms		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 4

Transformers

Learning Outcomes
On the completion of this module the student must be able to:

- Describe the construction of the single phase transformer
- Describe the principle of operation of the single phase transformer
- Calculate the voltage, current, turns, flux
- Calculate the losses, efficiency, phases

4.1 Introduction

The following module deals with the construction and operation of the single phase transformer and how to calculate voltage, turns, flux, losses, efficiency and phases.

4.2 Single phase transformer construction

Transformers are made up from primary and secondary coils (called windings) that are made from turns of insulated wire.

The coils are arranged on a core of magnetic material that increases the amount of magnetic flux set up by one coil and will make sure that most of it links with the other coil; in this way mutual inductance is increased.

Figure 4.1 A simple transformer

The single-phase voltage transformer has two coils or windings, a primary winding and a secondary winding that are not in electrical contact with each other.

When an electric current passed through the primary winding, a magnetic field is developed which induces a voltage into the secondary winding as shown in **Figure 4.2**.

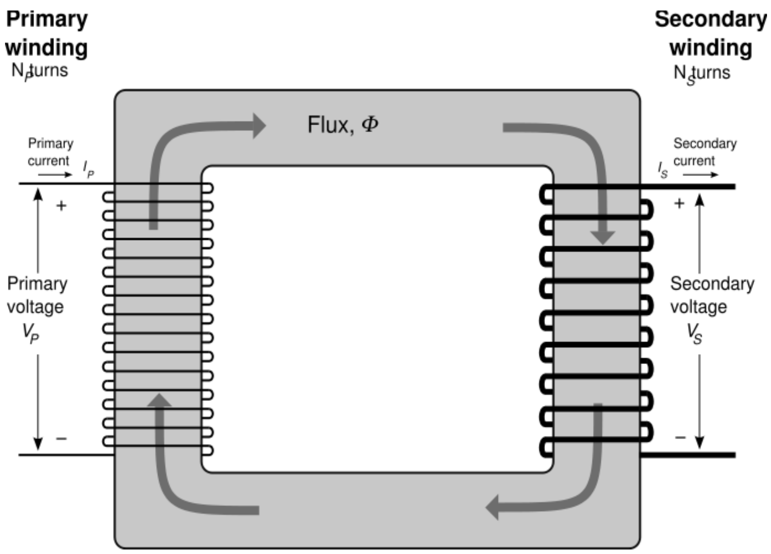


Figure 4.2 Simple transformer

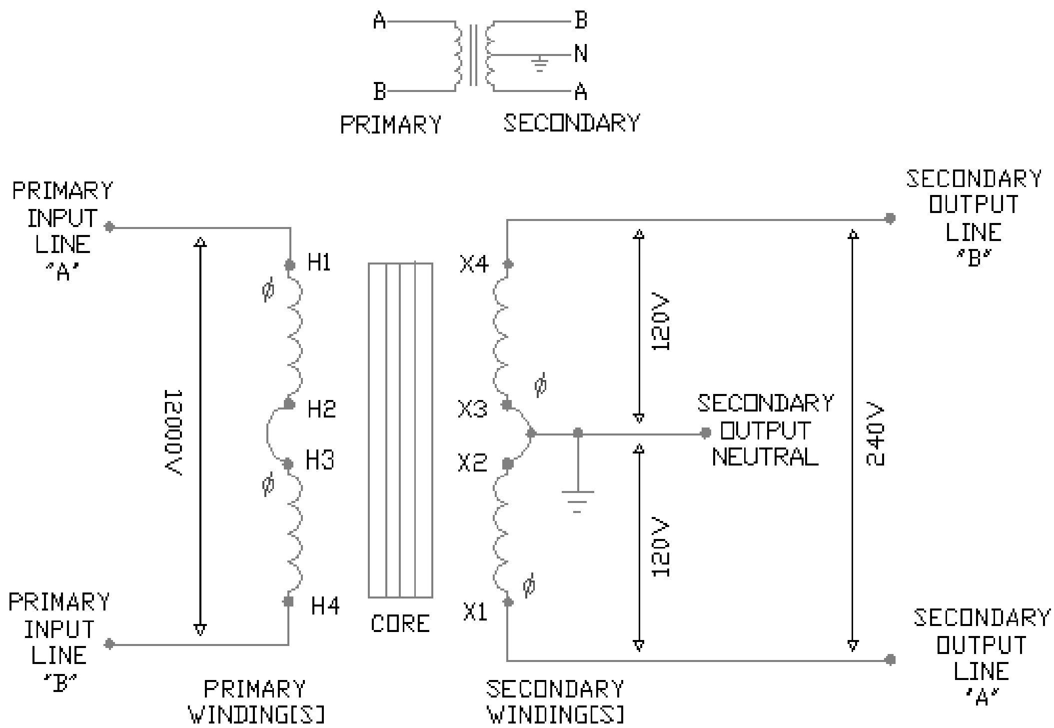


Figure 4.3 Circuit diagram for a simple transformer

A simple transformer is illustrated in **Figure 4.2** and the corresponding circuit diagram is shown in **Figure 4.3**. The primary winding has a voltage of V1 across it and is made of N1 turns of wire. The secondary coil has a voltage of V2 across it and is made from N2 turns.

4.1.1 Principle of operation of a transformer

Figure 4.4 shows a coil wound around a "*closed*" iron core. When a current flows through the coli, all *(except for a very small amount of leakage flux)* the magnetic lines of force (flux) pass through the *closed magnetic circuit*.

In the case of alternating current the magnetic lines of force *(flux)* reverse direction at the same rate as the current one of the useful applications of this phenomenon is the transformer.

> **Note:**
> The coils are electrically separate, ie they are insulated from each other. The coils are magnetically coupled by means of a laminated iron core.

When an alternating voltage is applied to the primary winding:

- an alternating current flows through it,
- this sets up an alternating flux in the iron core,
- which links with the secondary winding
- Inducing in it an electromotive force (EMF) of the same frequency (this is known as mutual induction).

If a load is connected to the secondary winding a current will flow. Electrical energy is transferred entirely magnetically from the primary winding to the secondary winding.

Standard transformers are used to step a voltage up or down with a corresponding decrease or increase in current.

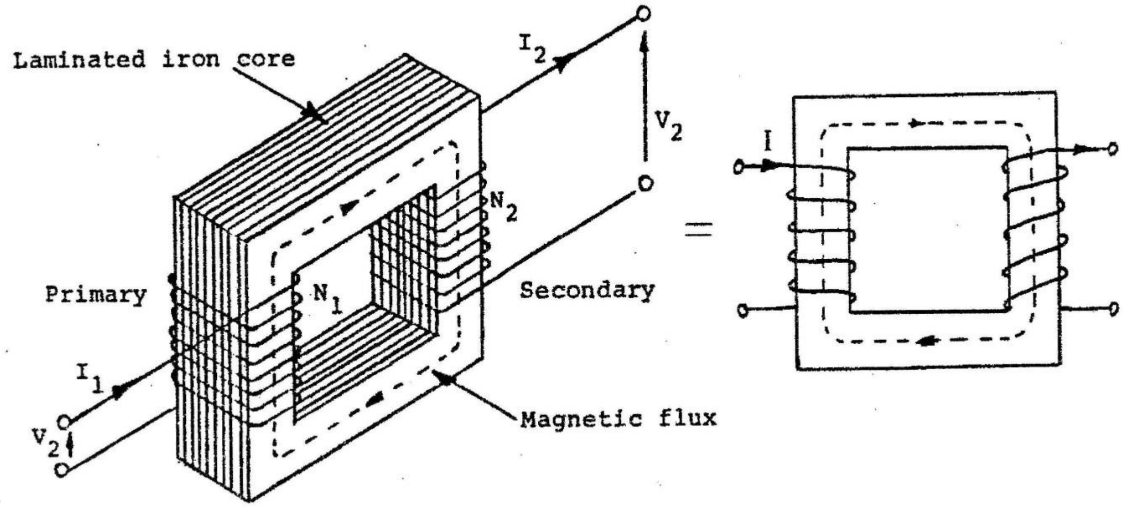


Figure 4.4 Principle of operation of a transformer

Advantages

- Their construction is simple.
- Their efficiency at full load is high, ± 97%.
- Because they have no moving parts their operation is silent.

4.1.2 Construction of a transformer

Essentially a transformer consists of a primary and secondary winding, electrically separate from each other, but magnetically coupled by means of a laminated iron core.

Figure 4.5 (a) shows the basic components of a transformer. In its most basic form, a transformer consists of:

- A primary coil or winding
- A secondary coil or winding
- A core that supports the coils or windings

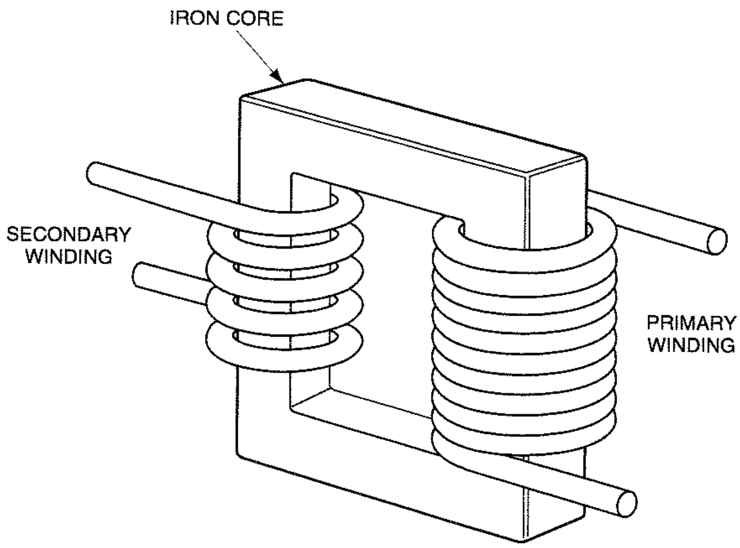


Figure 4.5 (a) Basic components of a transformer

	Definition: Core The core is built up of alternate layers of lightly insulated alloyed steel laminations. They are arranged in alternate layers so that their joints are staggered.

After assembly the core is clamped tightly and the coils are secured to avoid noise vibration (humming). **Figure 4.5(b)** illustrates the construction of a core type, shell type and a cross type transformer.

They are assembled inside the coils and clamped by means of high tensile bolts passing through the laminations or by means of sturdy angle iron clamps which protrude beyond the edges of the core. Fibre-glass bands are also sometimes used for clamping.

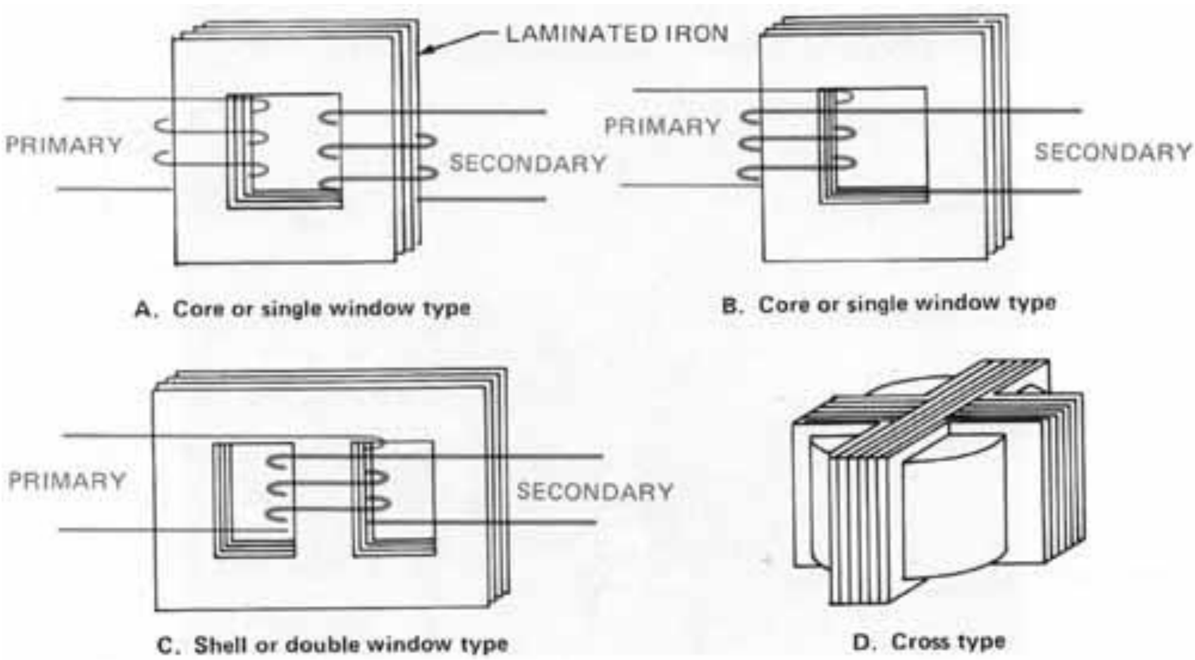


Figure 4.5 (b) Construction types of transformers

Bushings and Tap Changing: Connections to the coils are made through Insulated bushings. Various tappings on the coils are often made. This is done in order to obtain a wider range of voltages.

Tapping is often done to compensate for voltage variations caused by load variations such as peak periods on a winter morning. Tap Changing switches or terminals are fitted on the transformer when required.

4.1.3 Cooling of transformers

The dissipation of the heat losses generated in a transformer is of great importance, since the rating of the transformer is determined not only by these losses but also by the temperature rise of the transformer.

Cooling may be classified in two main groups:

- **Open Air cooling**: only smaller transformers make use of open air cooling.
- **Oil cooling**: The oil in which the core of a transformer is immersed serves a dual purpose. It improves the Insulation qualities and conducts the heat away from the windings and core to the cooling surfaces of the tank.

The Oil tank: An oil tank may have a smooth surface, but in order to increase the cooling surface it may be fitted with cooling fins, radiator tubes, (**Figure 4.6**), or radiator tanks.

Figure 4.6 Typical Oil cooled single phase transformer

Expansion: Provision for expansion may be in the form of free breathing through a breather. An expansion (conservator) tank as shown in **Figure 4.6** may also be used.

Breather: Changes in oil temperature cause changes in the volume of the oil inside the oil tank. This causes a displacement of the air in the top of the tank to take place through a breather. The breather contains a substance such as silica gel which extracts any moisture which may be present in the air.

Buchholz relay in transformer is an oil container housed the connecting pipe from main tank to conservator tank. It has mainly two elements. The upper element consists of a float.

The float is attached to a hinge in such a way that it can move up and down depending upon the oil level in the Buchholz relay Container. One mercury switch is fixed on the float.

Note:
The alignment of mercury switch depends upon the position of the float.

The lower element consists of a baffle plate and mercury switch. This plate is fitted on a hinge just in front of the inlet (main tank side) of **Buchholz relay in transformer** in such a way that when oil enters in the relay from that inlet in high pressure the alignment of the baffle plate along with the mercury switch attached to it, will change.

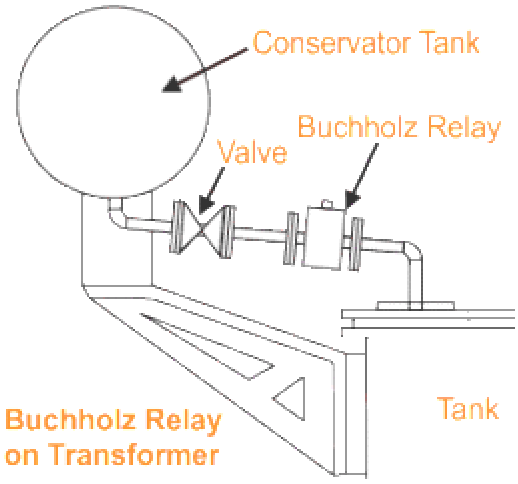


Figure 4.7 Buchholz relay on a single phase transformer

In addition to these main elements a Buchholz relay has gas release pockets on top. The electrical leads from both mercury switches are taken out through a molded terminal block.

4.2 Buchholz relay principle

The **Buchholz relay working principle** is very simple. Buchholz relay function is based on very simple mechanical phenomenon.

It is mechanically actuated. Whenever there will be a minor internal fault in the transformer such as an insulation faults between turns, break down of core of transformer, core heating, the transformer insulating oil will be decomposed in different hydrocarbon gases, CO_2 and CO.

The gases produced due to decomposition of transformer insulating oil will accumulate in the upper part the Buchholz container which causes fall of oil level in it.

Fall of oil level means lowering the position of float and thereby tilting the mercury switch. The contacts of this mercury switch are closed and an alarm circuit energized. Sometime due to oil leakage on the main tank air bubbles may be accumulated in the upper part the Buchholz container which may also cause fall of oil level in it and alarm circuit will be energized.

By collecting the accumulated gases from the gas release pockets on the top of the relay and by analyzing them one can predict the type of fault in the transformer.

More severe types of faults, such as short circuit between phases or to earth and faults in the tap changing equipment, are accompanied by a surge of oil which strikes the baffle plate and causes the mercury switch of the lower element to close.

This switch energized the trip circuit of the circuit breakers associated with the transformer and immediately isolate the faulty transformer from the rest of the electrical power system by inter tripping the circuit breakers associated with both LV and HV sides of the transformer. This is how **Buchholz relay functions**.

4.3 The ideal transformer

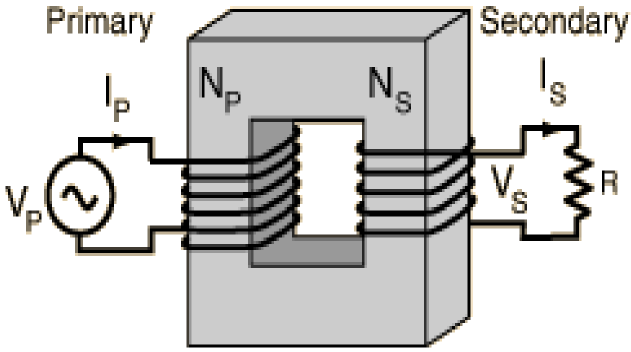


Figure 4.8 Simple single phase transformer

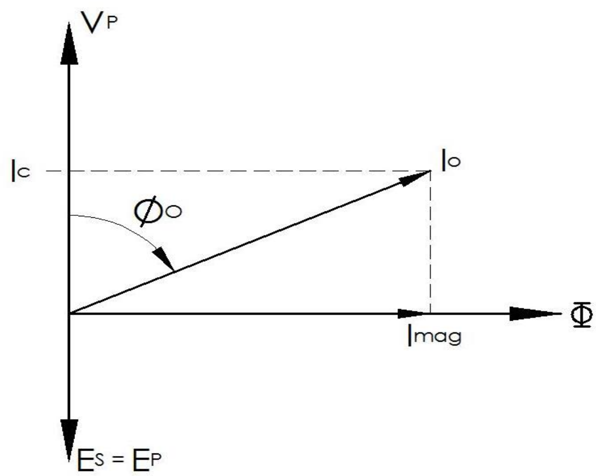


Figure 4.9 No load phasor diagram

$$V_P\, I_P = V_S\, I_S\, \cos\emptyset$$

$$\frac{V_P}{V_S} = \frac{I_S}{I_P}$$

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

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

$$\frac{E_P}{E_S} = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

$$\text{Average EMF induced in each turn} = 4\ \Phi_m\ f$$

$$\text{R.M.S. EMF induced in each turn} = 1.11 \times 4\ \Phi_m\ f$$

$$\text{No} - \text{load current } I_o = \sqrt{\text{I}_C{}^2 + \text{I}_{mag}{}^2}$$

Worked Example 4.1

A single-phase 222/2 220-V, 50 Hz transformer has a net area of 100 cm² and 200 turns on the primary windings. Calculate the maximum flux density in Tesla and the number of turns in the secondary windings.

Solution:

$E_1 = 4{,}44\phi_m f N_1$

$\phi_m = E_1/4{,}44 f N_1 = 222/4{,}44 \times 50 \times 200 \times 100 \times 10^{-4} = 0{,}5\ Tesla$

$N_2 = \frac{V_2 \times N_1}{V_1} = \frac{2220 \times 200}{222} = 2\ 000\ Turns$

Worked Example 4.2

The no-load current of a single-phase transformer is 10 A at a power factor of 0,708 lagging. Calculate the value of the magnetizing current and the value of the core loss current.

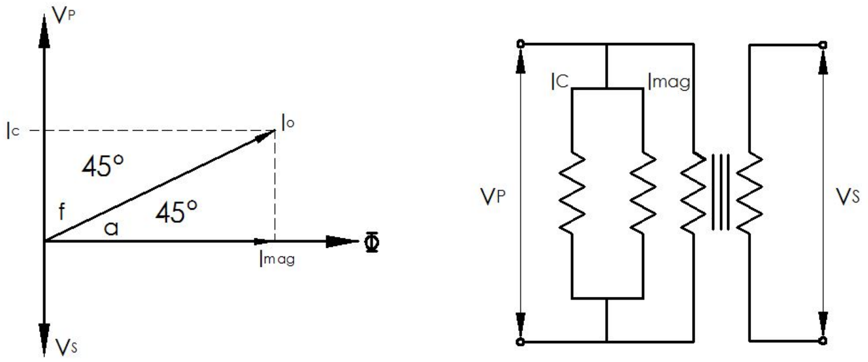


Figure 4.10

Solution:

$\phi_1 = cos^1 0{,}707 = 45° = 90 - 45° = 45°$

$I_o = 10D45° = 7{,}07 + j7{,}07$

$I_{mag} = 7{,}07\ A$

$I_c = 7{,}07\ A$

Worked Example 4.3

A 30 kVA single-phase transformer has a maximum core flux of 1,8018 mWb with 250 primary and 50 secondary winding.

Calculate the following:

1. Secondary voltage if the primary voltage is 100 V
2. Primary full-load current
3. Frequency in Hz

Solution:

1. $V_2 = \frac{N_2 V_1}{N_1} = \frac{100 \times 50}{250} = 20V$

2. $I_1 = \frac{S}{V} = \frac{30\ 000}{100} = 300\ A$

3. $f = E/4{,}44\ \phi_m N = 100/250 \times 1{,}8018 \times 10^{-3} \times 4{,}44 = 50\ Hz$

Activity 4.1

1. Give two advantages of a transformer.
2. Name the windings of a transformer.
3. What is the core of a transformer made from?
4. With reference to a transformer, what is a breather and what is its function?
5. Mention two main methods of cooling transformers.
6. What do you understand by mutual induction?
7. With the aid of a neat labelled sketch explain the construction and operation of a single-phase transformer.

Activity 4.2

A 48 kVA 4 800/48 V, 50 Hz single-phase transformer has 3 000 turns on the primary winding.

Determine the following:

1. The turns ratio
2. The number of secondary turns
3. The secondary full-load current
4. The maximum value of the core flux

[100:1; 30; 1000; 7.207]

Activity 4.3

A single-phase 50/500 V transformer has a net area of 20 cm^2 and a maximum flux density of 0,75 tesla. The primary winding has 150 turns.

Calculate:

1. The frequency
2. The number of turns in the secondary winding

[50.05; 1500]

Activity 4.4

The no-load current of a 2 500/50 V single-phase transformer is 15 A at a power factor of 0,2. The primary winding has 125 turns and the supply frequency is 50 Hz.

Calculate the following:

1. The maximum value of the flux in the core
2. The power loss on no-load
3. The value of the magnetizing current

[90; 7500; 14.6969]

Activity 4.5

A 60 kVA 6 000/600 V, 60 Hz single-phase transformer has 600 turns on the primary winding.

Calculate the following:

1. The turns ratio
2. The number of secondary turns
3. The secondary full-load current
4. The maximum value of the core flux

[10:1: 60; 100; 37.54]

Activity 4.6

The no-load current of a 3 000/150-V single-phase transformer is 25 A at power factor of 0,3. The primary winding has 150 turns and the supply frequency is 60 Hz.

Calculate the following:

1. The maximum value of the flux in the core
2. The power loss on no-load
3. The value of the magnetizing current

[75.075; 22.5; 23.484]

Activity 4.7

The no-load current of a 1 000/200 V single-phase transformer is 5 A at at power factor of 0,2. The primary winding has 50 turns and the supply frequency is 50 Hz.

Calculate the following:

1. The maximum value of the flux in the core
2. The power loss on no-load
3. The value of the magnetizing current

[22.5; 1; 1]

Activity 4.8

A transformer with a primary winding of 250 turns has an input of 115 V rms. The secondary winding has 65 turns. Find the output voltage.
[29.9]

Activity 4.9

A transformer with an output voltage of 75 V supplies a load consisting of R_L=33.5 ohms and X_L=22 ohms. Find the supply voltage and current if the transformer has the following parameters: R_P=2 ohms, X_P=5 ohms, R_O=7.5 ohms, X_O=3 ohms, R_S=0.25 ohms, X_S=1.2 ohms and N_P/N_S=3/2.

[121; 1.28; 37.3]

Activity 4.10

A single-phase transformer has 20 secondary turns and 40 primary turns. The secondary winding is connected to a 200 volt supply.

Calculate the following:

1. Primary voltage
2. Value of the primary current when the secondary current is 20 A
3. Primary power if the load has a power factor of 0,6

[400; 10; 2400]

Activity 4.11

An ideal kVA transformer has 50 primary turns and 500 secondary turns. The primary windings are connected to a 5 kV, 50 Hz supply.

Calculate:

1. The secondary voltage
2. The value of the secondary and the primary currents on full load
3. The maximum core

[50000; 1; 10; 0.4505]

Self-Check

I am able to:	Yes	No
• Describe the construction of the single phase transformer		
• Describe the principle of operation of the single phase transformer		
• Calculate the voltage, current, turns, flux		
• Calculate the losses, efficiency, phases		

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

Module 5

AC Machines

Learning Outcomes
On the completion of this module the student must be able to:

- Describe single phase motor construction and operation
- Describe Three phase motor construction and operation
- Describe induction motor construction and operation
- Describe single phase motor starter construction and operation
- Describe three phase motor starter construction and operation

5.1 Introduction

Electric energy is used for motors of one kind or another. Modern houses generally contain motors for such purposes as fans, furnace control, door-openers, pumps, dishwashers, spits, polishers, refrigerators, ovens, dehumidifiers and hair dryers.

Industrial motor uses are even wider and range from tiny, finger-size, sub-fractional-kilowatts motors through giants developing thousands of kilowatts.

Important Note!
Motors convert electrical power (voltage and current) into shaft torque and rotation.

Figure 5.1 shows the two main parts of motors; a fixed hollow cylinder or frame called the *stator* and a small rotating (usually more or less solid) cylinder called the *rotor*.

Motors have an iron cylindrical fixed part (the frame or stator) and an iron rotor that turns inside the stator.

Longitudinal slots on the inside stator face and rotor face are wound with electrical conductors.

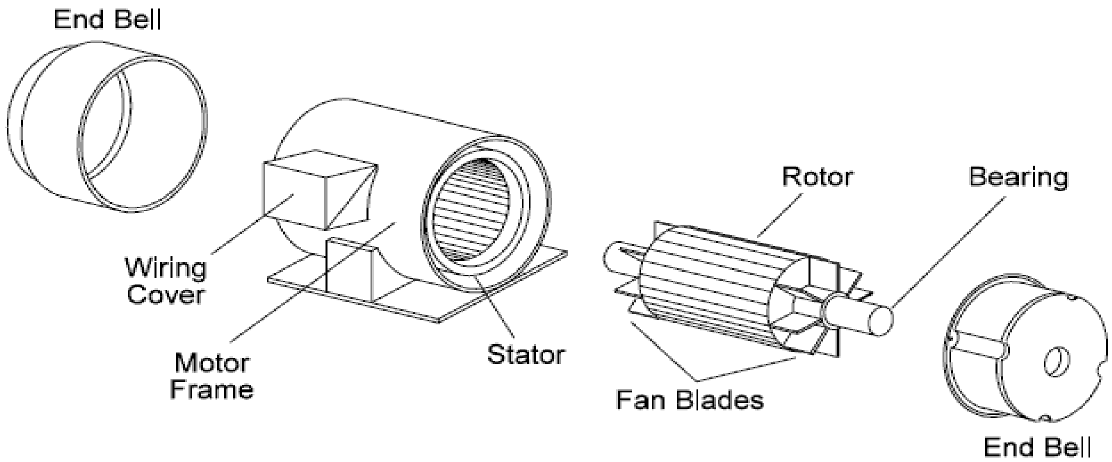


Figure 5.1 An AC Motor

5.1.1 Construction of 3-phase AC induction motor

Three-phase AC induction motors are commonly used in industrial applications. This type of motor has three main parts, rotor, stator, and enclosure. The stator and rotor do the work, and the enclosure protects the stator and rotor (**Figure 5.2**).

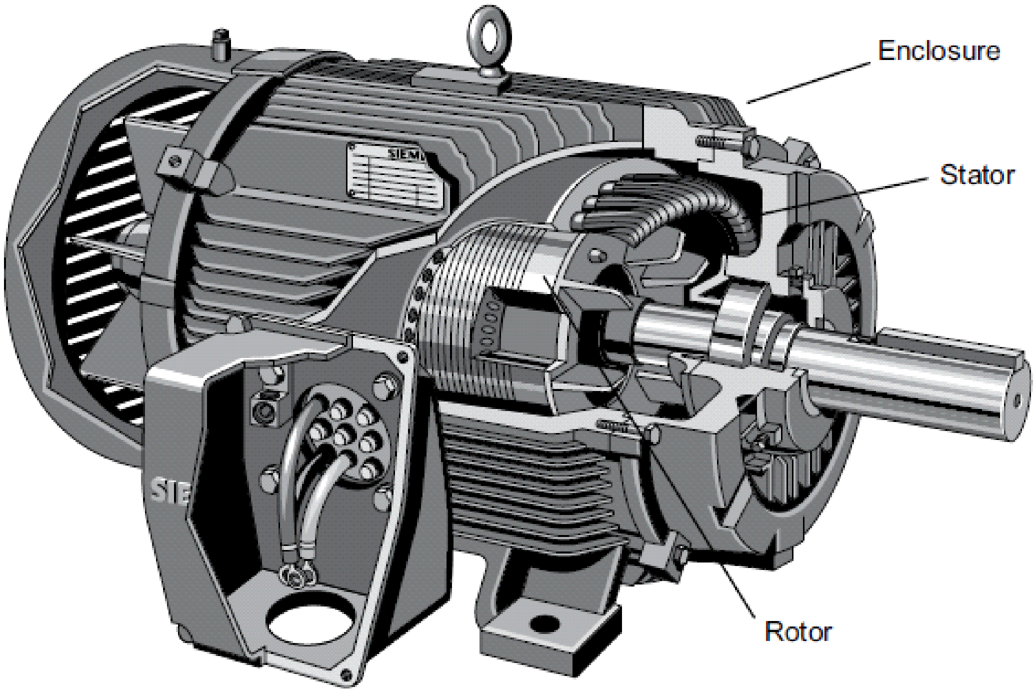


Figure 5.2 Construction of a three-phase AC induction motor

Stator Core: The stator is the stationary part of the motor's electromagnetic circuit. The stator core is made up of many thin metal sheets, called laminations. Laminations are used to reduce energy loses that would result if a solid core were used. Generally choice of material is steel to keep down hysteresis losses (**Figure 5.3**).

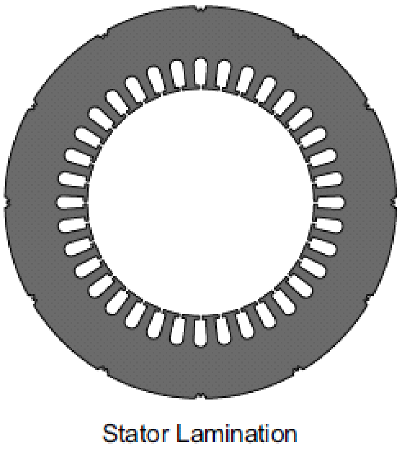


Figure 5.3 Stator core

Stator Windings: Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core (**Figure 5.4**).

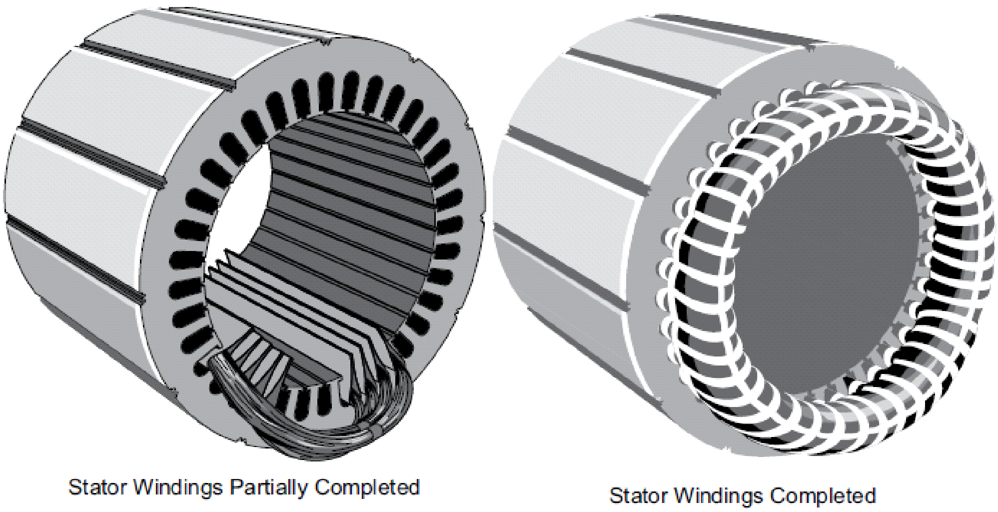


Figure 5.4 Stator windings

When the assembled motor is in operation, the stator windings are connected directly to the power source. Each grouping of coils, together with the steel core it surrounds, becomes an electromagnet when current is applied. Electromagnetism is the basic principle behind motor operation.

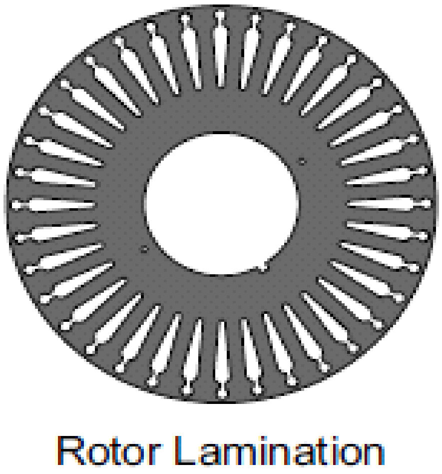


Figure 5.5 Rotor construction

Rotor Construction: The rotor is the rotating part of the motor's electromagnetic circuit. The most common type of rotor used in a three-phase induction motor is a squirrel cage rotor. Other types of rotor construction are discussed later in the course.

The squirrel cage rotor is so called because its construction is reminiscent of the rotating exercise wheels found in some pet cages. A squirrel cage rotor core is made by stacking thin steel laminations to form a cylinder (**Figure 5.5**).

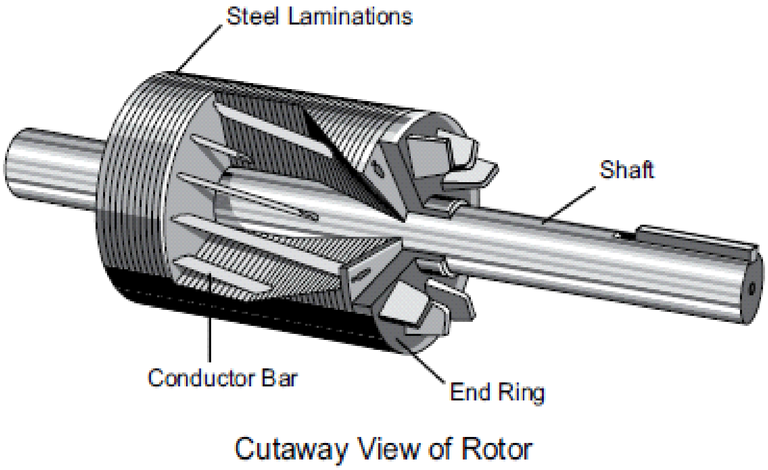


Figure 5.6 Section through of a rotor

Rather than using coils of wire as conductors, conductor bars are die cast into the slots evenly spaced around the cylinder. Most squirrel cage rotors are made by die casting aluminium to form the conductor bars. Siemens also makes motors with die-cast copper rotor conductors.

After die casting, rotor conductor bars are mechanically and electrically connected with end rings. The rotor is then pressed onto a steel shaft to form a rotor assembly.

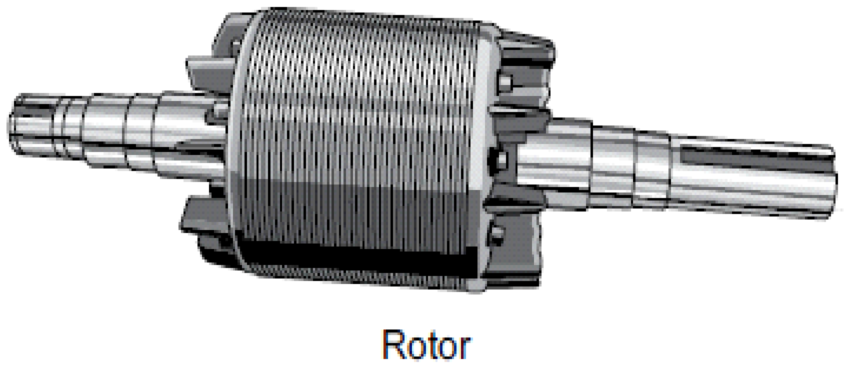


Figure 5.7 Rotor

Enclosure: The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator. There is no direct physical connection between the rotor and the stator (**Figure 5.8**).

The enclosure protects the internal parts of the motor from water and other environmental elements. The degree of protection depends upon the type of enclosure. Enclosure types are discussed later.

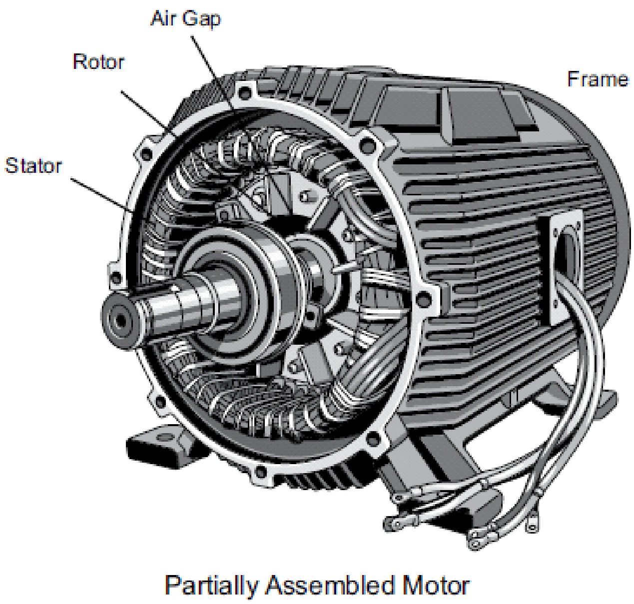
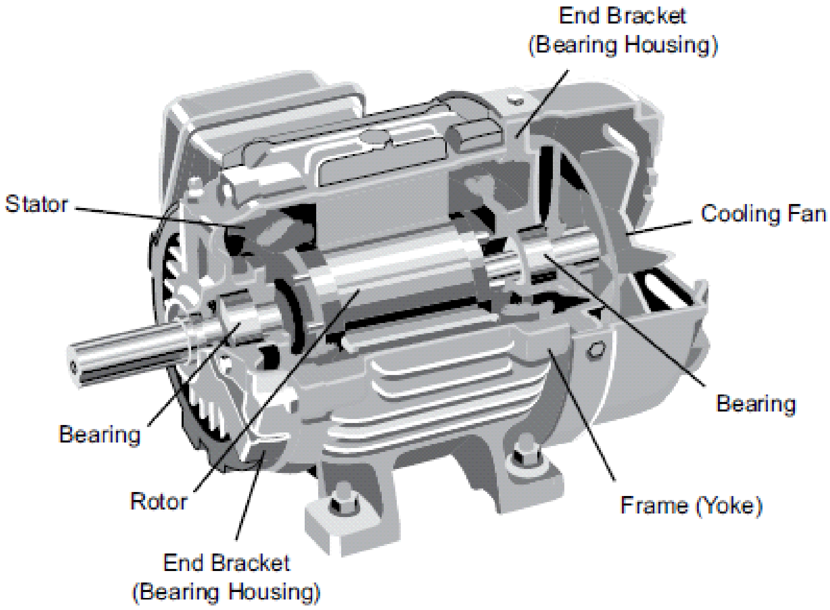


Figure 5.8 Partially assembled motor

Bearings, mounted on the shaft, support the rotor and allow it to turn. Some motors, like the one shown in the following illustration, use a fan, also mounted on the rotor shaft, to cool the motor when the shaft is rotating.



Cutaway View of Motor

Figure 5.9 Section through of a motor

5.1.2 Rotors

5.1.2.1 The wound rotor

Wound-motor or slip-ring motors differ from the squirrel-cage motor in rotor construction. As the name implies, the rotor is wound with insulated windings, similar to the stator windings.

With three-phase motors the rotor phase windings are star connected with the open end of each phase brought out to a slip-ring mounted on the rotor shaft, **Figure 5.10**.

In order to improve the starting torque, extra resistance may be inserted into the rotor circuit and reduced as the rotor accelerates.

> **Note:**
> The rotor winding is not connected to a supply, the slip-ring and brushes merely provide a means of connecting an external variable resistance into the rotor circuit.

In large machines slip-ring short circuiting and brush-lifting gear is incorporated, thus reducing wear and frictional loss.

To comply with SABS 0142 Regulation 6.6.7 an AC motor with a wound rotor shall have its stator switch so interlocked with the rotor-resistance starter, that the switch cannot be closed unless the starting handle is in the "start" position.

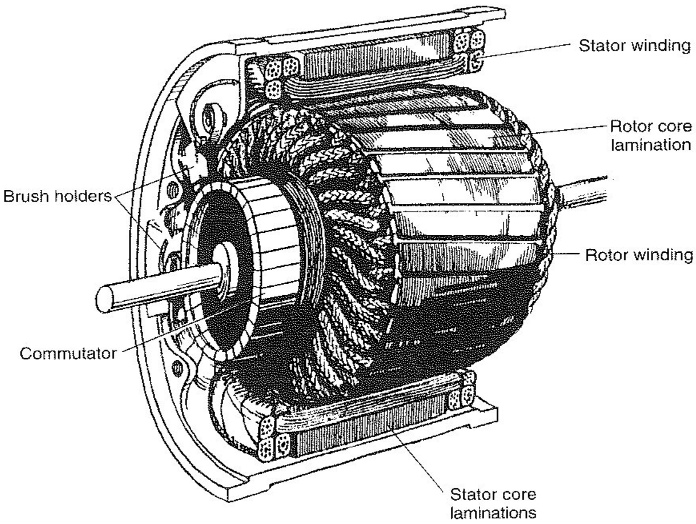


Figure 5.10 The wound motor

5.1.2.2 The squirrel-cage rotor

The rotor (or secondary) is also constructed of steel laminations but the windings consist of conductor bars placed close to the rotor surface, **Figure 5.11**. These conductors are heavy bars lightly insulated from the core and circuited at each end by means of a pair of stout end-rings.

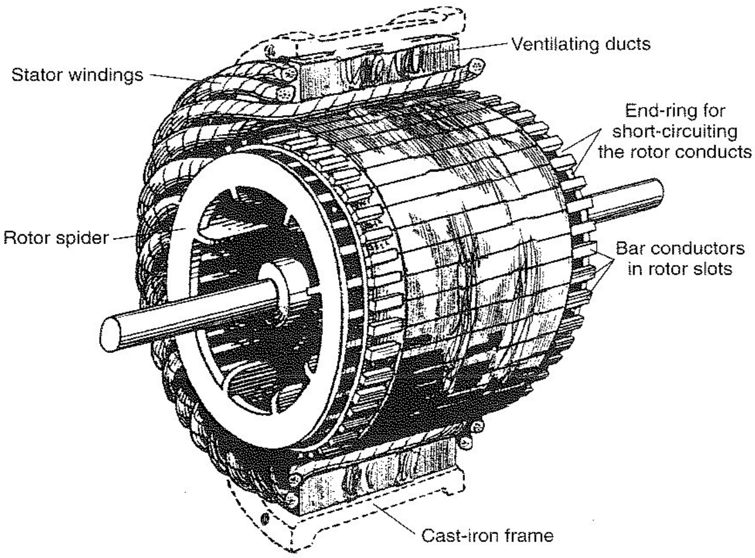


Figure 5.11 General arrangement of stator and rotor of a squirrel-cage motor

Fans are mounted on the ends of the rotor to assist in the cooling. In small squirrel- cage rotors the bars, end-rings and fans are of aluminium, cast in one piece instead of being welded together.

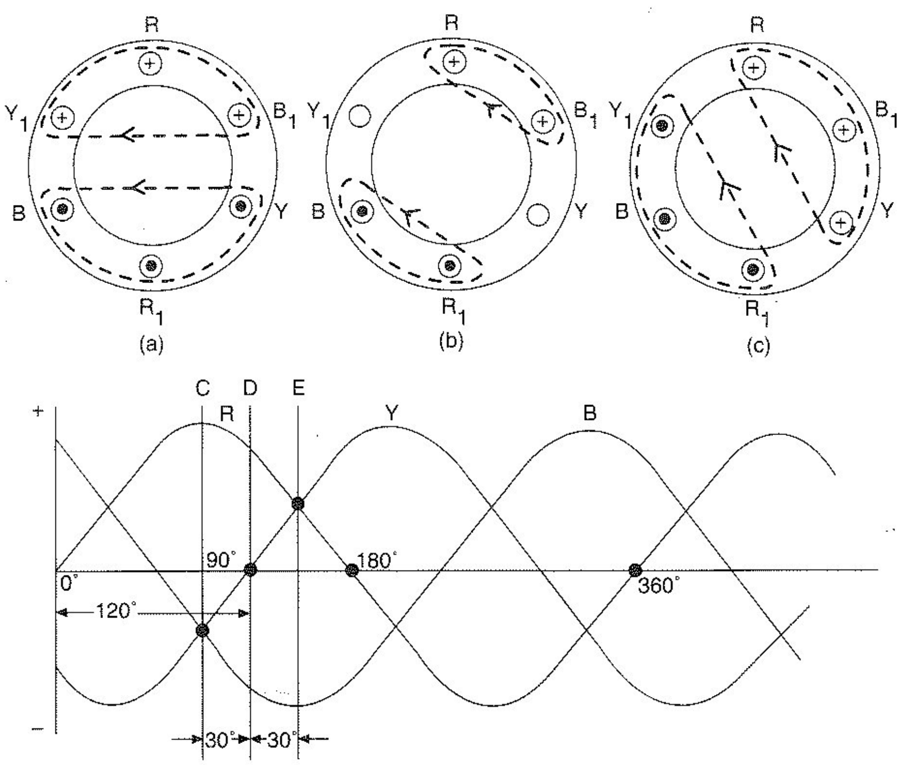
Note:
The slots are not always parallel to the shaft. They are usually skewed to reduce the magnetic humming noise and to ensure a more uniform torque.

To explain the production of a rotating magnetic field, consider a two-pole three- phase stator having for simplicity, only one slot per phase (**Figure 5.12 (a)**).

Let:
- R and R1 represent the start and the finish of the Red phase
- Y and Y1 represent the start and finish of the Yellow phase
- B and B1 represent the start and finish of the Black phase

It will be noted that R, Y and B are displaced 120° relative to one another. The sketches represent the *stator winding*. The rotor winding is not shown.

Let us assume that when a current is positive it will flow in conductors R, Y and B and therefore outward in conductors A1, Y1 and B1. Let the current in the three-phase system be represented as described below.



(d)

Figure 5.12 Rotor operation explained in terms of magnetic fields

At instant C (**Figure 5.12(d)**) the current in phase R is *positive* whereas in phase Y and B the currents are negative. These currents produce the magnetic flux in **Figure 5.12 (a)**.

At instant D (**Figure 5.12**), the current in phase R is positive, that in phase Y is zero and in phase B the current is negative. The magnetic flux to these currents is represented in **Figure 5.12 (b)**. It will be seen that the axis of this field has moved clockwise through 30° from that in **Figure 5.12(a)**.

At instant E the current in phase B is negative while the currents in both phase R and Y are positive. These currents produce the magnetic flux shown in **Figure 5.12 (c)**, the axis of the flux being displaced *clockwise* by another 30°.

The three cases discussed are sufficient to prove that for every interval of time corresponding 30° along the horizontal axis, the magnetic flux in a two-pole stator moves 30° in space. It also illustrates the fact that the stator remains steady but the magnetic flux moves in a clockwise direction.

5.2 Basic operating of an induction motor

5.2.1 Rotating magnetic field

The operation of an induction motor is dependent upon a rotating magnetic field for starting purposes:

In terms of fields, we now say that a time -varying magnetic field produces an electromotive force (EMF) which may establish a current in a suitable closed circuit. An electromotive force is merely a voltage that arises from a conductor moving in a magnetic field or from a changing magnetic field.

5.2.2 Slip

The stator winding is connected to the supply, and the poly-phase currents circulating through it produce a magnetic field which rotates at synchronous speed (speed equal to that of the rotating magnetic field).

If the rotor turned at synchronous speed, there would be no change in flux linkage, no induced current, and no torque. The small difference in speed that produces flux cutting and motor action is called the slip.

The slip full load for a squirrel-cage motor is typically 2% to 5%. Slip may also be described as the relative speed between the synchronous speed and the rotor speed.

Note:
Slip may be expressed in revolutions per minute, but is more commonly expressed in terms of the synchronous speed as either a percentage or as a per unit value.

Where:
s = per unit slip or percentage slip
N = synchronous speed of the field in revolutions per minute
N_r = actual speed of the rotor in revolutions per minute
n = synchronous speed of the field in revolutions per second
n_r = actual speed of the rotor in revolutions per second

> **Important**: The rotor field created by the induced rotor current moves ahead at a speed relative to the rotor structure.

The magnetic line of the stator field cuts the rotor conductors and induces current in them; the rotor follows after the stator field (**Figure 5.12**). There is absolutely no physical electrical connection between the stator and the rotor of the induction motor.

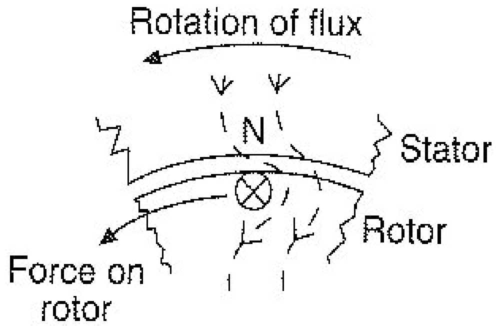


Figure 5.13 Force on rotor

Since the speed of the motor depends upon the frequency of the supply as well as the number of poles, the stator may be wound for a two-four-six- or eight-pole machine, depending upon the speed required.

The frequency of the current is given by the formula = pn

Where:
f = is the frequency in Hz
p = is the number of pole pairs
n = is the speed of the armature in revolutions per second (rev/sec)

Table 5.1 shows a few rotor speeds for the standard frequency of 50 Hz:

Number of poles	Calculation	Speed
2-pole	50 = 1 x n	n = 50 rev/sec, or 3000 rev/min
4-pole	50 = 2 x n	n = 25 rev/sec, or 1500 rev/min
12-pole	50 = 6 x n	n = 8 1/3 rev/sec, or 500 rev/min

Table 5.1

⚠	**Important**: The induction motor is essentially a transformer with a rotating secondary. The force that exists between primary and secondary coils in a transformer appears as useful torque in an induction motor.

5.3 Starting single-phase AC motors

Small motors may be started by the direct-on line method. Larger squirrel-cage motors may be started by a step-by-step resistance starter in series with the running winding. Wound-rotor motors are started by cutting out resistance step-by-step in the rotor external resistance until the rotor is running at normal speed.

5.3.1 Capacitor start/induction run motor

This motor may also be referred to as a split-phase induction motor.

To produce a torque at starting without resorting to a commutator and short circuited brushes some sort of rotary magnetic field must be produced.

A common method is to provide a second winding (called the starting winding) on the stator.

The stator winding is designed to have a much higher resistance than the main winding so that when the two windings are connected in parallel at starting, a fairly large phase difference will occur in the currents, and an imperfect rotary field will result.

When the motor has run up to normal speed, the starting winding is cut out of circuit by a centrifugal switch.

This obtains its out-of-phase current by use of a main or running winding and an auxiliary winding connected in parallel for starting. An external choke may be connected in series with the auxiliary winding to increase its reactance.

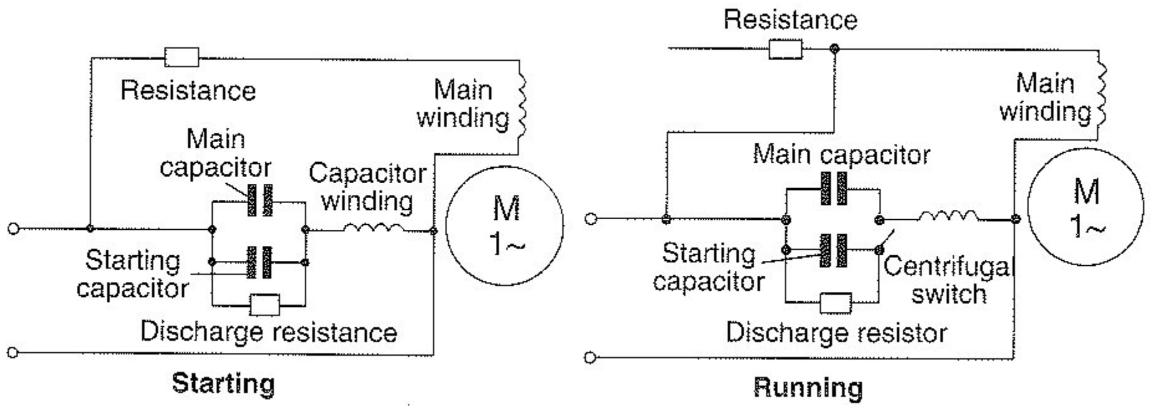


Figure 5.14 Capacitor start induction run motor

When the machine is running, only the main winding is left in circuit, the auxiliary winding and its external choke being cut out. This can be done by means of a three-position starting switch, or automatically by a centrifugally operated mechanism on the rotor shaft (**Figure 5.14**).

The split-phase induction motor has a shunt characteristic and runs at fairly constant speed at all loads within its working range without possibility of speed control. It will not start against load, and is most useful for equipment which requires a reasonably constant speed, such as machine tools, circular saws, etc.

Think about it!
A reduction of voltage has little effect on the speed but causes a reduction of torque.

5.3.2 Capacitor start/Capacitor run motor

The capacitor start motor consists of a running winding and a starting winding connected in parallel with each other. The capacitor winding has a starting capacitor, and a main capacitor (**Figure 5.15**).

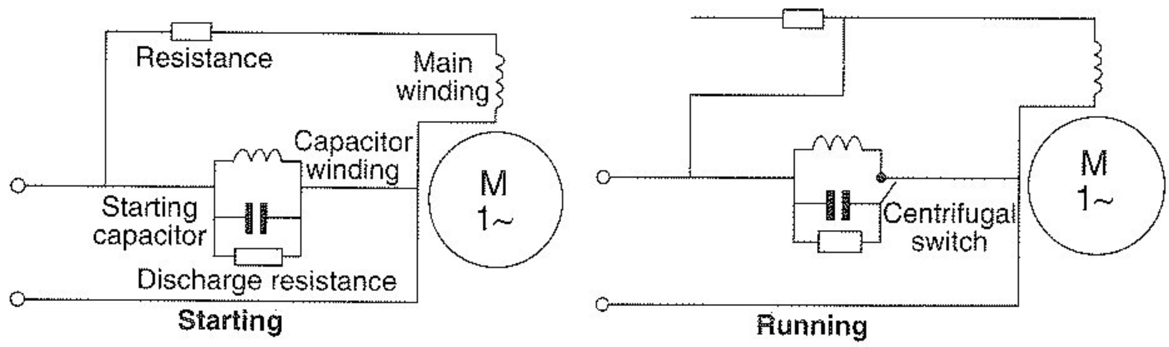


Figure 5.15 Single-phase capacitor start capacitor run motor

The two capacitors are used in parallel during starting. In the running position the main capacitor is left connected to provide power-factor correction, and the starting capacitor is disconnected and discharged through the discharge resistance.

The switching of the starting capacitor is done with an internal, centrifugally-operated switch to disconnect the capacitor from the starting winding as normal operating speed is approached.

5.3.3 The universal motor

The universal motor is also known as an AC series motor. When comparing the universal motor with a DC series motor, the biggest difference is the lamination of the universal motor's field coils. The reason for this is the alternating current used to power the universal motor.

The commutator has a large number of segments and the number of armature turns per sector is small. In this way good commutation is ensured. High-resistance brushes are also used to limit the current in the short-circuit coil and hence to aid in securing sparkless commutation.

When the current through both the field and the armature of a DC series motor is reversed, the motor still continues to run in the same direction. The same principle applies to the universal motor. When the alternating current is applied to the universal motor, the current through both the field and the armature reverses simultaneously.

As was the case for the DC series motor the universal motor also continues to run as the torque is in one direction. The load characteristics are similar for the DC series motor and the universal motor.

Note:
The starting torque of the universal motor is high; approximately three times the torque at rated load.

The power factor and efficiency is good. Because of the very high armature speed, universal motors develop very high outputs. The universal motor is commonly used in small appliances such as portable drills, angle grinders and vacuum cleaners, beverage mixers, floor polishers, sewing machines, etc.

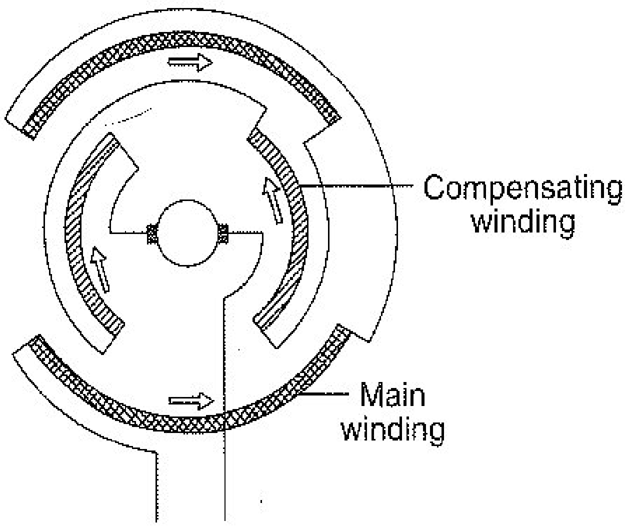


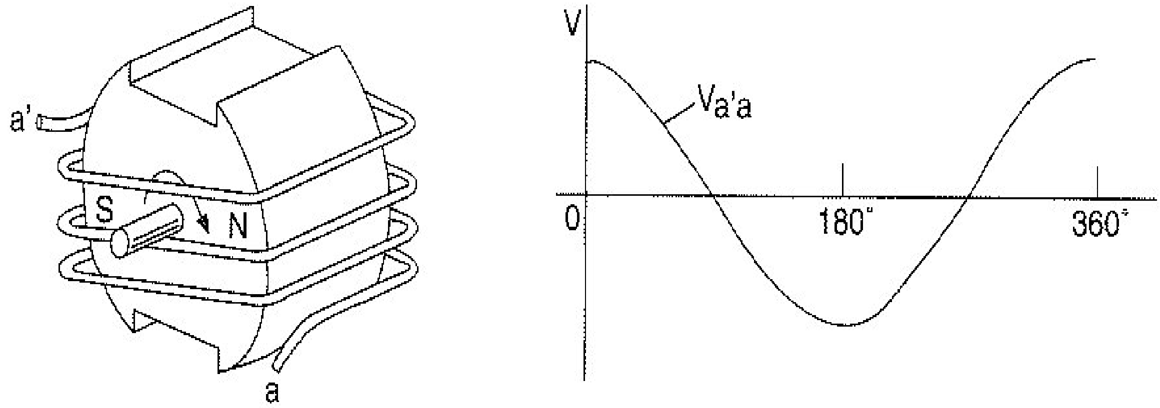
Figure 5.16 An example of a universal motor

5.4 Three-phase motors

The generation and transmission of electrical power is more efficient in three-phase systems employing combinations of three sinusoidal voltages.

In addition, three-phase circuits and machines possess some unique advantages, for example, power in three-phase circuit is constant rather than pulsating as it is in a single-phase circuit.

Also, three-phase motors start and run much better than single-phase motors. The most common three-phase system employs three balanced voltages, equal in magnitude and differing in phase by 360°/3 = 1200. The discussion here is restricted to balanced three-phase circuits.



(a) Elementary motor (b) Voltage induced in the winding

Figure 5.17 Generation of an alternating voltage

The elementary AC motor of **Figure 5.17** consists of a rotating magnet and a stationary winding. The turns of the winding are spread along the periphery of the machine.

The voltage generated in each turn of the four-turn winding is slightly out of phase with the voltage generated in its neighbour or because it is cut by maximum magnetic flux density an instant earlier or later. The voltage in the four turns are in series and, therefore, they add to produce voltage $V_{a'a}$.

	Note: If the winding was continued around the machine, the voltage generated in the last turn would be 180° out of phase with the voltage in the first and they would cancel, producing no useful effect.

For this reason, a winding is commonly spread over no more than one-third of the periphery; the other two-thirds can be used to generate two other similar voltages. The three sinusoids (sinusoids are obtained with a proper winding distribution and magnet shape) generated by the three similar windings are shown in **Figure 5.18**.

The three similar portions of the three-phase system are called "phases," because the voltage in phase *a'a* reaches its maximum first, followed by that in phase *b'b,* and that in phase *c'c*, we say the phase rotation is *abc*.

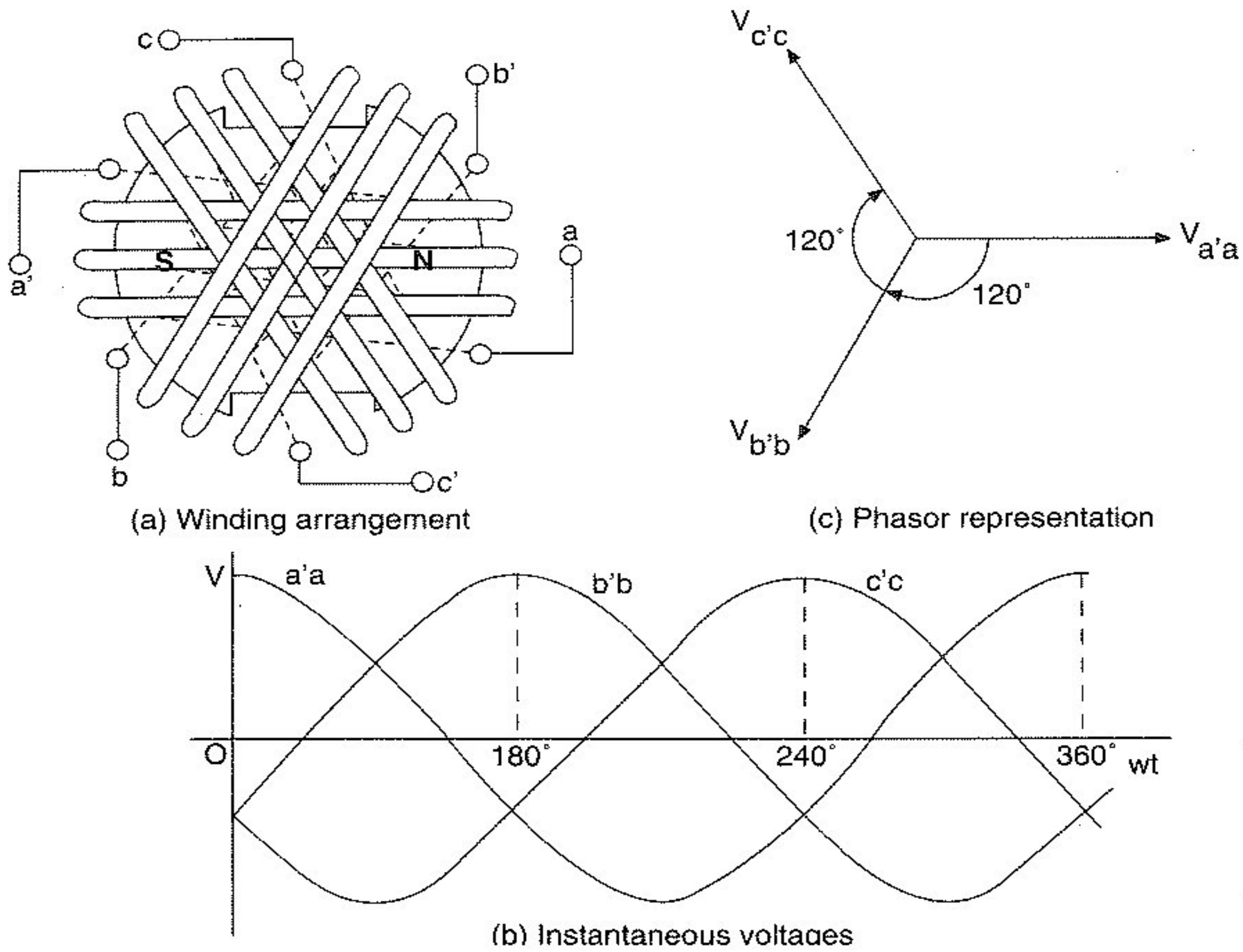


Figure 5.18 Balanced three-phase voltages

5.4.1 Start connections in three-phase motors

Because of the low starting resistance of a motor, a large current will flow when the motor is switched on.

This could damage the motor. To limit the starting current to a safe value, the motor (for three-phase large squirrel-cage motors) is started in star, reducing the voltage over each phase winding.

As previously indicated the stator's windings are connected in star to accomplish this.

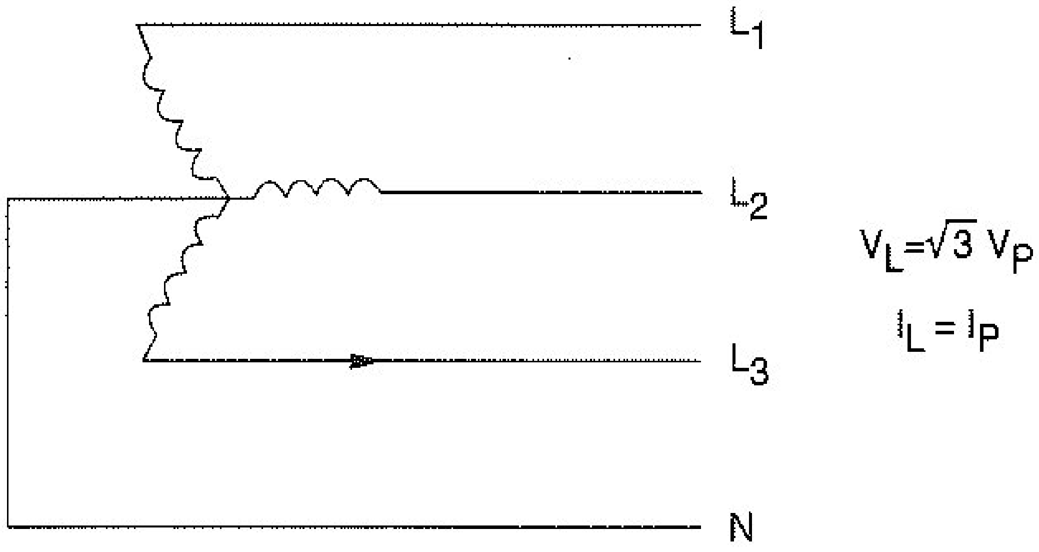


Figure 5.19 Three-phase start connection

5.4.2 Delta connection in three-phase motors
Three-phase induction motors run with their stator windings connected in delta (ZΔ). This is to ensure a constant voltage supply to the motor. 90% of all induction motors are of the squirrel-cage type.

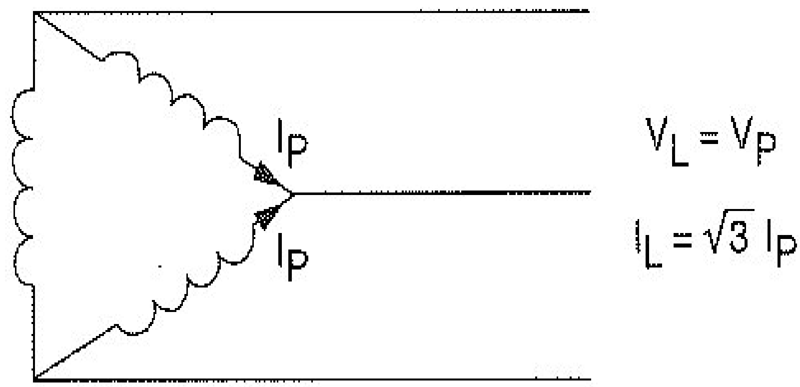


Figure 5.20 Three-phase Δ connection

5.5 The wound three-phase induction motor
5.5.1 Characteristics of three-phase induction motors
The main electrical parts are a stationary member, called the stator, and a rotating member, called the rotor.

The stator consists of a laminated core with partially closed slots spaced uniformly along its inner periphery. A three-phase winding, designed for the full supply voltage, is wound in these slots, and when excited by three-phase currents produce a rotary magnetic field of the required number of poles.

Note:
The winding is either star or delta connected according to the starting requirements and other conditions.

The rotor also consists of a laminated core with partially closed slots spaced uniformly along its outer periphery. Two types of winding are used, via normal three-phase winding with the ends connected to slip rings, and a permanently short-circuited winding, consisting of bars and short-circuiting end-rings (called a squirrel-cage).

In **Figure 5.21** a pictorial representation of a three-phase inductor motor is shown.

Three-phase motors are generally used as machine tools, woodworking machines, cranes, hoists, winders, fans, pumps, lifts, textile mills, etc. There are two kinds of induction motors, namely the slip-ring motor and the squirrel-cage motor.

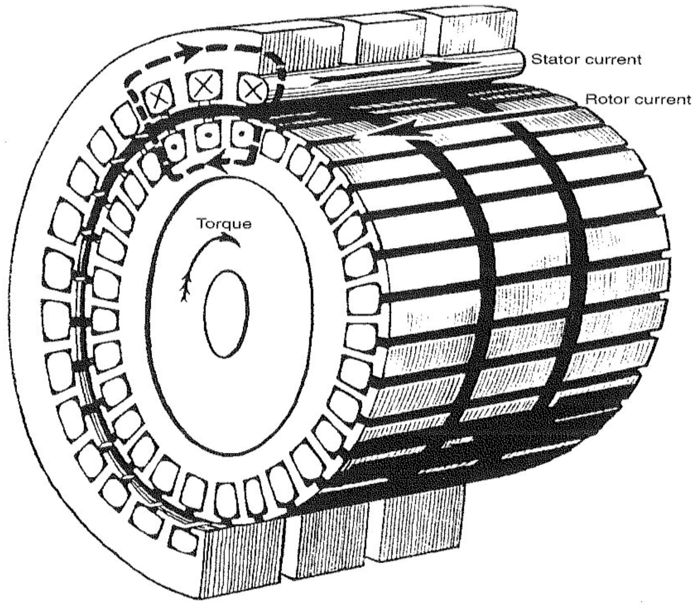


Figure 5.21 Pictorial representation of stator and rotor cores of a three-phase induction motor (showing the directions of currents, flux and torque at a particular instant)

5.5.2 Operation of a three-phase slip-ring induction motor
This motor has a three-phase wound stator. The rotor's winding is similar to the stators winding. The rotor usually consists of a slotted armature with a three-phase start-connected winding.

The ends of the rotor's windings are brought out to three slip-rings, which allow the behaviour of the motor to be altered by introducing resistors into the rotor circuit. Brushes bearing on the rings connect the phases to a tapped three-phase resistance. **Figure 5.22** shows the connections.

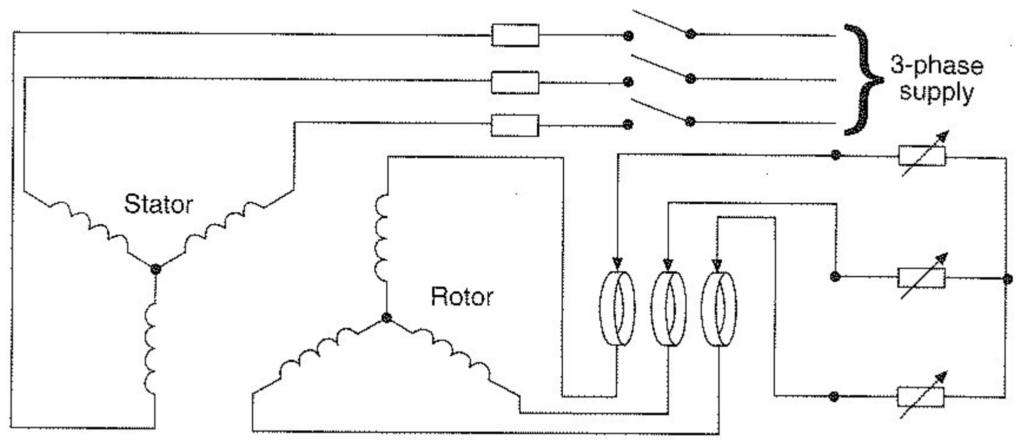


Figure 5.22 (a) Star connection at a three-phase induction motor

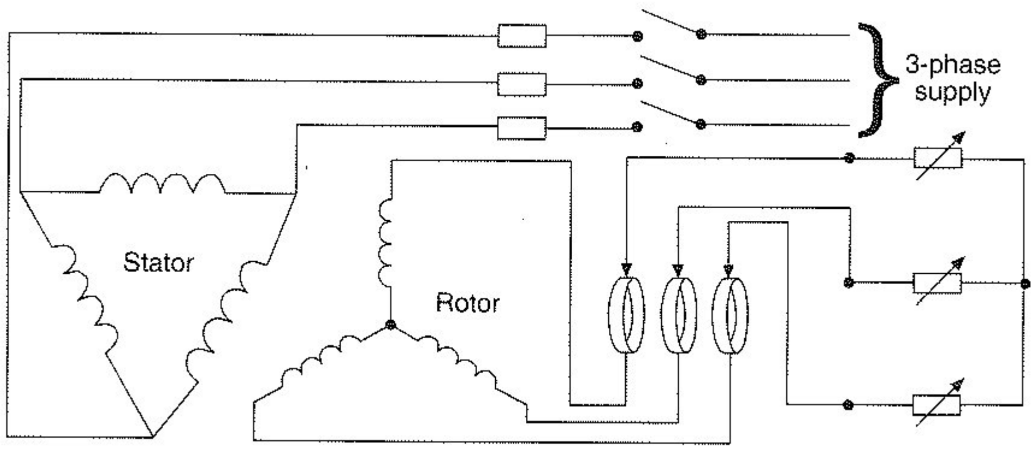


Figure 5.22(b) The squirrel-cage three-phase induction motor

5.6 The squirrel-cage three-phase induction motor

This motor has a three-phase wound stator, and a short-circuited cage rotor. There are no slip-rings and thus no moving connections. The motor is robust, simple, and cheap and is a single speed motor, with a "shunt" speed-load characteristic.

The starting torque of the squirrel-cage motor is small, and the motor is only suitable for light-duty starting. The power factor is low at starting, but is much better at full load.

Note:
The starting and running characteristics of the motor are fixed by the design of the rotor winding.

When a three-phase supply is switched on to the stator winding, a rotating field is set up. This induces emf's in the rotor and so currents flow in these windings. At starting, with the rotor stationary, the current is of supply frequency. The rotor turns in the same direction as the field until it reaches nearly synchronous speed.

When the motor is mechanically loaded, the rotor slows down slightly, the frequency and value of the rotor current increase, and more power is taken by the stator from the main power supply.

5.6.1 Starting of an induction motor

If the motor is started by means of a direct-on switch, the current is large resulting in a low power factor. For all but the smallest motors it is necessary to reduce the starting current.

Note:
With the ordinary squirrel-cage motor this can only be done by reducing the voltage supply to the stator.

5.6.2 Direct-on-line starter

For small machines direct-on -line starting is allowable. The basic connection for one type of direct-on-line starting. When the START button is pushed the magnetic operating coil is energized from two of the line conductors, and four sets of contacts close, providing current to the motor.

The start button may then be released as the retaining contacts, which are connected in parallel with the starting contactors, complete the circuit.

The operating coil holds the contacts in place while the motor is running and thus the motor is stopped by pressing the STOP button.

This action breaks the operating circuit, de-energizing the operating coil, breaking the contacts and stopping the motor.

The overload coils are so arranged that in the event of undue overload they will open the switch in the operating circuit and stop the motor.

Important Note!
SABS 0142 Regulation 6.6.1 states that a circuit supplying a motor shall have over-current protection and that this over-current protection device shall have a tripping value that is as near to the full-load rated current of the motor as it is practicable (Regulation 6.6.2)

5.6.3 The star-delta manual starter for a squirrel-cage rotor

The two ends of each phase of the stator winding are brought out to the starter which, when moved to the "starting" position, connects the winding in star.

After the motor has accelerated, the starter is quickly moved to the "running" position, thereby changing the connection to delta. This method may be obtained semi-automatic or automatic.

5.6.4 The semi-automatic starter

This is a cheap and simple method of squirrel-cage motor starting. The end of each phase of the stator winding, six in all, is brought out to a change-over switch. In the starting position the windings are connected in star so that each phase receives ()- of the normal supply voltage.

The current and torque are reduced in the square of the voltage ratio, that is, to one-third of the direct-on value. When the motor is running at or near its normal speed, the switch is changed over so as to connect the windings in delta, when each phase receives full mains voltage.

5.6.5 The automatic starter

When the starter button is pressed, the magnetic operating coil (MOC) is energized which closes the main contactor, the retaining contactors MCI and the star magnetic operating coil M2 which in turn closes the star contractor TR2 and opens the interlock contactor Y_1

The timer relay starts timing and after a preset time opens the timing contactors.

The star magnetic operating coil de-energizes and the star contactor falls out, closing the delta contactors, thereby energizing the delta contactors coil and the motor is connected in delta.

Y_1 is an interlock contact which prevents the delta contactors from energizing while the star contactor is still closed.

5.7 Testing of a three-phase AC motor

There are three electrical tests that are normally carried out on the stator windings of a motor, namely:

- A insulation resistance test between windings
- A insulation resistance to earth test
- A insulation resistance test with an open-circuit and with a short-circuit.

5.7.1 Insulation tests

Important Note!
SABS 0142 Regulation 6.6.1 states that a circuit supplying a motor shall have over-current protection and that this over-current protection device shall have a tripping value that is as near to the full-load rated current of the motor as it is practicable (Regulation 6.6.2)

5.7.2 Insulation resistance test between windings

An insulation resistance tester (megger) is connected between terminals a. and b, (**Figure 5.23)**, then a, and c, then b, and c, and readings of each one taken in turn. The value of resistance should be at least mega-ohms, SABS 0142 Regulation 8.3.1.2.

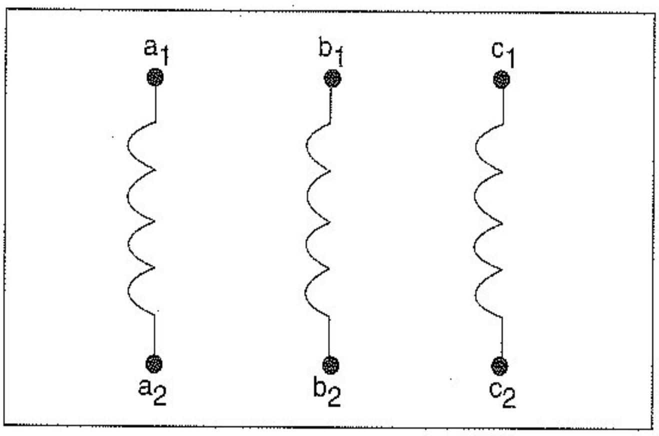


Figure 5.23 Insulation resistance test between windings

5.7.3 Insulation resistance to earth test

This test is necessary to insure a good insulation between the three- phases of the motor.

An insulation resistance tester is connected (refer to **Figure 5.24**) between earth and al, then earth and b1, then earth and c1 and readings of each one taken in turn. The value of the resistance should be at least mega-ohms. This fault occurs when the isolation deteriorates, resulting in a short between phases.

5.7.4 The short-circuit and open-circuit test

A low reading megger is connected between a_l, and a_2, then b_1 and b_2, then c_1, and c_2, with reference to **Figure 5.24** and readings taken in turn. This reading will differ from motor to motor but must be the same for each winding of the same motor.

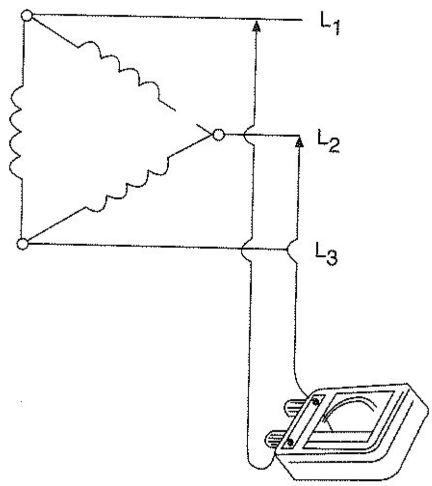


Figure 5.24 High-reading megger indication in open circuit

Note:
The resistance of the stator winding is low, in the region of a fraction of an ohm to a few ohms.

The reason for this low resistance is that the windings on the stator are only one wire that is being wound, and the resistance measure is thus only the resistance of the wire. A lower reading on one of the coils will indicate a short circuit of some turns and a very high, or infinity reading on open circuit. Refer to **Figure 5.24**.

5.8 Regulations for motor control

The SABS code 0142 Regulation 6.6 is dedicated to motors. It is thus important to familiarize yourself with these codes.

The circuit supplying a motor shall have overcurrent protection unless the motor (SABS code 0142 Regulation 6.6.1):

- forms part of equipment that has built-in overcurrent protection, or
- has an integral thermal protector with an accessible reset button, or
- has an automatic resetting thermal protector and there is no likelihood of mechanical damage or of injury to persons when the motor restarts, or is a high impedance type that can stall without overheating (such as the motor of an electric clock).

The overcurrent protection device shall (SABS code 0142 Regulation 6.6.2):

- have a tripping value that is as near to the full-load rated current of the motor as is practicable;
- have sufficient time-delay to allow the motor to start and accelerate under normal conditions;
- prevent a multiphase motor from continuing to operate under load if single phasing occurs; and

- in the case of an automatically controlled motor, have to be manually reset after operation before allowing automatic restarting of the motor.

Any manually operated device used to control a motor shall be readily accessible to the person who operates it. (SABS code 0142 Regulation 6.6.3)

Except in the case of a motor that is an integral part of a submersible pump, a motor shall be supplied through a manually operated device that is (SABS code 0142 Regulation 6.6.4):
- readily accessible and mounted on or next to the motor; or
- visible from the motor; or
- lockable in the open position; or
- housed in a lockable enclosure other than a distribution board.

Alternatively, the motor may be controlled by any other manually operated disconnection arrangement that provides at least the same isolating distance, for safety, as a disconnecting device.

Important Note!
Examples of such arrangements are withdrawable circuit-breakers, removable links and fuses.

Except in the case of a direct-on-line starter, a starter shall have an under-voltage release that opens the circuit if the supply voltage drops sufficiently to cause the motor to stop.

When the supply voltage is restored to a value that would cause the motor to restart, and unexpected restarting could cause injury to the operator of the motor, the starter shall have a means of preventing the motor from restarting, whatever the type of starter. (SABS code 0142 Regulation 6.6.5)

A starter that has a starting position and a running position shall be so constructed that the starting handle cannot be left in the starting position and cannot be moved to the running position without first being moved to the starting position.

Except in the case of liquid-filled starters and in the case of equipment that is designed to allow the starter handle to be left in a position other than the starting position or the running position, the starting handle shall automatically return to the starting position (SABS code 0142 Regulation 6.6.6) when the motor is stopped or when the starter handle is released before the motor reaches full speed.

Activity 5.1

1. Name three methods that can be used to overcome the effects of armature reaction
2. What is the chief purpose of a DC starter?
3. Give the three main parts of an induction motor
4. What is the purpose of the capacitor in a single phase capacitor motor?
5. What motor is superior in efficiency and the most extensively used of all types of electric motors?
6. How can the field coils of DC machines be connected with self-excitation?
7. What is the purpose of a pole shoe in a DC machine?
8. Why are the rotor bars of an induction motor skewed?
9. Name any four disadvantages of a single phase motor compared to a three-phase motor.

Self-Check

I am able to:	**Yes**	**No**
• Describe single phase motor construction and operation		
• Describe Three phase motor construction and operation		
• Describe induction motor construction and operation		
• Describe single phase motor starter construction and operation		
• Describe three phase motor starter construction and operation		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 6

Generation and Supply of AC Power

Learning Outcomes
On the completion of this module the student must be able to:

- Describe and apply the basic principles of AC generation and AC distribution
- Describe supply systems (comparison between single phase and three phase, difference between three phase 3 wire and three phase 4 wire system, star/delta-calculations: line/phase relations)

6.1 Introduction

This module describes how to apply the basic principles of AC generation and distribution. It also describes supply system and makes the comparison between single phase and three phase; three phase 3 wire and three phase 4 wire system; star/delta-calculations and line/phase relations.

6.2 Reticulation system

Electricity is most often generated at a power station by electro-mechanical generators, primarily driven by heat engines fuelled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind.

Note:
There are many other technologies that can be and are used to generate electricity such as solar photovoltaic and geothermal power.

Electricity is generated in power stations through the turning of the shaft of a three-phase alternator. This is often powered by steam, heated through coal, gas, oil or nuclear power. From the alternator electricity goes to a transformer. The output of most alternators is 25,000V (25 kV) and needs to be transformed to:

- 400 kV or 275 kV for the super grid
- 132 kV for the original national grid
- 66 kV and 33 kV for secondary transmission
- 11 kV for local sub-station distribution and industry
- 400 V for commercial consumer supplies
- 230 V for domestic consumer supplies.

Electricity is transmitted at very high voltage in order to compensate for power losses in power lines. When voltage is increased, current reduces for a given value of power.

The effect of volt drop can be calculated using the formula:

Vd=IR

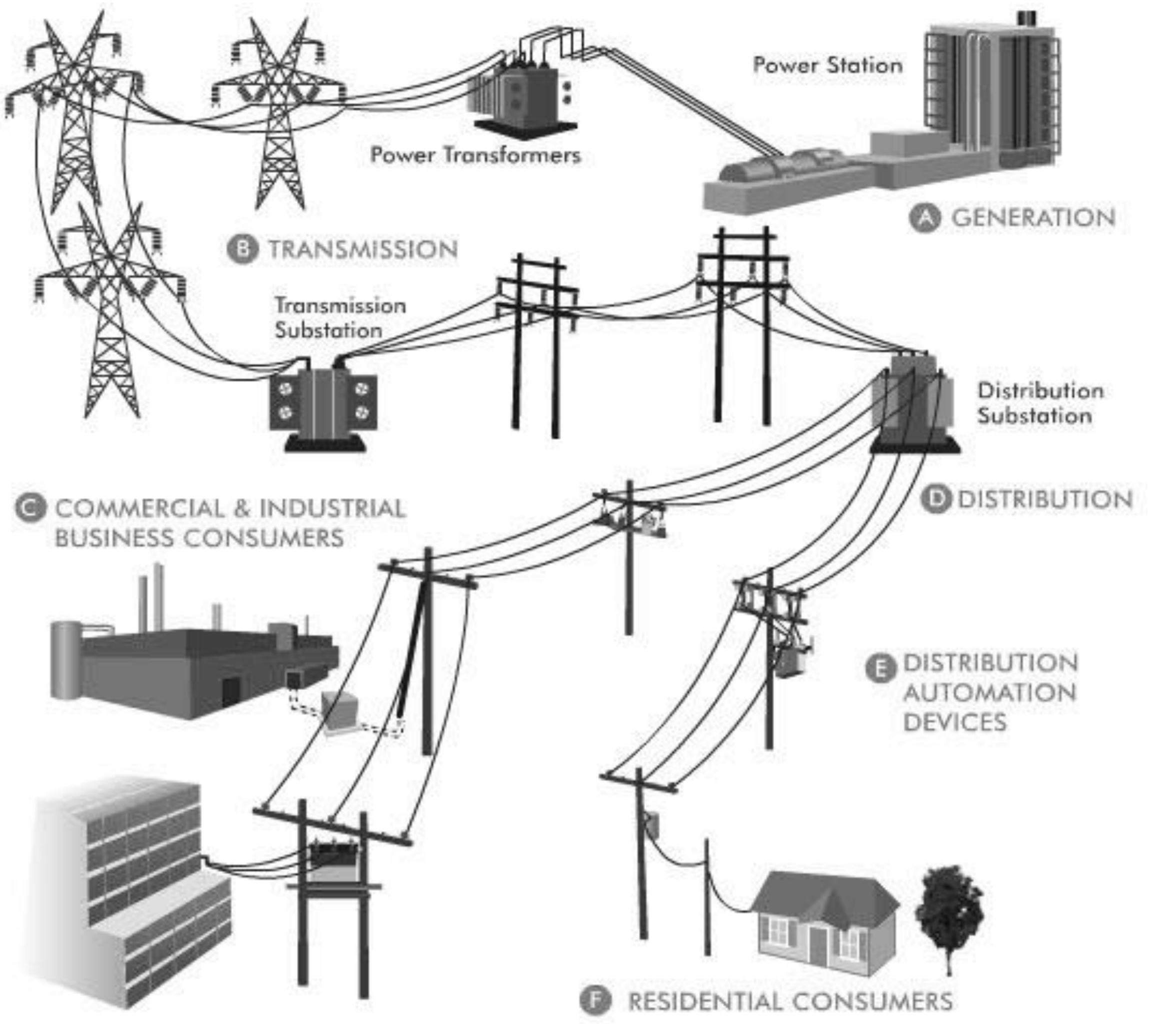


Figure 6.1 General reticulation system

So, for example, if a supply cable with resistance 2 Ω (ohms) were carrying 1000 amps, then the volt drop along its length would be 2000 volts. If the supply cable was carrying 100 amps, then the volt drop would be reduced to 200 volts.

From the super grid, electricity is transmitted to the original national grid. Electricity is transmitted around these grids via steel-cored aluminium conductors, suspended from steel pylons.

From here sub-stations transform the grid supply down to 11 kV and distribute the electricity to a series of local sub-stations. These transform the supply to 400 V /230 V and distribute the power to the customer.

The supply arrives at the customers' main intake position. These contain an overcurrent device and energy metering system, and are controlled by a main switch.

6.3 Three phase generator

6.3.1 Simple Single-Phase Alternator (Generator)

Figure 6.2 shows a single-loop coil rotating between the poles of a magnet. In order to make electrical connection with the rotating coli use is made of Slip-rings and carbon brushes.

As the coil rotates its sides cut through the magnetic flux except when the sides move parallel to the magnetic lines. The emf is at a maximum. When the sides are moving at right angles to the flux and it reverses direction as the sides change from one pole to another, **Figure 6.2**.

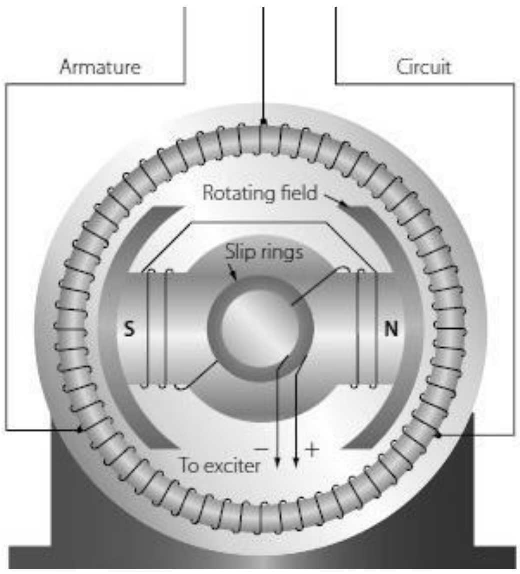


Figure 6.2 Single phase alternator (generator)

6.3.2 Three-phase alternating current (AC)

Electricity for domestic use such as appliances, swimming pool motors and lighting is single phase alternating current, refer to single phase. Heavy users of electrical power, on the other hand, make more use of three-phase AC power.

Note:
Three-phase power is cheaper to generate and transmit.
Three-phase motors are simpler, less expensive and more powerful.

The simplest approach to the study of three phase systems is to consider a three phase circuit as merely a combination of three single-phase circuits.

6.3.3 Simple Three-Phase Alternator (Generator)

The three-phase alternator (generator) can be considered as 3 single phase armature windings wound on the same core, mutually displaced by 120 degrees, rotating in the same field as illustrated in **Figure 6.3**.

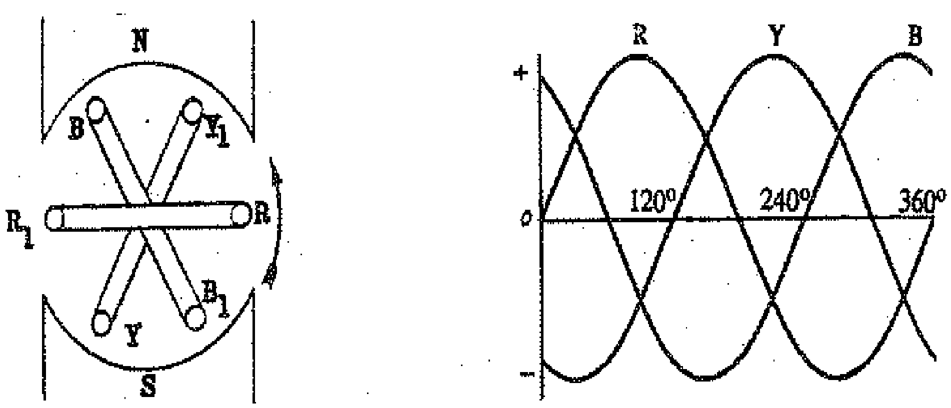


Figure 6.3 Simple Three-Phase Alternator

When drawing three-phase waveforms care should be taken with the starting points of the waves. The base line of each half cycle should be divided into three equal sizes (**Figure 6.3**).

The wave of the first phase starts at zero and is projected upwards, the wave of the second phase starts below the x-axis and is approaching negative maximum while the wave of the third phase has just passed positive maximum and is on its way down to zero.

6.4 Three phase transformer

Trying to deliver electricity long distance at high voltage and then reducing it to a fractional voltage for indoor lighting became a recognized engineering roadblock to electric power distribution with many, not very satisfactory, solutions tested by lighting companies.
The theory of the single phase transformer is quite easy to understand. It is time for the three phase transformer. The basic theory remains the same.

The three phase transformer can be realized by properly connecting three numbers of single phase transformer or designed as a single unit. The three numbers of single phase type requires more materials and costlier whereas the single unit three phase transformer requires less materials and so cheaper.

When a winding fault occurs in one unit of the three single phase type then only that particular unit is replaced by a similar unit, but a winding fault in three phase single unit type requires replacement of the complete transformer. The three single phase type requires more space.

Note:
The three single phase type transformer are mainly used for extra high tension bulk power transmission and at generating stations. In this case four single phase transformers are used.

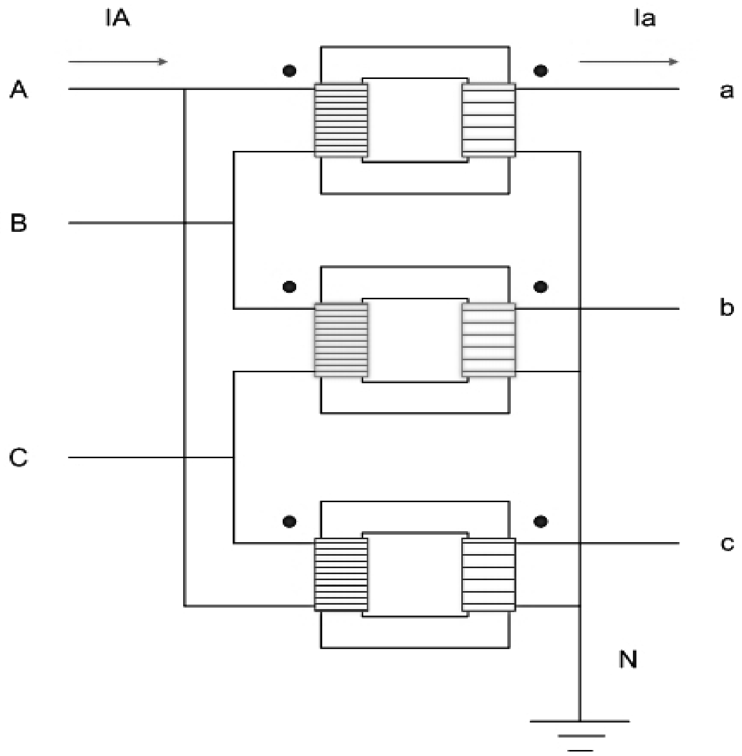


Figure 6.4 Three single phase transformers connected to form a three phase transformer

Three single phase units are connected to grid and the fourth one is kept ready. Many times this type of arrangement is also done in Hydro power stations or other hilly areas where transportation of large single three phase unit is not convenient or road permit is not available. Where space availability at the switch yard is less, the single unit 3-phase type should be preferred.

Note:
A balanced three phase system will always form the sides of the equilateral triangle. It is simple to remember that as the winding connections form the delta or star so also their respective voltage phasors.

We have already discussed about single phase type. In the diagram it is shown how three numbers of single phase units can be connected for D-Y arrangement (primary in delta and secondary in star or Y). Three single phase units also called bank of transformers.

In the diagram (**Figure 6.4**) the windings of the same phase are coloured same for easy understanding.

The Vector (phasor) diagram shown in **Figure 6.4** is also coloured. The arrows denote the voltage in a particular winding. The magnitude of red, green and blue arrows are same, denoting the same magnitude of voltage in all the three windings.

The directions are 120° apart, means the voltage waves are 120° phase displaced from each other. The direction of arrow for example is BA, which is due to the polarity (dot mark) of winding shown (you can think that 'A' is positive with respect to 'B'). Similarly AC and BC.

6.5 Three phase domestic supply

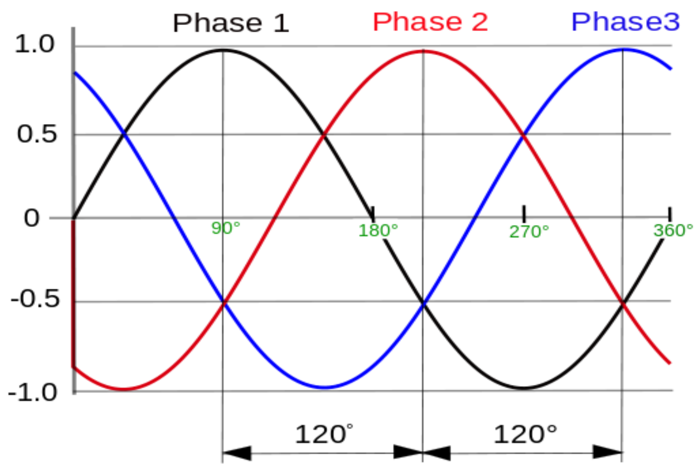


Figure 6.5 The wave form of a three phase electrical supply

Figure 6.6 is a multi-line circuit diagram that represents the layout of a three-phase, four wire, 400 V/230 V, 50 Hz distribution board (DB) with circuit breakers, isolator switches and electrical devices connected to it.

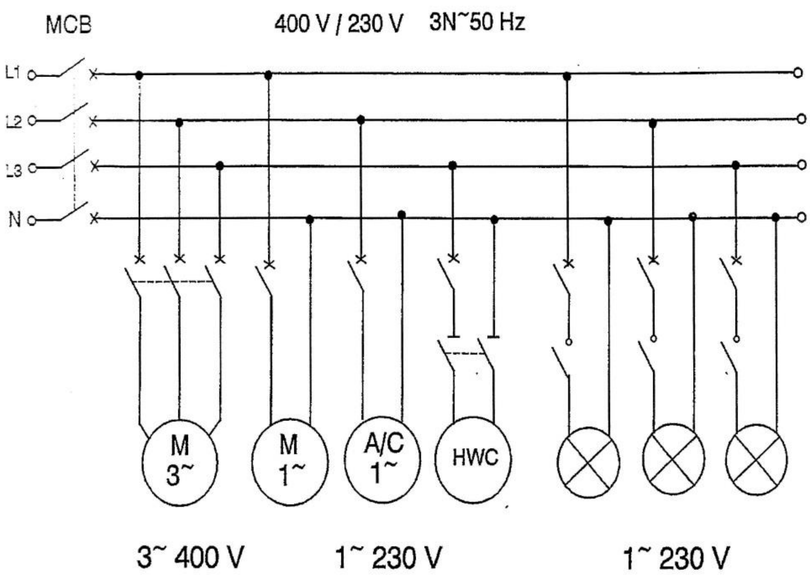


Figure 6.6 Circuit diagram for distribution board

Activity 6.1

1. What device is used on a transformer that serves as a protection system and what does it also activate?
2. In which system does failure of one interconnecting feeder interrupt the supply to any of the other substations?
3. Why are coal fired power stations normally built far away from the main load points?
4. Name any two types of power stations
5. Name two types of feeders used in transmission systems

Self-Check

I am able to:	Yes	No
• Describe and apply the basic principles of AC generation and AC distribution		
• Describe supply systems (comparison between single phase and three phase, difference between three phase 3 wire and three phase 4 wire system, star/delta-calculations: line/phase relations)		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 7

Measuring Instruments and Protective Devices

Learning Outcomes
On the completion of this module the student must be able to:

- Describe the construction and operation of the ammeter
- Describe the construction and operation of the voltmeter
- Describe the construction and operation of the ohm-meter
- Describe the construction and operation different switchgear devices
- Describe the construction and operation of protective devices

7.1 Introduction

This module describe the construction and operation of various measuring instruments and protective devices such as the ammeter, voltmeter, ohm-meter and various switchgear devices.

7.2 Measuring instruments

We know that the reading on an analogue measuring instrument is the result of current flowing through a coil in the instrument. All that remains is to explain how this basic device allows us to measure current, potential difference and resistance.

Current - Current flow is measured by connecting a measuring instrument in series in the circuit where the current flow is to be determined. However, if we need to measure 10 A it would probably melt the wire inside the coil.

Thus, a very low resistance shunt resistor is used in parallel with the coil so that only a small portion of the current, approximately 20 mA, passes through the coil. If we need to measure 2 A, a different shunt resistor is required, since we still need approximately 20 mA for full scale deflection.

Potential difference - Voltage is measured by connecting a measuring instrument in parallel with a portion of a circuit. To limit the current flowing through the coil, a resistor is placed in series with it. Again, different resistors are required for different applied voltages.

Resistance - The resistance of a component can be determined by measuring the current flow through it when the voltage drop across it is known. The potential difference is known, as an ohmmeter has its own voltage source. This combined test supplies the resistance value of the component.

An ohmmeter should never be used on a live circuit, as this could destroy the instrument. Most analogue meters are most accurate in the range from "11 o'clock to 1 o'clock".

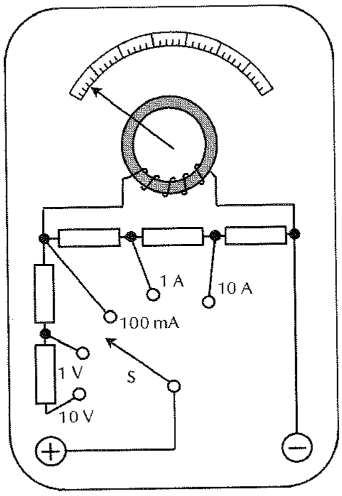


Figure 7.1

By alternating the position of switch, S, this multimeter can be made to function as a voltmeter (0 - 10 V or 0 - 1 V) or an ammeter (0- 100 rnA, 0- 1 A or 0- 10 A).

Let us discuss the different types of measuring instruments.

7.2.1 Voltmeter

A voltmeter is an instrument used to measure voltage. For instance, a voltmeter can be used to see if there is more electricity left in a battery. The creation of voltmeters became possible when Hans Oersted invented the simplest voltmeter in 1819.

Technically, all voltmeters are ammeters, as they measure current rather than voltage. Although current is measured in amps, Ohm's Law, which establishes the relationship between voltage, current and resistance, can be used to scale the amps to volts. **Figure 7.2** shows a typical voltmeter.

Figure 7.2 Voltmeter

Figure 7.3 Ammeter

7.2.2 Ammeter

Most electricians use a clamp on type amp meter where the circuit conductor, one at a time, is encircled by the jaws of the meter. A reading is them displayed either with an analog needle or a digital readout.

Figure 7.3 shows a typical ammeter.

When the current flow is large or small, there are attachments which can be used on the conductor to either amplify or reduce thee induced current so a reading can be obtained.

A simple way to make a low value reading with a small conductor is to pass the circuit conductor through the jaws of the meter more than just the once which is typical.

Then the actual current flow is the reading divided by the number of turns or passes the circuit conductor makes through the jaws. There are also amp meters which allow for a reading by just placing the circuit conductor in the notch at the end of the meter probe.

This is a much quicker way to take a reading when smaller conductors are to be measured.

7.2.3 Wattmeter (electrodynamometer) type

Power is measured with a wattmeter. In a common type wattmeter, the voltage applied to the "voltage coil" (the moving coil of **Figure 7.4 (a) and (b)**) establishes a magnetic field strength directly proportional to the voltage.

The current flowing in the "current coil" (the field coil) reacts with the magnetic field to produce a torque proportional to the current and the voltage torque.

The resulting deflection is proportional to the average *VI* product and the scale is calibrated to read average power in watts.

Important: P = VI cos∅ Watts

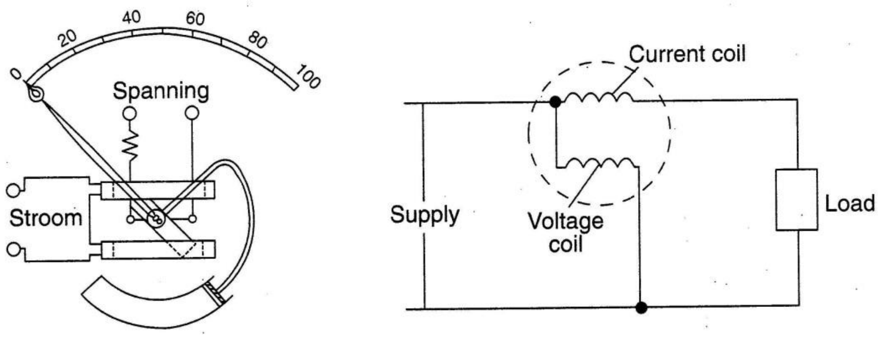


Figure 7.4 (a) Dynamometer wattmeter (b) Theoretical diagram of wattmeter

In effect, a wattmeter is a combination of an Amp and Voltmeter.

Figure 7.5 illustrates how the wattmeter is connected in a single-phase circuit.

Care must be taken when connecting this measuring instrument, because if connected wrongly it will damage the instrument.

The current coil (representing the Amp reading) must be connected in series with the load and the voltage coil (representing voltage reading) must be connected in parallel with the load.

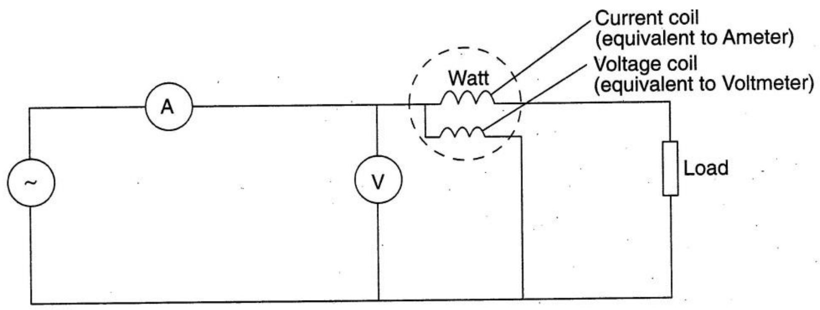


Figure 7.5 Connecting of a wattmeter

7.2.4 Kilowatts-hour meter (energy meter)

Such meters are necessary in order to register the energy supplied to an electricity consumer over a given period.

Energy is the product of power and time, and a wattmeter element whose movement is allowed to continue and move a train of gears with indicating fingers, constitutes an energy meter when properly calibrated.

There are various types of energy meters:

- mercury motor ampere-hour meters, direct current, calibrated to read kilowatts- hours at the declared voltage
- electrolytic ampere-hour meter, direct current, or rectified alternating current, calibrated as type 1, to read kilowatts-hours or kilovolt-ampere-hours
- induction type energy meter, alternating current

7.2.5 The induction type kilowatts-hour meter
The induction type wattmeter consists of a voltage coil and current coils. The voltage coil is wounded on a laminated iron core forming a nearly closed magnetic circuit.

The circuit is thus highly inductive, and the current in the coil lags about 85° behind the voltage.

The current coils are wound on an open magnetic circuit which has very little inductance. A light aluminium disc is mounted in front of the magnets so that its rim will pass between the two pairs of poles.

Each pair of poles sets up eddy current in the disc. These eddy currents react other, causing the disc to move.

The control is by hair-springs. Damping is provided by means of a permanent magnet which is set up retarding eddy current in the disc during movement. **Figure 7.6** is a diagram of a single-element wattmeter.

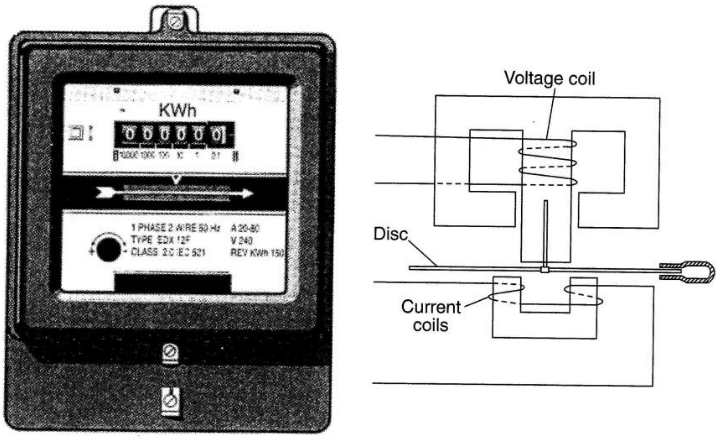


Figure 7.6 Single-phase induction kilowatts-hour meter

7.2.6 The frequency meter
The frequency of a signal can be determined or measured by counting the number of cycles over a fixed period of time.

The moving-iron frequency meter reflects a constant indication of frequency. Different types of deflection frequency meters are available, but in all cases one or more tuned circuits are employed, turned to the lower and upper frequency limits.

The principle is that, at resonance, the current increases considerably; the greatly increased current, used to produce torque, is due to a small change in frequency. The simplest form of moving-iron frequency meter incorporates two adjacent fixed coils and a central moving-iron capable of attraction into either coil.

The two coils are turned, one with an inductance and one with a capacitance, in such a way that small changes in frequency causes a differential pull on the moving-iron and therefore also on the pointer.

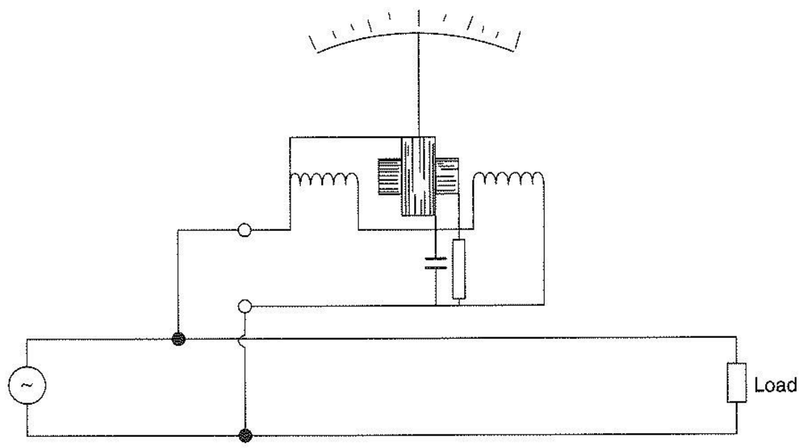


Figure 7.7 Moving-iron frequency meter

7.2.7 Power factor meter
The power factor meter instrument is simple and comprises volt and current windings, as does the wattmeter.

Note:
For single-phase systems there is one volt and one current circuit.

Power factor meters have 360° scales, the pointer standing in the upper or lower half of the scale according to the direction of the flow of power in the circuit in which it is connected.

Figure 7.8 shows the connection for a power factor meter suitable for a phase system or currents. The instrument has accordingly one vol circuit and one current circuit. It is most important that the connection should be made correctly.

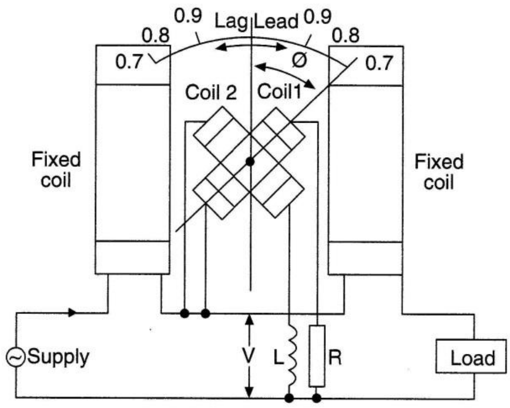


Figure 7.8 Single-phase power factor meter

7.2.8 Maximum demand meter

In some localities the charge for electric supply is based upon the maximum load which is applied to the whole circuit. In this case it is merely necessary to have an instrument which will register this current without any regard for the number of hours during which it is used.

> **Note:**
> This meter may be seen as an "ordinary" energy-meter with a passive pointer, displaying the maximum demand used for a specific time.

Many types of meters for measuring this demand have been developed and one such meter is the Integrated-demand meter.

Integrated-demand meters consist of an integrating meter element (kWh or kvarh) driving a mechanism in which a timing device returns the demand actuator to zero at the end of each timing interval, leaving the maximum demand on a passive pointer, display or chart, which in turn is manually reset to zero at each reading period, generally one month.

7.3 Switchgear and protective devices

7.3.1 Shunt resistors

A shunt is a high precision resistor which can be used to measure the current flowing through a circuit. Using Ohm's Law we know that the voltage dropped across a resistor divided by the resistance of that resistor is equal to the current, therefore if we measure the voltage across a shunt resistor in a circuit, we can easily calculate the current.

7.3.2 Instrument transformers

A transformer that transfers primary current, voltage, or phase values to the secondary circuit with sufficient accuracy to permit connecting an instrument to the secondary rather than the primary; used so only low currents or low voltages are brought to the instrument.

Instrument transformers are used to measure very high voltages or currents with the help of a small 'voltmeter' or 'current meter'. These are called 'potential transformers' (PT) and 'current transformers' (CT) respectively.

Note:
The PT basically is a step down power transformer and CT is a step up power transformer. These are also used as protecting devices.

7.3.3 Circuit breaker ratings and conductor sizes
The neutral of an electrical system can be insulated from earth or earthed. In South Africa, the SABS Code of Practice lays down that on all Low Voltage (LV) systems, the neutral shall be earthed at the supply transformer or generator and an earth continuity conductor be provided and connected to all exposed conductive parts.

The purpose of this is to ensure that when an earth fault occurs anywhere on the electrical installation, it can be discharged safely to earth.

7.3.4 Overload currents
Every component making up an electrical installation is designed for use at a particular rated current. When it is used within these limits it will have a specific service life expectancy, that is, the length of time for which the installation will remain operational safe.

Under normal conditions the heat generated by the flow of current though the resistance of the component (proportional to I2R) must be transferred across the insulation to the cooling medium.

Unfortunately, materials that are good electrical insulators are often good thermal insulators and if the current rating of the component is exceeded, there is a build-up of heat within the insulation.

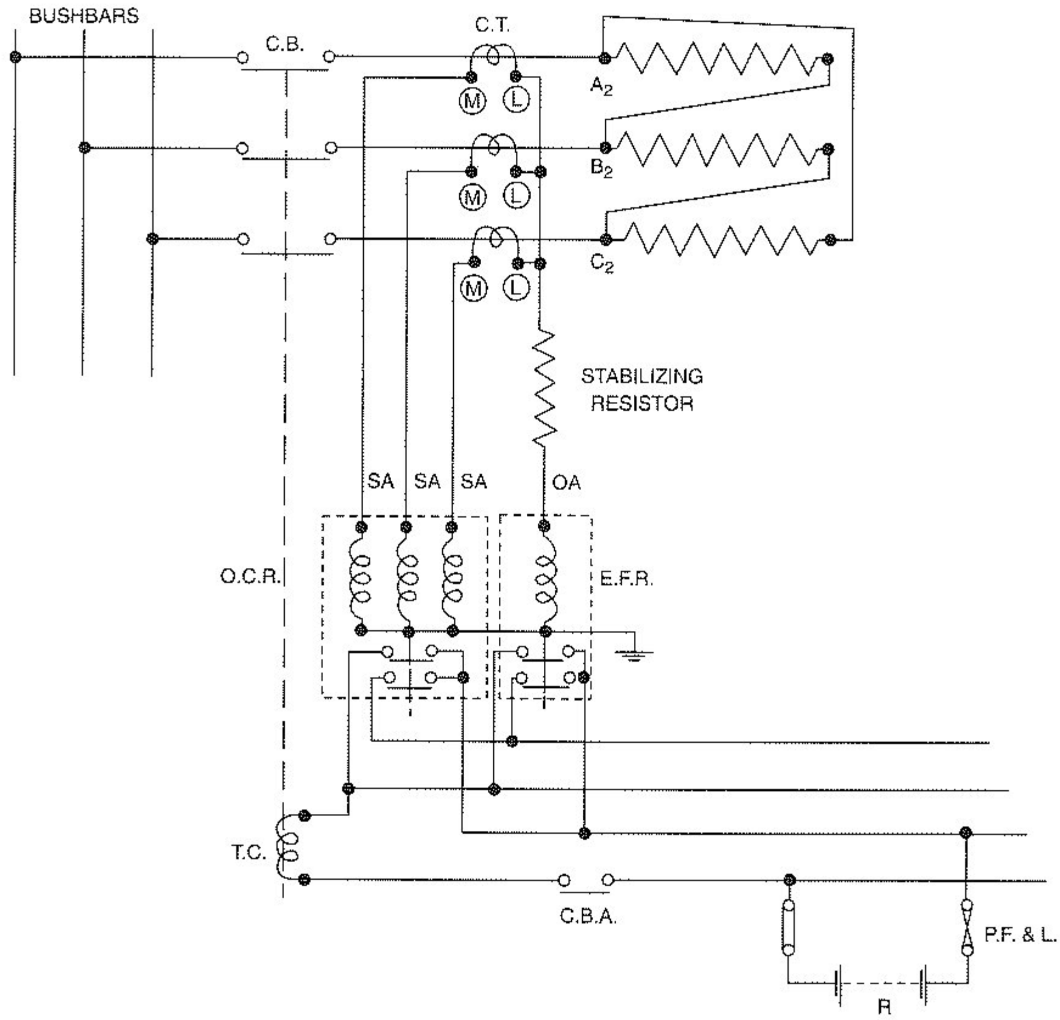
Note:
When a component is overloaded, the temperature in the insulation exceeds the limit beyond which the insulation begins to deteriorate and the service life will be shortened.

This deterioration depends on both the temperature rise and time for which the insulation is exposed to the overload. Precaution should be taken to avoid, or at least reduce to a minimum, overloading of components.

Overcurrent protection is achieved by applying three Current Transformers (CT'S) in a balanced three-phase circuit. An overcurrent relay (0CR) is connected to each CT. These OCR can be set for a specific tripping current depending on the needs of the circuit.

In the effect of an overload in one of the three phases the CT will supply more current than the tripping current and set of the OCR, resulting in the energizing of the coil of the OCR. Opening the contacts of the OCR.

As a result the current supply to the tripping coil (TC) is broken which causes the circuit breaker (CB) to open, cutting the supply from the busbars.



CB Circuit-breaker CT Protective Current Transformer CBA Circuit-breaker Auxiliary Switch TC Trip Coil O.C.R. Overcurrent Relay EFR Earth Fault Relay PF&L. Protective Fuse and link B. Battery

Figure 7.9 Overcurrent and earth-fault protection

Any form of balanced protection must be maintained, unless the three current transformers are perfectly matched in ratio and other characteristics, these through currents, often of extremely high magnitude, can readily cause a "spill" current to appear at the relay and if of sufficient magnitude, cause it to operate.

This is a particular hazard when a sensitive earth-fault relay is set to operate at 1 A or less, as no matter how well the current transformers are designed and manufactured, the primary current will not be reproduced perfectly in each secondary and a "spill" current will result.

Note:
The stabilising resistor is added to increase the stability of the relay circuit and to reduce the value of "spill" current reaching the relay.

Earth faults are detected when the magnitude of the" spill" current is large enough to activate the coil of the earth fault relay (EFR), resulting in the relay contactors to open, cutting the supply to the load as described in the overhead protection explanation.

7.3.5 Types of circuit breakers
7.3.5.1 The Hydraulic Magnetic Circuit Breaker (HMCB)
Time delay operation - **Figure 7.10** indicates the operation of the HMCB. At an overcurrent flow, the magnetic force of the coil overcomes the coil core spring, the core closest to the pole piece attracts the armature and actuates the trip bar.

Note:
The delay is obtained by the viscosity of silicon oil.

Instantaneous operation - If the overcurrent is excessive the armature is instantly attracted without the influence of the moving core.

Features of the HMCB are:
- Circuit breakers always carry 100% of rated current and always trip within pre-determine percentage of rated current, irrespective of ambient temperature conditions.
- The operation is not dependent on thermal action to activate the tripping mechanism, therefore the pre-determine tripping point is not changed by a variation in temperature. The tripping characteristic is mainly determined by the number of turns of the solenoid coil.
- A wide variety of tripping characteristics is available to suit particular protection needs.
- No nuisance tripping caused by high ambient temperature.
- Immediate reset after fault has been cleared.

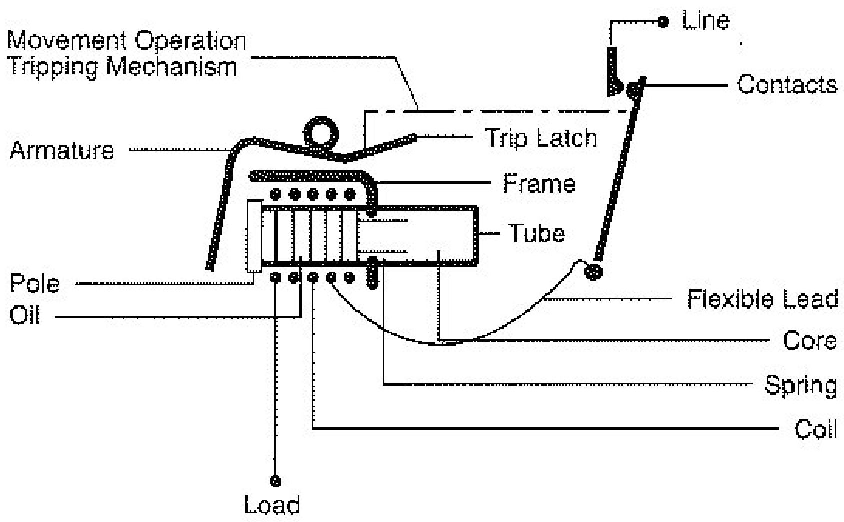


Figure 7.10 HMCB Operation

7.3.5.2 Thermal Magnetic Circuit Breakers (TMCB)

Time delay operation- Figure 7.11 indicates the trip operation of a TMCB. An overcurrent heats and bends the hi-metal to actuate the trip bar.

Instantaneous operation- If the overcurrent is excessive, magnetisation is strong enough to attract the armature and actuate the trip bar.

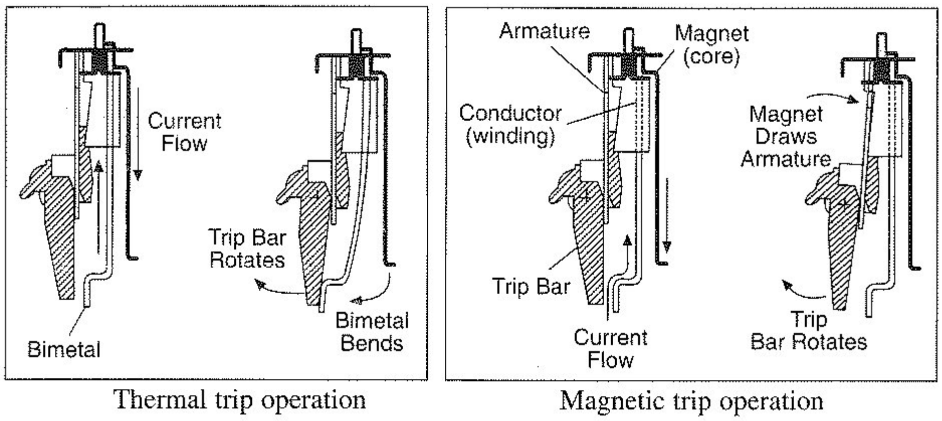


Figure 7.11 Trip operation of TMCB

Features of the TMCB are:

- Thermal overload elements automatically re-rate themselves for variations in ambient temperature, safeguarding equipment under high ambient conditions and permitting safe loading under low ambient conditions.
- Thermal circuit breakers can be calibrated to operate at specific ambient temperatures.
- A high proportion of faults and fires are caused by loose external connections to the circuit breaker terminals developing into high resistance (hot) connections. Thermal overload elements detect this dangerous situation and trip to isolate the circuit.

- Fast electromagnetic trip under short circuit conditions (in the order of 20 milliseconds seconds).

7.3.5.3 Seltronic Coordination Circuit Breakers (SCCB)
Principle of operation- **Figure 7.12** serves as a block diagram to explain the principle of operation of a SCCB. In-built current transformers (CTs) monitor the load current, one CT per phase.

The transformer current is rectified via the electronic printed circuit board. The largest converted phase current is selected to trigger a signal to a low energy shunt trip to operate the tripping mechanism.

Note:
The control circuit is isolated from the mains.

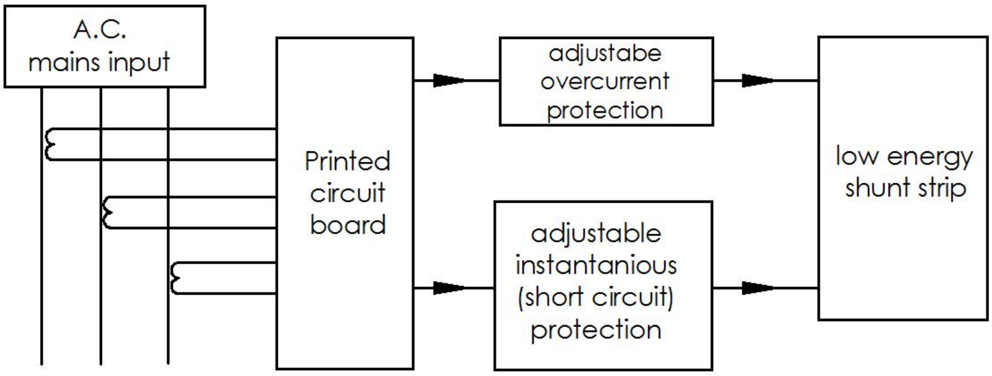


Figure 7.12 Principle of operation – SCCB: Solid State Control

Features of the Seltronic coordination circuit breaker are:
- Highly accurate adjustment of current rating to give close overload protection with adjustable plug from 100% down to 50% Rating,.
- Short time delay tripping adjustment to discriminate between inrush current and overload currents, making the SCCB ideal for motor starting.
- Long and short time delay adjustment to provide selective tripping coordination.
- The SCCB can be mounted horizontally, vertically or on their sides. The mounting position does not change the tripping characteristics.

7.3.6 Low tension circuit-breakers: moulded case circuit breakers (MCCB)
A circuit-breaker may be defined as a mechanical switching device that is capable of automatically breaking current under specified abnormal circuit conditions such as those of overcurrent.

All electrical wiring connected to the wiring of your college and home must be protected to prevent:

- fire
- a short circuit
- overloading

Except for a circuit-breaker that is mounted next to the appliance or socket-outlet that it controls, each circuit-breaker shall be labelled to show which circuit or appliance it controls. (SABS 0142 Regulation 7.10.1)

The circuit breaker acts as a fuse. When the circuit becomes overloaded, the contact point open magnetically and causes the current to stop flowing. The circuit-breaker must be reset after the cause of the overload has been removed (see **Figure 7.13**).

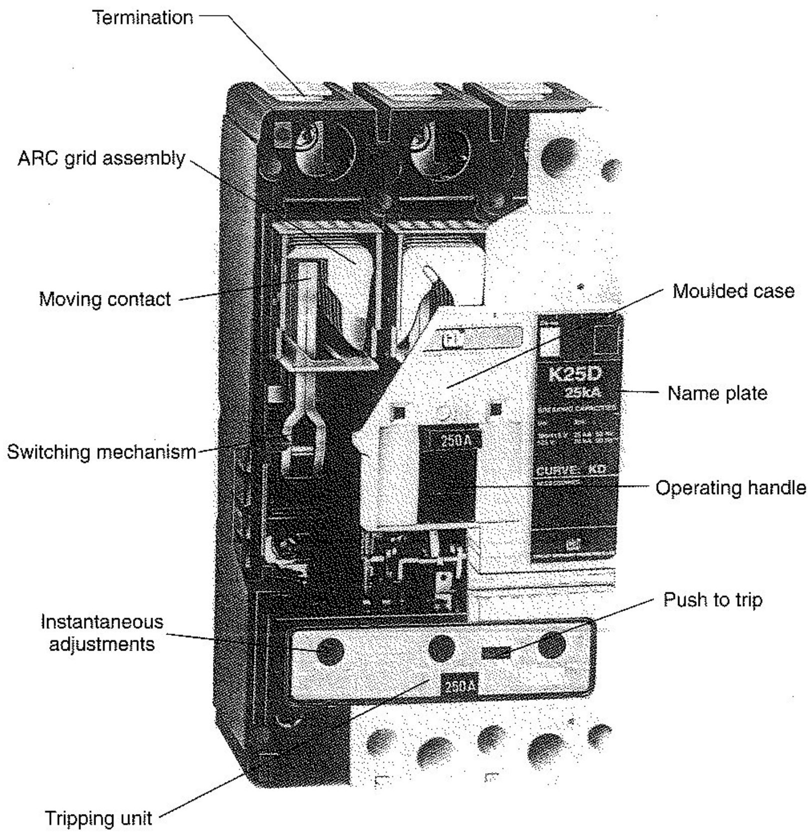


Figure 7.13 Construction of a MCCB

The circuit breaker is operated by the ON/OFF handle which actuates a quick-make, quick-break over-centre switching mechanism that is mechanically trip-free from the handle, so that the contacts cannot be held closed against overload currents.

Note:
The circuit breaker mechanism is so constructed that all poles of a multi-pole circuit breaker open, close and trip simultaneously.

The circuit breaker mechanism and current carrying parts are enclosed in a high strength, fire retardant, glass polyester case.

Figure 7.14 indicates the trip position. The automatic trip condition is in the centre position. To reset the handle, move the handle to the "off' position to engage the mechanism and then return the handle to the "on" position.

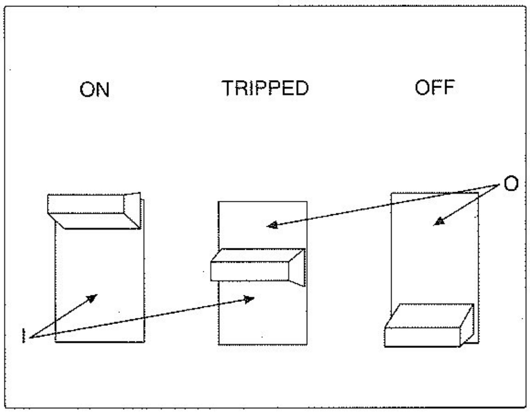


Figure 7.14 Operating handle trip position

Figure 7.15 indicates the construction of a de-ion arc extinguisher which comprises a set specially shaped steel grids isolated from each other.

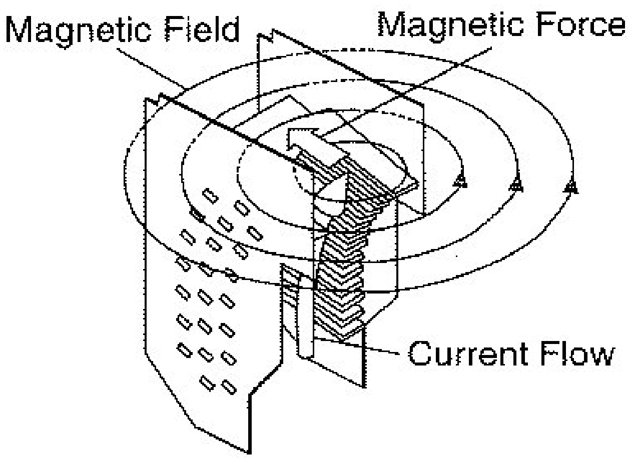


Figure 7.15 Construction of a de-ion arc extinguisher

The function of the de-ion arc extinguisher is to extinguish the arc formed when the circuit breaker trips.

Worked Example 7.1

A 400 V-DC supply is connected across a circuit of a 200-ohm resistor in series with a resistor of unknown value. A voltmeter having a resistance of 800 ohms is connected across the 200-ohm resistor and shows a reading of 200 volts.

Calculate the value of the unknown resistor.

Solution:

$$I_v = \frac{V}{R_v} = \frac{200}{800} = 0{,}25\ A$$

$$I_R = \frac{V}{R} = \frac{200}{200} = 1A$$

$$V_x = I_R + I_v = 400 - 200 = 200\ V$$

$$R_x = \frac{V_x}{I_T} - \frac{200}{1{,}25} = 160\ \Omega$$

Worked Example 7.2

A moving-coil instrument has a resistance of 100 ohms and gives a full-scale deflection when 2 000 mA flows through it. Calculate the v alue of the additional component required to enable the instrument to be used as:

1. An ammeter, reading 0 – 12 A
2. A volt meter, reading 0 – 300 V

Solution:

$$I_{SH} = I_L + I_m = 12 - 2 = 10\ A$$

$$R_{SH} = \frac{V_m}{I_{SH}} = \frac{I_m \times R_m}{I_{SH}} = \frac{2 \times 100}{10} = 20\Omega$$

$$R_{SE} = \frac{V}{I_m} - R_m = \frac{300}{2} - 100 = 50\ \Omega$$

Worked Example 7.3

In a Wheatstone bridge ABCD, a resistor of unknown value is connected between A and B. When the bridge is balanced, the resistance between B and C is 50 ohms, that between C and D is 90 ohms and between D and A is

18 ohms.

Calculate the unknown value of the resistance.

Solution:

$$\frac{R_{AB}}{R_{SC}} = \frac{R_{AD}}{R_{DC}}$$

$$R_{AB} = \frac{R_{AD} \times R_{BC}}{R_{DC}} = \frac{18 \times 50}{90} = 10\Omega$$

Activity 7.1

1. Explain the function of the following instruments:
   a) wattmeter (electrodynamometer type)
   b) voltmeter
   c) ammeter
   d) kilowatts-hour meter
   e) frequency meter
   f) power factor meter
   g) maximum demanded meter
2. Illustrate, by means of a circuit diagram, how the following instruments are connected in single phase circuits:
   a) wattmeter
   b) kilowatts-hour meter
   c) frequency meter
   d) power factor meter
   e) maximum demand meter

Activity 7.2

1. List FOUR types of circuit breakers.
2. Explain the time delay operation and the instantaneous operation for the following circuit breakers:
   a) TMCB
   b) HMCB
   c) SCCB

Activity 7.3

A milli-ammeter with a 40-ohm coil resistance, indicates a full-scale deflection when a current of 100 mA flows through it.

Calculate the value of the series resistance required to alter the ammeter to measure 0-5 V.

[10]

Activity 7.4

A milli-ammeter with 5 ohms coil resistance indicates a full-scale deflection when a current of 1 000 mA flows through it.

Determine the value of the resistances required to enable the instrument to be used as a ….

1. 10 V voltmeter
2. 1,5 A ammeter

[5; 0.5; 10]

Activity 7.5

A 500 V DC supply is connected across the circuit of a 100 ohm resistor connected in series with a resistor of unknown value. A voltmeter with a resistance of 500 ohms is connected across the 100 ohm resistor and shows a reading of 50 volts.

Calculate the value of the unknown resistor.

[0.1; 0.5; 0.6; 450; 750]

Activity 7.6

The value of a resistor is measured by the voltmeter-ammeter method. The internal resistance of the voltmeter is 500 ohms. When the voltmeter is connected directly across the resistance to be measured, then the ammeter reads 2 A and that of the voltmeter 250 V.

Calculate the value of the unknown resistor:

1. Approximately
2. Accurately and
3. The percentage error in the value of the resistance

[2; 0.5; 125; 166.67; 25]

Self-Check

I am able to:	Yes	No
• Describe the construction and operation of the ammeter		
• Describe the construction and operation of the voltmeter		
• Describe the construction and operation of the ohm-meter		
• Describe the construction and operation different switchgear devices		
• Describe the construction and operation of protective devices		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Past Examination Papers

higher education & training

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

29 July 2015 (Y-Paper)
13:00 – 16:00

Requirements: **Graph paper**
Calculators may be used.

This question paper consists of 5 pages and a 2-page formula sheet.

DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N4
TIME: 3 HOURS
MARKS: 100

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
2. Read ALL the questions carefully
3. Number the answers according to the numbering system used in this question paper.
4. Write neatly and legibly.

QUESTION 1:

1.1 A coil having 2 000 turns of conductor wire with a cross-sectional area of 200 mm^2 and a mean length per turn of 200 mm, has an inductance of 4 henry.

Calculate the following:

1.1.1 The resistance of the winding if the specific resistance of the conductor is 2 micro-ohm metres (3)

1.1.2 The average value of the EMF induced in the coil when 'a current of 10 A is reversed in 20 seconds (2)

1.2 A resistor of unknown value R is connected in parallel with a resistance of 30 ohms. This combination is connected in series. with a resistance of 20 ohms. The circuit is then connected across a 120 V DC-supply.

Calculate the following:

1.2.1 The value of the resistor R when a 3 A current is drawn from the supply (5)

1.2.2 The power dissipated in the circuit (1)

1.3 Distinguish between a positive and a .negative temperature coefficient of resistance. (3)

1.4 The field coil of a motor has a resistance of 100 ohms at 25 oc. By how much will the resistance increase if the motor attains a temperature of 125 ºC when running? Take the temperature. coefficient of resistance as 0,004 per degree Celsius at 25 ºC. (4)

1.5 Explain Kirchhoff's first law. (2)

[20]

QUESTION 2:

2.1 Calculate the magnetomotive force that is required to produce a flux of 3 mWb in a magnetic circuit having a reluctance of 30 000 A/Wb. (2)

2.2 Two batteries of EMF 90 V and 180 V and internal resistance of 0,6 ohms and 0,6 ohms respectively, are connected in parallel to supply a load resistance of 2,4 ohms.

Use Kirchhoff's laws to calculate the following:

2.2.1 The current supplied by each battery (7)

2.2.2 The voltage across the load (2)

2.3 Define the *farad.* (3)

2.4 Two capacitors connected in series have respective volt readings of 90 V and 30V.

If the total charge equals 900 μC, calculate the following:

2.4.1 The total capacitance

2.4.2 The value of each capacitor (2 x 3) (6)

[20]

QUESTION 3:

3.1 The open-circuit characteristics of a shunt-excited DC machine are as follows:

Terminal voltage (V)	10	20	25	29	30,5	31
Field current (A)	1	2	3	5	6,5	7,5

Plot a graph and determine

3.1.1 The voltage to which the machine will excite on no-load when shunt is connected if the total field resistance is 5 ohms

3.1.2 The critical resistance (2 x 5) (10)

3.2 A long-shunt, compound-wound DC machine has an armature resistance of 0,3 ohms, a series field resistance of 0,1 ohm, and a shunt-field resistance of 20 ohms. The machine draws a current of 40 A from a 200 V- DC-supply when run as a motor. (5)

Calculate the EMF generated in the armature.

3.3 What is the purpose of a pole shoe in a DC machine? (2)

3.4 Make a neat sketch to illustrate magnetic fringing, leakage flux and useful flux. (3)

[20]

QUESTION 4:

4.1 What can be done to improve the power factor? (2)

4.2 A 50 Hz sinusoidal voltage has an RMS value of 141 ,4 V.

Calculate:

4.2.1 The time for the voltage to reach a value of 100 V from zero for the first time, and (4)

4.2.2 draw a phasor diagram showing the waveform of this voltage. (2)

4.3 A coil with a resistance of 100 ohms and an inductance of 1, 59156 henry is connected in series with a 15,914 microfarad capacitor. This circuit is connected across a 632,455 V, 50 Hz supply.

Calculate the voltage drop across the following:

4.3.1 The coil (7)

4.3.2 The capacitor, and (1)

4.3.3 draw the phasor diagram to represent the distribution of the voltage and the current in the circuit. (4)

[20]

QUESTION 5:

5.1 The value of a resistor is measured by the voltmeter-ammeter method. The internal resistance of the voltmeter is 200 ohms. When the voltmeter is connected directly across the resistance to be measured, then the ammeter reads 2 A and the voltmeter 100 V.

Calculate the value of the unknown resistor:

5.1.1 Approximately, and

5.1.2 accurately

5.1.3 Calculate the percentage error. in the value of the resistance.

(3 x 2) (6)

5.2 The no-load current of a 1 000/200 V single-phase transformer is 5 A at a power factor of. 0,2. The primary winding has 50 turns and the supply frequency is.50 Hz,
Calculate the following:

5.2.1 The maximum value of the flux in the core

5.2.2 The power loss on no-load

5.2.3 The value of the magnetising current

(3 x 2) (6)

5.3 What device is used on a transformer that serves as a protection system (2) and what does it also activate?

5.4 Why are the rotor bars of an induction motor skewed? (2)

5.5 Name any FOUR disadvantages of a single-phase motor compared to a three-phase motor. (4)

[20]

TOTAL: 100

ELETROTECHNICS N4

FORMULA SHEET

Any applicable formula may also be used.

1. Principles of electricity

$$E = V + Ir$$

$$V = IR$$

$$R_{se} = R_1 + R_2 + \dots R_n$$

$$R_p = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_n}}$$

$$R = \rho \frac{\ell}{a}$$

$$\frac{R_1}{R_2} = \frac{1 + \alpha_o T_1}{1 + \alpha_o T_2}$$

$$R_t = R_\theta \left[1 + \alpha_\theta \left(t - \theta\right)\right]$$

$$P = VI = I^2 R = \frac{V^2}{R}$$

$$\Phi = \frac{mmf}{S} = \frac{IN}{S}$$

$$H = \frac{IN}{\ell}$$

$$F = B\ell I$$

$$E = \frac{\Delta\Phi}{\Delta t} . N$$

$$E = B\ell v$$

$$E = \frac{L\Delta I}{\Delta t}$$

$$L = \frac{\Delta\Phi}{\Delta I} . N$$

$$Q = VC$$

$$Q_{se} = Q_t = Q_1 = Q_2 \dots = Q_n$$

$$C_{se} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots \frac{1}{C_n}}$$

$$Q_p = Q_1 + Q_2 + \dots Q_n$$

$$C_p = C_1 + C_2 + \dots C_n$$

2. Direct-current machines

$$E = \frac{2Z}{c} . \frac{Np}{60} . \Phi$$

$$c = 2a$$

$$E_{gen} = V + I_a R_a$$

$$E_{mot} = V - I_a R_a$$

$$R_{start} = \frac{(V - E)}{I_a} - R_a$$

3. Alternating-current machines

$$E_m = 2\pi BANn$$

$$e = E_m \sin\left(2\pi f . t \times 57{,}3\right)^\circ$$

$$E_{ave} = 0{,}637\ E_m$$

$$E_{rms} = 0{,}707\ E_m$$

$$T = \frac{1}{f}$$

$$f = \frac{Np}{60}$$

$$\omega = 2\pi f$$

$$Z_L = R + j\omega L$$

$$Z_c = R - j\frac{1}{\omega C}$$

$$pf = \cos\phi = \frac{R}{Z}$$

$$S = VI$$

$$P = V.I\cos\phi = I^2R$$

$$Q = V.I\sin\phi$$

4. *Transformers*

$$E = 4{,}44\ f\ \Phi_m\ N$$

$$k_t = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

5. *Measuring instruments*

$$R_{SH} = \frac{i_m\ R_m}{I_{sh}}$$

$$R_{se} = \frac{V}{i_m} - R_m$$

Marking Guidelines

higher education
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Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

29 July 2015 (Y-Paper)
13:00 – 16:00

QUESTION 1

1.1 1.1.1 $L = 2\,000 \times 0{,}2 = 400\ m$ √

$$R = \frac{\rho x L}{A}$$

$$= \frac{2x10^{-6} x\ 400}{200x10^{-6}} \quad √√$$

$$= 4\ \Omega$$

(3)

1.1.2 $E = \frac{LI}{t} \times 2$ √

$$= \frac{4 \times 10}{20} \times 2$$

$$= 4\ V$$ √

(2)

1.2 1.2.1 $V_{SE} = IR_{SE} = 3x20 = \underline{60\ V}$√

$$R_P = \frac{V_P}{I_T} = \frac{60}{3} = 20\ \Omega \quad √$$

$$V_T = V_{SE} + V_P$$

$$120 = 60 + V_P$$

$$V_P = \underline{60\ V} \quad √$$

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R}$$

$$\frac{1}{R_X} = \frac{1}{R_P} - \frac{1}{R_1} \quad √$$

$$= \frac{1}{20} - \frac{1}{30}$$

$$= 0{,}1667$$

$$R_X = \underline{60\ \Omega} \quad √$$

(5)

1.2.2 $P = 120 \times 3 = 360\ W$ √ (1)

1.3 Positive temperature coefficient of resistance refers to materials whose resistance rises when the temperature increases. √
Negative temperature coefficient of resistance refers to materials whose resistance falls when the temperature increases. √ (3)

1.4 $R_t = R_{20}[1 + \alpha_\theta(t - \theta)]$

$$= 100[1 + 0{,}004(125° - 25°)]$$

$$= 100[1 + 0{,}004(100)] \quad √√√√ \quad \textbf{With / Met 40 ohm}$$

$$= 100(1{,}4)$$

$$= 140\ \Omega$$

(4)

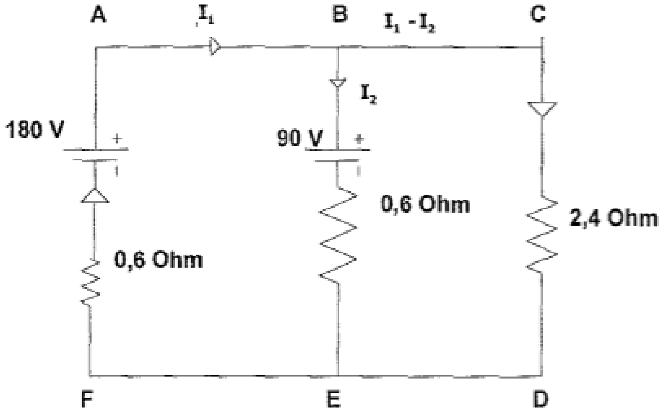
1.5 That the sum of the currents flowing towards a junction is equal to the sum of the currents flowing away from that junction √√ (2)

[20]

QUESTION 2

2.1 Mmf = ΦxS = 0,003x30 000 = 90 A √√ (2)

2.2



√

Consider loop: ABEFA

$\sum E - \sum IR = 0$

$(E_1 - E_2) - (I_1R_1 + I_2R_2) = 0$

$(180 - 90) - (0{,}6I_1 + 0{,}6I_2) = 0$ √

$90 - 0{,}6I_1 - 0{,}6I_2 = 0$................(1)

:loop: ACDFA

$\sum E - \sum IR = 0$

$(E_1 - (I_1R_1 + R_3(I_1 - I_2)) = 0$

$180 - 0{,}6I_1 - 2{,}4I_1 + 2{,}4I_2) = 0$ √

$180 - 3I_1 + 2{,}4I_2 = 0$................(2)

Eq./Verg. (1)x4 = 360 - 2,4I_1 - 2,4I_2=0 ....(3) √

Eq./Verg.(2) + (3) = 540 −5,4I_1 = 0√

Thus/ Dus: I_1=540/5,4 = 100 A

Substitute I_1 = 100 A into/in Eq. (1)

$90 - 0{,}6(100) = 0{,}6I_2$

I_2 = 90 – 60/0,6 =30/0,6 = 50 A

√$I_1 - I_2 = 50$ A

2.2.1 Current across 180 V Battery = 100 A √

Current across 90 V Battery = 50 A √ (7)

2.2.2 Voltage across the load = IR = 50 x 2,4 = 120 V √ (2)

2.3 One farad is that capacitance which will accumulate a charge of one Coulomb when connected across a voltage of one volt √√√ (3)

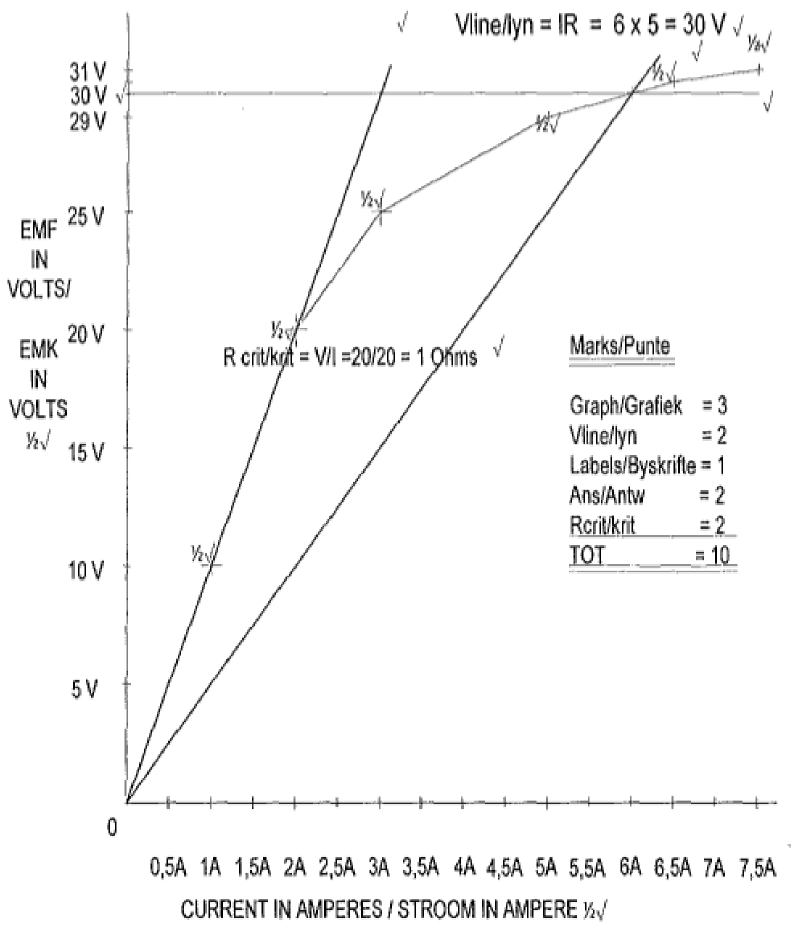
2.4 2.4.1 **C = Q/V = 900/90 & = 900/30**
= 10 µF √√ **& = 30 µF** √√

2.4.2 $$C_s = \frac{1}{\frac{1}{10}+\frac{1}{30}} = 7{,}5\ \mu F$$ √√

(2 x 3) (6)
[20]

QUESTION 3

3.1



(10)

3.2

$$I_{SH} = \frac{V}{R_{SH}} = \frac{200}{20} \checkmark = 10\ A$$

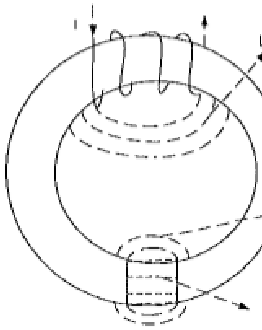
$$I_a = I_L - I_{SH} = 40 - 10 \checkmark = 30\ A$$

$$E = V - I_aR_a + I_aR_{SE} = 200 - [(30 \times 0,3) + (30 \times 0,1)] \checkmark\checkmark\checkmark = 200 - (9+3) = 188\ V$$

(5)

3.3 To hold the field windings in place and to increase the cross-sectional area √ √ (2)

3.4



(3)
[20]

QUESTION 4

4.1 By making the circuit more capacitive √ To run a synchronous motor with little or no load with rotor over excited by a high direct current √ By use of suitable corrective apparatus (machines) √ (Any 2 x 1) (2)

4.2 4.2.1

$$V_{rms/wgk} = 0,707V_m$$

$$141,4 = 0.707V_m \checkmark$$

$$V_m = \frac{141,4}{0,707} = 200\ V$$

$$v = V_m \text{Sin} 2\pi ft \times \frac{180}{\pi}$$

$$100 = 200\ \text{Sin}\ 2\pi 50\ t\frac{180}{\pi}$$

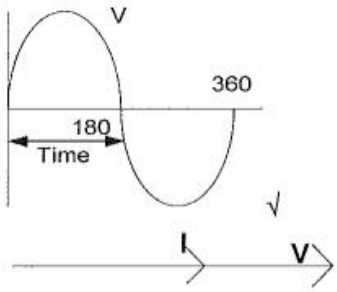
$$\frac{100}{200} = \text{Sin}\ 18\ 000\ t \quad \checkmark\checkmark\checkmark$$

$$18\ 000t = \text{Sin}^{-1} 0,5$$

$$t = \frac{30}{18\ 000} = 1,67\ ms$$

(4)

4.2.2



(2)

4.3 4.3.1 $X_L = 2\pi fL = 2\pi 50 \times 1,59156 = 500\ \Omega$ √

$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi 50 \times 15,914 \times 10^{-6}} = 200\ \Omega$ √

$Z_{COIL} = \sqrt{R^2 + X_L{}^2} = \sqrt{100^2 + 500^2} = 509,902\ \Omega$ √

$Z = \sqrt{R^2 + (X_C{}^2 - X_L{}^2)} = \sqrt{100^2 + (200 - 500)^2} = 316,23\ \Omega$ √ (7)

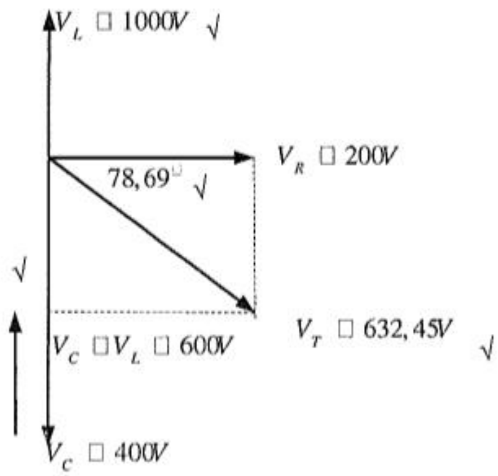
4.3.2 I = V/Z =632,455/316,22 = 2 A √

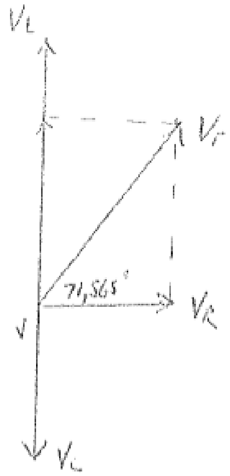
$\Theta = \text{Cos}^{-1}$ R/Z = 100/316,23 = 71,565° √

$V_C = IX_C = 2 \times 200 = 400$ V √

$V_{COIL} = IZ_{COIL} = 2 \times 509,902 = 1019,80$ V √ (1)

4.3.3





(4)
[20]

QUESTION 5

5.1 5.1.1 $R_V = 200\Omega$ V = 100 V I = 2 A

$$I_V = \frac{V}{R_V} = \frac{100}{200} = 0,5A \surd$$

$$R_{app} = \frac{V}{I} = \frac{100}{2} = 50A \surd$$

5.1.2 $$R_X = \frac{V}{I - I_V} = \frac{100}{2 - 0,5} = 66,67A \surd\surd$$

5.1.3 $$\% \text{ Error} = \frac{R_X - R_{app}}{R_X} = \frac{66,67 - 50}{66,67} = 25\% \surd\surd$$

(3 x 2) (6)

5.2 5.2.1 $E_1 = 4{,}44\Phi_m fN_1$

$\Phi_m = E_1 / 4{,}44fN_1 = 1\ 000/4{,}44x50x50 = 90{,}09$ mWb $\surd\surd$

5.2.2 $$Powerloss = V_1 I_0 Cos\phi_0 = 1000x5x0,2 = 1000W \surd\surd$$

5.2.3 $$I_C = \frac{Coreloss}{V_P} = \frac{1000}{1000} = 1A \surd$$

$$I_M = \sqrt{I^2{}_O - I^2{}_C} = \sqrt{5^2 - 1^2} = 4,89898A \surd$$

(3 x 2) (6)

5.3	Buchholtz device which activates an alarm √ √	(2)
5.4	To reduce magnetic noise and to eliminate variation in starting torque at different positions of the rotor √√	(2)
5.5	Lower efficiency √ Lower power factor √ Weaker torque √ More noisier √ Vibrates more √ (Any 4 x 1)	(4)
		[20]
	TOTAL:	**100**

Past Examination Papers

higher education & training

Department: Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

13 April 2015 (Y-Paper)
13:00 – 16:00

Requirements: **Graph paper**

Calculators may be used.

This question paper consists of 6 pages and 1 formula sheet of 2 pages.

DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N4
TIME: 3 HOURS
MARKS: 100

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
2. Read ALL the questions carefully
3. Number the answers according to the numbering system used in this question paper.
4. Write neatly and legibly.

QUESTION 1:

1.1 The field coil of a motor has a resistance of 300 Ω at 75 ºC. Calculate the final resistance if the temperature is 200 ºC. Take the temperature coefficient of resistance as 0,004 ºC at 75 ºC. (4)

1.2 Distinguish between a positive and a negative temperature coefficient of resistance. (3)

1.3 A coil having 1 500 turns of conductor with a combined cross-sectional area of 300 mm^2 and a mean length per turn of 400 mm, has an inductance of 3 H.

Calculate the following:

1.3.1 The resistance of the winding if the resistivity (specific resistance) of the conductor is 4 $\mu\Omega.m$ (5)

1.3.2 The average value of the EMF induced in the coil when a current of 60 A reversed in 15 seconds (2)

1.4 Two capacitors connected in series have voltage readings of 40 V and 10 V respectively. The total charge equals 400 μC

Calculate the following:

1.4.1 The total capacitance (2)

1.4.2 The value of each capacitor (4)

[20]

QUESTION 2:

2.1 Explain Kirchhoff's first law. (2)

2.2 Two batteries of EMF 65 V and 50 V and internal resistance of 0,3 Ω and 0,6 n respectively, are connected in parallel to supply a load resistance of 2,8 n.

Use Kirchhoff 's laws and calculate the following:

2.2.1 The current supplied by each battery (7)

2.2.2 The voltage across the load (2)

2.3 Define a *farad.* (3)

2.4 A resistor of unknown value R is connected in parallel with a resistance of 180 Ω. This combination is connected in series with a resistance of 25 Ω. The circuit is then connected across a 280-V DC-supply. ()

Calculate the following:

2.4.1 The value of the resistor R when a 4-A current is drawn from the supply (5)

2.4.2 The power dissipated in the circuit (1)

[20]

QUESTION 3:

3.1 The open-circuit characteristics of a shunt-excited DC motor are as follow:

Terminal voltage (V)	200	400	500	580	610	620
Field current (A)	10	20	30	50	65	75

Using the above values, plot a graph and determine the following:

3.1.1 The voltage which the motor will excite on no-load when shunt connected if the total field resistance is 10 Ω. (8)

3.1.2 The critical resistance (2)

3.2 A long-shunt compound-wound DC motor has an armature resistance of 0,3 Ω, a series-field resistance of 0,1 Ω and a shunt-field resistance of 48 Ω. The motor draws a current of 210 A from a 480-V DC supply. (5)

Calculate the EMF generated in the armature.

3.3 What is the purpose of a pole shoe in a DC motor? (2)

3.4 Name any THREE types of capacitors. (3)

[20]

QUESTION 4:

4.1 What can be done to improve the power factor in a circuit? (2)

4.2 A 50 Hz sinusoidal voltage has an RMS value of 424,2 V.

Calculate the following:

4.2.1 The time for the voltage to reach a value of 300 V from zero for the first time (4)

4.2.2 Draw a phasor diagram and show the waveform of this voltage. (2)

4.3 A coil with a resistance of 200 Ω and an inductance of 0,3183 H is connected in series with a 10,61-μf capacitor. This circuit is connected across a 565/-685 V, 50 Hz supply. ·

Calculate the voltage drop across the following:

4.3.1 The coil (7)

4.3.2 The capacitor (1)

4.3.3 Draw the phasor diagram to represent the distribution of the voltage and the current in the circuit. (4)

[20]

QUESTION 5:

5.1 The value of a resistor is measured by the voltmeter-ammeter method. The internal resistance of the voltmeter is 800 Ω. When the voltmeter is connected directly across the resistor to be measured, the ammeter reads 1,25 A and the voltmeter 200 V.

Calculate the value of the unknown resistor as follows:

5.1.1 Approximately (1)

5.1.2 Accurately (3)

5.1.3 The percentage error in the value of the resistor (2)

5.2 The no-load current of a 3 000/150-V single-phase transformer is 25 A at a power factor of 0,3. The primary winding has 150 turns and the supply frequency is 60 Hz.

Calculate the following

5.2.1 The maximum value of the flux in the core

5.2.2 The power loss on no-load

5.2.3 The value of the magnetising current (2 x 3) (6)

5.9 Name THREE types of power stations used to generate electricity. (3)

5.10 Why is the rotor bars of an induction motor skewed? (2)

5.11 Name the THREE main parts of an induction motor. (3)

[20]

TOTAL: 100

ELETROTECHNICS N4

FORMULA SHEET

Any applicable formula may also be used.

1. Principles of electricity

$$E = V + Ir$$

$$V = IR$$

$$R_{se} = R_1 + R_2 + \dots R_n$$

$$R_p = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_n}}$$

$$R = \rho \frac{\ell}{a}$$

$$\frac{R_1}{R_2} = \frac{1 + \alpha_o T_1}{1 + \alpha_o T_2}$$

$$R_t = R_\theta [1 + \alpha_\theta (t - \theta)]$$

$$P = VI = I^2 R = \frac{V^2}{R}$$

$$\Phi = \frac{mmf}{S} = \frac{IN}{S}$$

$$H = \frac{IN}{\ell}$$

$$F = B\ell I$$

$$E = \frac{\Delta\Phi}{\Delta t} . N$$

$$E = B\ell v$$

$$E = \frac{L\Delta I}{\Delta t}$$

$$L = \frac{\Delta\Phi}{\Delta I} . N$$

$$Q = VC$$

$$Q_{se} = Q_t = Q_1 = Q_2 \dots = Q_n$$

$$C_{se} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots \frac{1}{C_n}}$$

$$Q_p = Q_1 + Q_2 + \dots Q_n$$

$$C_p = C_1 + C_2 + \dots C_n$$

2. Direct-current machines

$$E = \frac{2Z}{c} . \frac{Np}{60} . \Phi$$

$$c = 2a$$

$$E_{gen} = V + I_a R_a$$

$$E_{mot} = V - I_a R_a$$

$$R_{start} = \frac{(V - E)}{I_a} - R_a$$

3. Alternating-current machines

$$E_m = 2\pi BANn$$

$$e = E_m \sin (2\pi f . t \times 57{,}3)^\circ$$

$$E_{ave} = 0{,}637 E_m$$

$$E_{rms} = 0{,}707 E_m$$

$$T = \frac{1}{f}$$

$$f = \frac{Np}{60}$$

$$\omega = 2\pi f$$

$$Z_L = R + j\omega L$$

$$Z_c = R - j\frac{1}{\omega C}$$

$$pf = \cos\phi = \frac{R}{Z}$$

$$S = VI$$

$$P = V.I\cos\phi = I^2R$$

$$Q = V.I\sin\phi$$

4. *Transformers*

$$E = 4{,}44\ f\ \Phi_m\ N$$

$$k_t = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

5. *Measuring instruments*

$$R_{SH} = \frac{i_m\ R_m}{I_{sh}}$$

$$R_{se} = \frac{V}{i_m} - R_m$$

Marking Guidelines

higher education & training

Department: Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

13 April 2015 (Y-Paper)
13:00 – 16:00

QUESTION 1

1.1 $R_t = R_{20}[1+\alpha_\theta(t-\theta)]$

$= 300[1+0,004(200-75°)]$

$= 300[1+0,004(125°)]$

$= 300(1,5)$

$= 450\ \Omega$ (4)

1.2
- Positive temperature coefficient of resistance refers to materials whose resistance rises when the temperature increases. √
- Negative temperature coefficient of resistance refers to materials√ whose resistance falls when the temperature increases. √ (3)

1.3 1.3.1 L = 1 500 x 0,4 = 600 m √

$R = \frac{\rho \times L}{A}$ √√

$= \frac{4\times10^{-6} \times 600}{300 \times 10^{-6}}$ √√

$= 8\ \Omega$ (5)

1.3.2 $E = \frac{LI}{t} \times 2$ √

$= \frac{3 \times 60}{15} \times 2$

$= 24$ V √ (2)

1.4 1.4.1 C = Q/V = 400/40 & = 400/10

= 10 μF √√ & = 40 μF √√ (2)

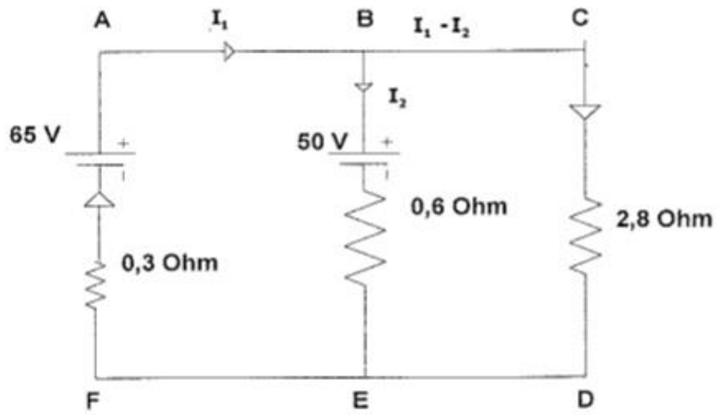
1.4.2 $C_s = \frac{1}{\frac{1}{10}+\frac{1}{40}} = 8\ \mu F$ √√ (4)

[20]

QUESTION 2

2.1 The sum of the currents flowing towards a junction is equal to the sum of the currents flowing away from that junction √√ (2)

2.2



√

2.2.1 Consider loop/Vanaf lus:ABEFA :loop/lus:ACDFA

$\sum E - \sum IR = 0$ $\sum E - \sum IR = 0$

$(E_1 - E_2) - (I_1R_1 + I_2R_2) = 0$ $(E_1 - (I_1R_1 + R_3(I_1 - I_2) = ($

$(65 - 50) - (0,3I_1 + 0,6I_2) = 0$ √ $65 - (0,3I_1 + 2,8I_1 - 2,8I_2$

$15 - 0,3I_1 - 0,6I_2 = 0$..........(1) $65 - 3,1I_1 + 2,8I_2 = 0$......

Eq./Verg. (1)x4,667 = $70 - 1,4I_1 - 2,8I_2 = 0$

...............(3) √

Eq./Verg.(2) + (3) = $\underline{135 - 4,5I_1 = 0}$√

Thus/Dus: $I_1 = 135/4,5 = \underline{30\ A}$

Substitute/Vervang $I_1 = 30$ A into/in Eq./Verg. (1)

$15 - 0,3(30) = 0,6I_2$

$I_2 = 15 - 9/\ 0,6 = -\ 6/0,6 = \underline{10\ A}$

$I_1 - I_2 = 30 - 10 = 20$ A √

Current across 65-V Battery = 30 A √

Current across 50-V Battery = 10 A √ (7)

2.2.2 Voltage across the load = IR = 20 x 2,8 = $\underline{56\ V}$√ (2)

2.3 One farad is that capacitance which will accumulate a charge of 1 coulomb when connected across a voltage of 1 volt √√√ (3)

2.4 2.4.1 $V_{SE} = IR_{SE} = 4 \times 25 = \underline{100\ V}$ √

$R_P = \frac{V_P}{I_T} = \frac{180}{4} = 45\ \Omega$ √

$V_T = V_{SE} + V_P$

$280 = 100 + V_P$

$V_P = \underline{180\ V}$ √

$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R} \qquad \frac{1}{R_x} = \frac{1}{R_p} - \frac{1}{R_1}$ √ $= \frac{1}{45} - \frac{1}{180}$

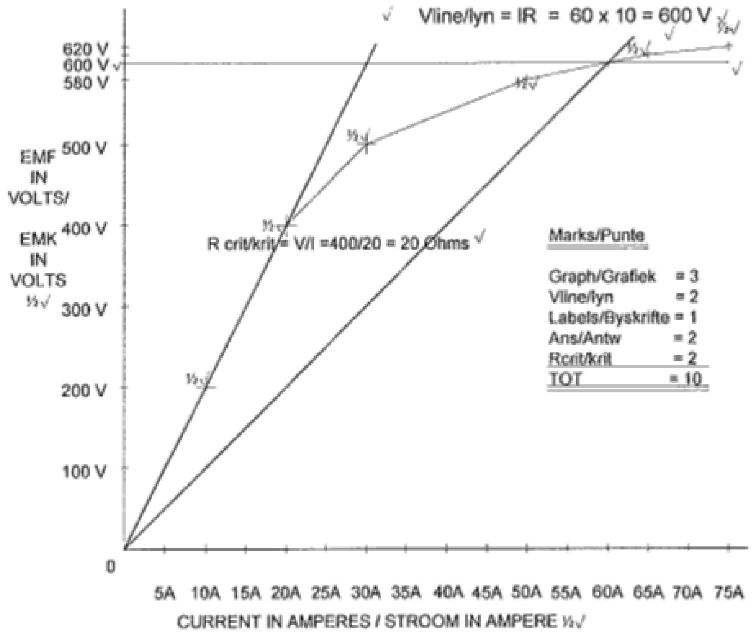
$\frac{1}{R_x} = 0{,}0167 \quad \therefore \quad R_X = \underline{60\ \Omega}$ √ (5)

2.4.2 $P = V I = 280 \times 4 = \underline{1\ 120\ W}$ √ (1)

[20]

QUESTION 3

3.1



(10)

3.2

$I_{SH} = \frac{V}{R_{SH}} = \frac{480}{48}$ √ $= 10\ A$

$I_a = I_L - I_{SH} = 210 - 10$ √ $= 200\ A$

$E = V - I_aR_a + I_aR_{SE}$

$= 480 - [(200 \times 0{,}3) + (200 \times 0{,}1)]$ √√√

$= 480 - (60 + 20)$

$= 400\ V$ (5)

3.3 To hold the field windings in place and to increase the cross-sectional area √√ (2)

3.4
- Air√
- Paper√
- Mica√
- Ceramic
- Polycarbonate
- Electrolytic (Any 3 x 1) (3)

[20]

QUESTION 4

4.1 Making the circuit more capacitive √ To run a synchronous motor with little or no load with rotor over-excited by a high direct current√ By use of suitable corrective apparatus (machines) √ (Any 2 x 1) (2)

4.2 4.2.1

$$V_{rms/wgk} = 0{,}707V_m$$

$$424{,}2 = 0.707V_m \quad √$$

$$V_m = \frac{424{,}2}{0{,}707}$$

$$= 600\ V$$

$$v = V_m \sin 2\pi ft \times \frac{180}{\pi}$$

$$300 = 600 \sin 2\pi 50\, t \frac{180}{\pi} \quad √√√√$$

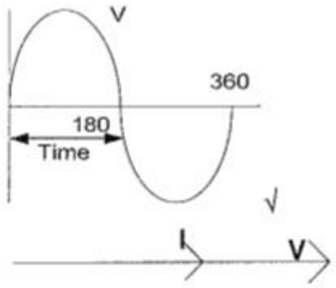
$$\frac{250}{500} = \sin 18\ 000\ t$$

$$1\ 8000t = \sin^{-1} 0{,}5$$

$$t = \frac{30}{1\ 8000} = 1{,}67\ ms$$

(4)

4.2.2



(2)

4.3 4.3.1 $X_L = 2\pi fL = 2\pi 50 \times 0,3183 = 100\ \Omega$ √

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi 50 \times 1,061 \times 10^{-6}} = 300\ \Omega \ \surd$$

$$Z_{COIL} = \sqrt{R^2 + X_L^2} = \sqrt{200^2 + 100^2} = 223,607\ \Omega \ \surd$$

$$Z = \sqrt{R^2 + (X_C^2 - X^2_L)} = \sqrt{200^2 + (300-100)^2} = 282,843\ \Omega \ \surd$$

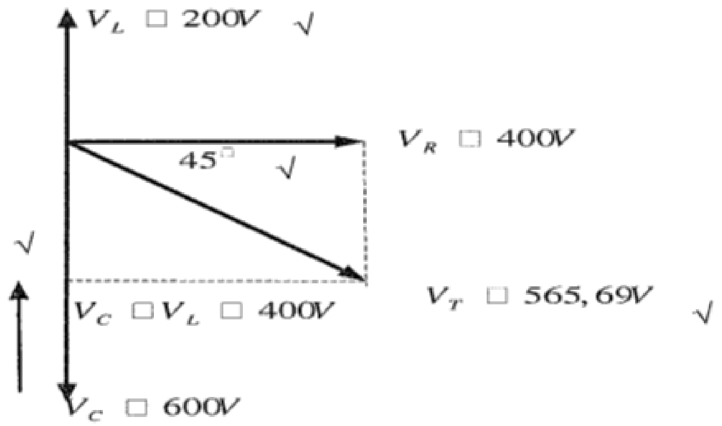
I = V/Z = 565,685/282,843 = 2 A √

$$\Theta = \text{Cos}^{-1}\frac{R}{Z} = \text{Cos}^{-1}\frac{200}{282,843} = 45° \ \surd$$

$$V_{COIL} = IZ_{COIL} = 2 \times 223,607 = 447,214\ V \ \surd$$ (7)

4.3.2 $V_C = IX_C = 2 \times 300 = 600\ V$ √ (1)

4.3.3



(4)

[20]

QUESTION 5

5.1 5.1.1 $R_V = 800\Omega$ V = 200 V I = 1,25 A

$$R_{app} = \frac{V}{I} = \frac{200}{1,25} = 160A \ \surd$$

$$I_V = \frac{V}{R_V} = \frac{200}{800} = 0,25A \ \surd$$ (1)

5.1.2 $$R_X = \frac{V}{I - I_V} = \frac{200}{1,25 - 0,25} = 200\Omega \ \surd\surd$$ (3)

5.1.3 $$\% \text{ Error} = \frac{R_X - R_{app}}{R_X} = \frac{200-160}{200} = 20\% \ \surd\surd$$ (2)

5.2 5.2.1 $E_1 = 4{,}44\Phi_m fN_1$

$\Phi_m = E_1 / \mathbf{4{,}44fN_1} = 3\ 000/4{,}44 \times 60 \times 150 = 0{,}075075 = 75{,}075$ mWb√√

5.2.2 $Powerloss = V_1 I_0 Cos\phi_0 = 3000x25x0,3 = 22,5Kw$ √√

5.2.3 $I_C = \frac{Coreloss}{V_P} = \frac{22500}{3000} = 7,5A$ √

$I_M = \sqrt{I^2{}_O - I^2{}_C} = \sqrt{25^2 - 7,5^2} = 23,484A$ √

(3 x 2) (6)

5.3
- Coal-fired power station
- Hydro-electric power station
- Nuclear power station (3)

5.4 To reduce magnetic noise and to eliminate variation in starting torque at different positions of the rotor √√ (2)

5.5
- Rotor
- Stator
- End plates (3)

[20]

TOTAL: 100

Past Examination Papers

higher education & training
Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

NOVEMBER 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

25 November 2014 (Y-Paper)
13:00 – 16:00

Requirements: **Graph paper**

Calculators may be used.

This question paper consists of 6 pages and a formula sheet of 2 pages.

DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N4
TIME: 3 HOURS
MARKS: 100

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
2. Read ALL the questions carefully
3. Number the answers according to the numbering system used in this question paper.
4. Write neatly and legibly.

QUESTION 1:

1.1 An aluminium conductor 2 000 m long is connected in parallel with a copper conductor with the same length. When a current of 300 A is passed through the combination, it is found that the current through the copper conductor is 100 A. The diameter of the aluminium conductor is 30 mm.

Calculate the following:

1.1.1 The diameter of the copper conductor if the resistivity of copper is 0,017 micro-ohm metres and that of aluminium 0,027 micro-ohm metres (7)

1.1.2 The voltage drop across the conductors (1)

1.2 A resistance of 3 ohms is connected in parallel with a resistance of 15 ohms. The combination is connected in series. with a third resistance of 3,5 ohms if the whole circuit is connected across a battery having an EMF of 24 V and an internal resistance of 2 ohms.

Calculate the following:

1.2.1 The terminal voltage of the battery (3)

1.2.2 The current through each resistor of the parallel resistors. (3)

1.3 Define temperature coefficient of resistance at 0 ºC (3)

1.4 A conductor of effective length of 500 mm moves with a velocity of 10 m/s perpendicular to a magnetic field of uniform flux density of 3 T.

Calculate the following:

1.4.1 The EMF induced in the conductor (1)

1.4.2 The force acting on the conductor when it carries a current of 10 A (1)

1.4.3 The power required to move the conductor (1)

[20]

QUESTION 2:

2.1 Two capacitors each having a potential difference (PO) of 500 V and 250 V respectively are connected in series across a DC supply. (4)

Calculate the total capacitance and the capacitance across each capacitor if a charge of 1 500 micro-coulomb is measured across the capacitors.

2.2 The field coils of a motor has a resistance of 300 ohms at 100 ºC. After a run at full load, the resistance increases to 600 ohms at 350 ºC. (4)

Find the temperature coefficient of resistance at 100 ºC.

2.3 A battery having an EMF of 55 volts and an internal resistance of 0,3 ohms is connected in parallel with a direct-current generator of EMF *75* volts and internal resistance of 0,25 ohms. The combination is used to supply a load having a resistance of 2,5 ohms.

Use Kirchhoff 's laws to calculate the following:

2.3.1 The value and direction of the current through the battery (5)

2.3.2 The value and direction of the current through the generator (2)

2.3.3 The potential difference across the load (2)

2.7 Define the *ampere* (3)

[20]

QUESTION 3:

3.1 Calculate the speed of a 8 pole series generator having a wave wound armature with 600 conductors and resistance of 1,2 ohm supplying a load of 23,75 kW at 950 V. The resistance of the field winding brush contact resistance is 0,8 ohm. The field sets up a flux per pole of 20 mWb. (5)

3.2 What type of winding would be used for:

3.2.1 A high-voltage low-current (1)

3.2.2 A high-current low-voltage DC machine. (1)

3.3 The open-circuit characteristics of a shunt-excited DC machine is as follows: (8)

Terminal voltage (V)	20	40	80	120	160	170	180
Field current (A)	0,2	0,4	0,8	1,2	2,0	2,4	3,0

Plot a graph and determine the open-circuit voltage if the field circuit resistance is 60 ohms.

3.4 A short-shunt compound generator supplies a load current of 200 A. It has a shunt-field resistance of 30 ohms, an armature resistance of 0, 1 ohms and a series field resistance of 0,4 ohms. (5)

Calculate the armature EMF if the terminal voltage is 220 V.

[20]

QUESTION 4:

4.1 A sinusoidal AC supply has a maximum value of 353,607 V and a periodic time of 60 milliseconds.

Calculate the following:

4.1.1 The RMS value of the voltage (1)

4.1.2 The average value of the v9ljagS (1)

4.1.3 The frequency (1)

4.1.4 The instantaneous' value 3 milliseconds after the commencement of the cycle (2)

4.2 A 60 kVA 6 000/600 V, 60 Hz single-phase transformer has 600 turns on the primary winding.

Calculate the following:

4.2.1 The turns ratio (1)

4.2.2 The number of secondary turns (2)

4.2.3 The secondary full-load current (2)

4.2.4 The maximum value of the core flux (2)

4.3 In a certain circuit having two parallel branches the instantaneous branch circuits are represented by:

$$i_1 = 45 \sin\left(wt + \frac{\pi}{4}\right)$$

$$i_1 = 60 \sin\left(wt - \frac{\pi}{4}\right)$$

4.3.1 Determine the total current and write it in the form (5)

$$i = I_{max} \sin(wt + \theta)$$

4.3.2 Represent these currents by drawing a phasor diagram. (3)

[20]

QUESTION 5:

5.1 At what speed must a FOUR pole alternator be driven to produce an EMF (2) having a frequency of 50 Hz?

5.2 What motor is superior in efficiency, and the most extensively used of all types of electric motors? (2)

5.3 An impedance of 50 *L*- 45° ohms and an impedance of 50 *L* 45° 0hms are connected in parallel to a 500 volt, 50Hz supply.

Determine the following:

5.3.1 The total impedance (3)

5.3.2 The current in each branch (2)

5.3.3 The current flowing in the circuit (1)

5.3.4 The overall power factor(~md (1)

5.3.5 Draw the phasor diagram to 6resent)he current in the circuit. (3)

5.4 A milli-ammeter with a 50 ohms coil resistance indicates a full-scale deflection when a current of 500 mA flows through lt.

Calculate the value of the resistances required to enable the instrument to be used as a:

5.4.1 50 V voltmeter (2)

5.4.2 1 Ammeter (2)

Why are coal fired power stations normally built far away from the main load points? (2)

[20]

TOTAL: 100

ELETROTECHNICS N4

FORMULA SHEET

Any applicable formula may also be used.

1. Principles of electricity

$$E = V + Ir$$

$$V = IR$$

$$R_{se} = R_1 + R_2 + \dots R_n$$

$$R_p = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_n}}$$

$$R = \rho \frac{\ell}{a}$$

$$\frac{R_1}{R_2} = \frac{1 + \alpha_o T_1}{1 + \alpha_o T_2}$$

$$R_t = R_\theta \, [1 + \alpha_\theta \, (t - \theta)]$$

$$P = VI = I^2 R = \frac{V^2}{R}$$

$$\Phi = \frac{mmf}{S} = \frac{IN}{S}$$

$$H = \frac{IN}{\ell}$$

$$F = B\ell I$$

$$E = \frac{\Delta\Phi}{\Delta t} \, . \, N$$

$$E = B\ell v$$

$$E = \frac{L\Delta I}{\Delta t}$$

$$L = \frac{\Delta\Phi}{\Delta I} \, . \, N$$

$$Q = VC$$

$$Q_{se} = Q_t = Q_1 = Q_2 \dots = Q_n$$

$$C_{se} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots \frac{1}{C_n}}$$

$$Q_p = Q_1 + Q_2 + \dots Q_n$$

$$C_p = C_1 + C_2 + \dots C_n$$

2. Direct-current machines

$$E = \frac{2Z}{c} \, . \, \frac{Np}{60} \, . \, \Phi$$

$$c = 2a$$

$$E_{gen} = V + I_a \, R_a$$

$$E_{mot} = V - I_a \, R_a$$

$$R_{start} = \frac{(V - E)}{I_a} - R_a$$

3. Alternating-current machines

$$E_m = 2\pi BANn$$

$$e = E_m \sin \, (2\pi f \, . \, t \times 57{,}3)^\circ$$

$$E_{ave} = 0{,}637 \, E_m$$

$$E_{rms} = 0{,}707 \, E_m$$

$$T = \frac{1}{f}$$

$$f = \frac{Np}{60}$$

$$\omega = 2\pi f$$

$$Z_L = R + j\omega L$$

$$Z_c = R - j\frac{1}{\omega C}$$

$$pf = \cos\phi = \frac{R}{Z}$$

$$S = VI$$

$$P = V.I\cos\phi = I^2R$$

$$Q = V.I\sin\phi$$

4. *Transformers*

$$E = 4{,}44\ f\ \Phi_m\ N$$

$$k_t = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

5. *Measuring instruments*

$$R_{SH} = \frac{i_m\ R_m}{I_{sh}}$$

$$R_{se} = \frac{V}{i_m} - R_m$$

Marking Guidelines

higher education & training

Department: Higher Education and Training REPUBLIC OF SOUTH AFRICA

NOVEMBER 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N4

(8080074)

25 November 2015 (Y-Paper)
13:00 – 16:00

QUESTION 1

1.1 1.1.1

$$A_a = \frac{\pi d_a^2}{4} = \frac{\pi(30x10^{-3})^2}{4} = 7,0685834x10^{-4} m^2 ✓$$

but $I_a = I_T - I_c = 300 - 100 = 200A$ √

$$Va = IaRa$$
$$= 200x0,076394372 = 15,27887454\ V ✓$$
$$R_c = \frac{V_c}{I_c} = \frac{15,27887454}{100} = 0,152788744\ \Omega ✓$$

$$R_a = \frac{P_a x L_a}{A_a} = \frac{0,027x10^{-6} x\ 2\ 000}{7,0685834x10^{-4}} = 0,076394473\ \Omega ✓$$

$$d = \sqrt{\frac{4P_cL_c}{\pi R_c}} = \sqrt{\frac{4x0,017x10^{-6}x2000}{\pi(0,152788744)}} = 16,833mm ✓✓$$

(7)

1.1.2 V11 = 15,279 V (1)

1.2 1.2.1

$$R_T = R_{se} + \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}} \qquad I = \frac{E}{R_T + r} \qquad V = IR_T$$

$$= 3,5 + \frac{1}{\frac{1}{3}+\frac{1}{15}} \qquad = \frac{24}{6+2} \qquad = 3x6$$

$$= 3,5 + \frac{1}{0,4} \qquad = \frac{24}{8} \qquad = \underline{18\ V} ✓$$

$$= 3,5 + 2,5 \qquad = \underline{3\ A} ✓$$

$$= \underline{6\ \Omega} ✓$$

(3)

1.2.2 $I_P = 2,A$

But $V_P = I\ R_P = 3\ x2,5 = \underline{7,5\ V}$ ✓

Thus

$$I_1 = \frac{V}{R_1} = \frac{7,5}{3} = 2,5\ A$$

✓

$$I_2 = \frac{V}{R_2} = \frac{7,5}{15} = 0,5\ A$$

(3)

1.3 The temperature coefficient of resistance of a material at 0 ˚C is the increase in resistance of a sample having a resistance of one ohm at0 ˚C, when its temperature is raised by 1 ˚C (or 1 K) ✓✓✓ (3)

1.4 1.4.1 EMF = BLV = 3 x 0,5 x 10 = 15 V ✓

1.4.2 F = BLI = 3 x 0,5 x 10 = 15 N ✓

1.4.3 P = VI = 15 x 10 = 150 W (3)

[20]

QUESTION 2

2.1 $C_S = \frac{1}{\frac{1}{6}+\frac{1}{3}} = 2\,\mu F$ ✓✓

$Q_T = Q_1 = Q_2 = V_1C_1 = V_2C_2$

$C_1 = Q_1 / V_1 = 1\,500/250 = 6\,\mu F$ ✓

$C_2 = Q_2 / V_2 = 1\,500/500 = 3\,\mu F$ ✓ (4)

2.2 $R_t = R_{25}[1+\alpha_{100}(t-\theta)]$

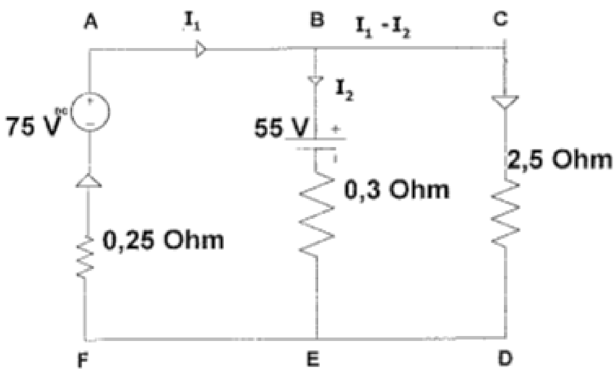
$600 = 300[1+\alpha_{100}(350° - 100°)]$

$\alpha_{100}(250°) = \frac{(\frac{600}{300}-1)}{0,004}$ ✓✓✓✓

$\alpha_{100} = (\frac{2-1}{250})$

$\alpha_{100} = 0,004$ per °C (4)

2.3



✓

2.3.1 Consider loop:ABEFA lus:ACDFA

$\sum E - \sum IR = 0$ $\sum E - \sum IR = 0$

$(E_1 - E_2) - (I_1R_1 + I_2R_2) = 0$

$(75 - 55) - (I_1 0,25 + I_2 0,3) = 0$ √

$20 - I_1 0,25 + I_2 0,3 = 0 ....(1)$

$(E_1 - (I_1R_1 + R_3(I_1 - I_2) = 0$

$75 - [0,25I_1 + 2,5(I_1 - I_2)] = 0$ √

$75 - 2,75\ I_1 + 2,5\ I_2 = 0 ......(1)$

Eq. (1)x2,5/0,3 $166,67 - 2,083 I_1 - 2,5 I_2 = 0$ ✓

Eq. (2) + (3) = $\underline{241,67 - 4,83 I_1 = 0}$ ✓

Thus: $I_1 = 241,67/4,83 = \underline{50\ A}$

Substitute $I_1 = 50$ A into/in Eq.

$20 - 0,25(50) = 0,3 I_2$

$I_2 = 7,5/0,3 = \underline{25\ A}$ ✓

$I_1 - I_2 = \underline{25\ A}$ (5)

2.3.2 $I_G = I_1$ 50 A✓ (2)

2.3.3 $I_L = I_1 - I_2$ 25 A

$V_L = I_L \times R_L$

$= 25 \times 2,5$

$= 62,5$ V (2)

2.4 The ampere is defined as the current which if maintained in two straight parallel conductors of infinite length of negligible cross-sectional area, and placed 1 metre apart in a vacuum, would produce between the conductors a force of 2×10^{-7} newton per metre of length. ✓✓✓ (3)

[20]

QUESTION 3

3.1 Vloed =0,02 Wb P = 4 C = 2 Z = 600

$I_a = I_L = P / V = 23,75x10^3 / 950 = 25A$ √

$E = V + I_a(R_a + R_{se})$

$= 950 + 25\ (1,2 + 0,8)$

$= \underline{1\ 000\ V}$✓

$E = (2Z/C)(NP/60) \times \Phi_m$

$1\ 000 = (2x600/2)(N4/60)x0,02$✓

$1\ 000 = 0,8N$

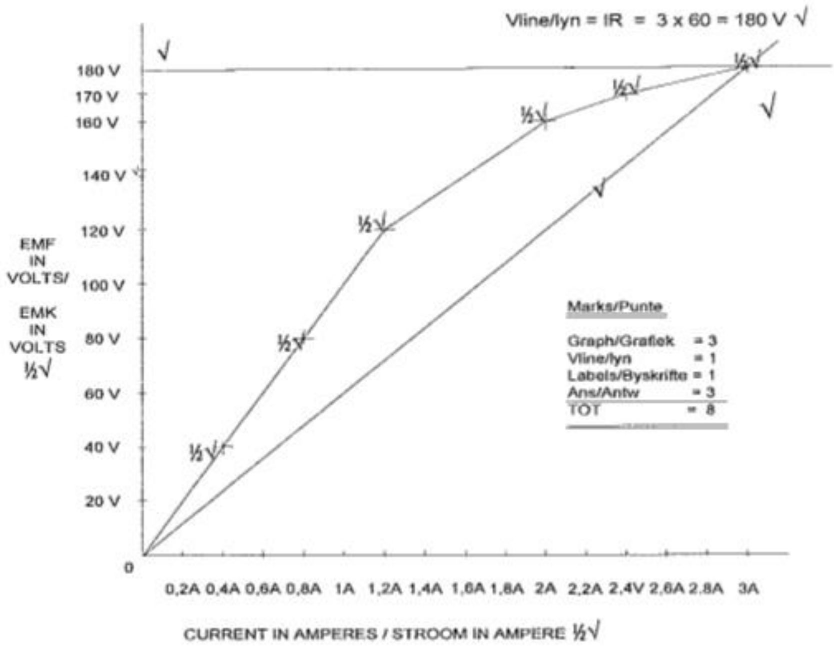
$N = 1\ 000/0,8$

$= \underline{1\ 250\ RPM}$✓ (5)

3.2 3.2.1 Wave ✓

3.2.2 Lap ✓ (2)

3.3



(8)

3.4

$I_{SH} = \frac{V + I_L R_{SE}}{R_{SH}}$

$= \frac{220 + (200 \times 0,4)}{30}$ ✓✓

$= \frac{300}{30}$

$= \underline{10\ A}$

$E = V + I_a R_a + I_L R_{SE}$ ✓

$= 220 + (210 \times 0,1) + 200(0,4)$

$= 220 + 21 + 80$ ✓

$= \underline{321\ V}$

$I_a = I_L + I_{SH}$

$= 200 + 10$

$= \underline{210\ A}$ ✓

(5)

[20]

QUESTION 4

4.1 4.1.1 $E_R = 0{,}707\,E_M = 0{,}707 \times 353{,}607 = 250$ V ✓

4.1.2 $E_{AVE} = 0{,}637\,E_M = 0{,}637 \times 353{,}607 = 225{,}25$ V ✓

4.1.3 $f = 1/T = 1/60 \times 10^{-3} = 16{,}67$ Hz ✓

4.1.4 $e = E_M \text{ Sin } 2\Pi ft \times 180/\Pi$
$= 353{,}607 \text{ Sin}(2\Pi\, 16{,}67 \times 0{,}003 \times 180/\Pi)$ ✓
$= 353{,}607 \text{ Sin}18$
$= 353{,}607 \times 0{,}309$
$= 109{,}273$ V ✓ (5)

4.2 4.2.1 $\frac{N_1}{N_2} = 6\,000/600 = 10$ (10:1) ✓

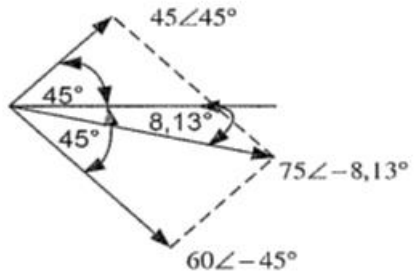
4.2.2 $N_2 = \frac{N_1 V_2}{V_1} = \frac{600 \times 600}{6000} = 60$ **Turns** ✓✓

4.2.3 $I_2 = \frac{S}{V} = \frac{60\,000}{600} = 100$ **A** ✓✓

4.2.4 Core Flux $= E/4{,}44fN = 6\,000/4{,}44 \times 60 \times 600 = 37{,}54$ mWb ✓✓ (7)

4.3 4.3.1 $i_1 = 45\angle 45° = 31{,}82 + j31{,}82$ ✓✓
$i_2 = 60\angle -45° = 42{,}43 - j42{,}43$
Total I $= 74{,}246 - j\,10{,}607 = 75\angle -8{,}13°$ ✓✓
$I_T = 75 \text{ Sin}(wt - 8{,}13°)$ ✓ (5)

4.3.2



(3)
[20]

QUESTION 5

5.1 $f = \frac{PN}{60}$

$N = \frac{f x 60}{P} = \frac{50 x 60}{2} = 1\,500\ RPM$ ✓✓ (2)

5.2 AC motors (or) Induction motors √√ (2)

5.3 $Z_1 = 50\angle -45 = 35,36 - j35,36$

$Z_2 = 50\angle 45 = 35,36 + j35,36$

$Z_1 + Z_2 = 70,711 + j0$ ✓

5.3.1 $Z_T = \frac{Z_1 Z_2}{Z_1 + Z_2} = \frac{2500\angle 0°}{70,711\angle 0°} = 35,36\angle 0° = 35,36\ \Omega$ ✓✓ (3)

5.3.2 $I_1 = \frac{V}{Z_1} = \frac{500\angle 0°}{50\angle -45°} = 10\angle 45° = 7,071 + j7,071\ A$ ✓

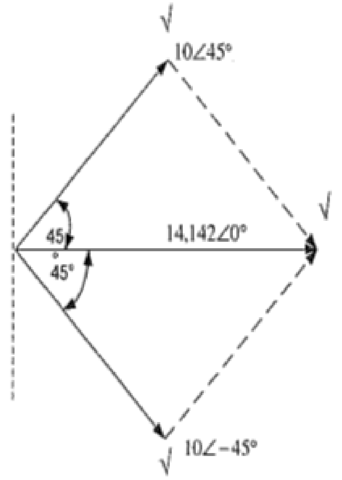
$I_2 = \frac{V}{Z_2} = \frac{500\angle 0°}{50\angle 45°} = 10\angle 45° = 7,071 - j7,071\ A$ ✓ (2)

$I_T = I_1 + I_2 = 14,142 + j0 = 14,142\angle 0°\ A$ ✓ OR (1)

5.3.3 $I_T = \frac{V}{Z_T} = \frac{500\angle 0°}{35,36\angle 0°} = 14,142\angle 0° = 14,142 + j0\ A = 14,142\ A$ ✓

5.3.4 p.f = Cos 0 = 1✓ (1)

5.3.5



(3)

5.4 5.4.1 $R_{SE} = \frac{V}{I_M} - R_M = \frac{50}{500x10^{-3}} - 50 = 50\ \Omega$ ✓✓

$I_{SH} = I_L - I_M = 1 - 500x10^{-3} = 0,5\ A$ ✓

5.4.2 $R_{SH} = \frac{I_M R_M}{I_{SH}} = \frac{500x10^{-3}\ x\ 50}{0,5} = 50\ \Omega$ ✓

(4)

5.5 To be near the coalfields in order to reduce transport cost ✓✓ (2)

[20]

TOTAL: 100

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