ELECTRICAL THEORY SECTION 2

1. INTRODUCTION

It is important electrical workers have a good working knowledge of the principles and theory of electricity so that they can work safely on electric lines and associated equipment. This is especially so because electricity cannot be seen and is only evident from the effects that can be experienced, (for example, light, heat and force).

Unfortunately this increases the risk of harm to people working on or using electric lines or associated equipment. Electrical workers must use their training in electrical principles and theory to anticipate how electricity may flow and to ensure they work safely without causing harm to themselves or others.

2. WHAT IS ELECTRICITY?

Electricity may be explained by means of the "electron theory".

In nature, all substances can be grouped into two classes, compounds and elements. Compounds are combinations of elements in definite proportions. For example ordinary water consists of two parts hydrogen combined with one part oxygen, while common salt consists of one part sodium combined with one part chlorine. The substances hydrogen, oxygen, sodium and chlorine are known as "elements". If a small amount of any element is divided into smaller and smaller parts, eventually a very small amount known as an "atom" is obtained.

The "electron theory" assumes that these atoms are made up of smaller particles, electrical in nature, called "protons", "electrons" and "neutrons".

A proton is a positively charged particle.

An electron is a negatively charged particle, much lighter in weight than the proton.

A neutron is about the same weight as the proton but has no charge – it may be a combination of a proton and an electron.

The protons and neutrons form the nucleus of the atom and the lighter electrons are imagined to revolve around this nucleus much the same as the planets revolve around the sun.

In all normal materials, there are as many electrons as protons in the atom. The atom therefore, shows no electric charge. Figure 1 shows an atom of hydrogen with one electron and one proton while Figure 2 shows an atom of helium with two electrons, two protons and two neutrons.

In materials containing more complex compounds (some may have atoms with as many as 92 electrons and 92 protons and 146 neutrons) the electrons are presumed to rotate in orbits of different diameters. When there are only a few electrons in the outer orbits they are considered to be able to leave the atom fairly easily. These "free electrons" may then be captured by another atom that may also have lost an electron.

This action takes place more readily in metals such as copper, aluminium or steel.

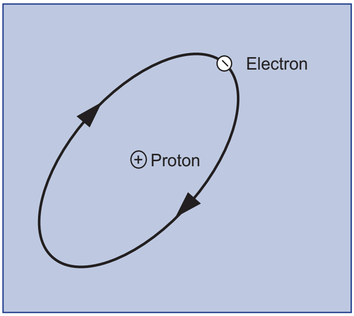


Figure 1. Hydrogen atom

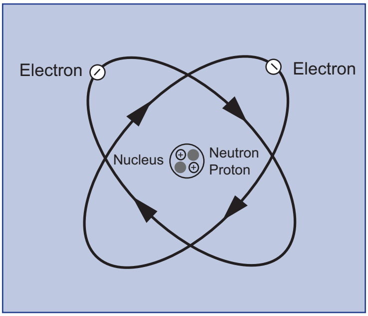


Figure 2. Helium atom

Flow of electrons

Under certain conditions "free electrons" can be caused to travel from atom to atom in a definite direction. For example, when a piece of copper wire has its ends connected to the positive and negative poles of a battery a definite drift of electrons will take place towards the positive pole of the battery, (see Figure 3).

The drift of electrons in a definite direction constitutes an "electric current" and if the number of electrons taking part is great enough, the current can be detected by suitable means. This theory is used mostly in the application of electronics, (semi-conductors, diodes etc).

However, owing to certain conventions adapted in the early days of research, the actual current (conventional current flow) is assumed to flow from the positive terminal and through the conductor to the negative terminal of the battery, that is, in the opposite direction to the drift of electrons.

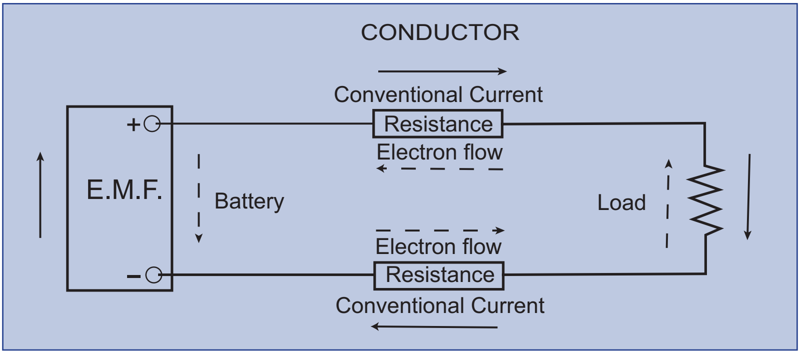


Figure 3. Conventional current flow compared with electron flow in an electrical circuit

The "force", as it might be termed, supplied by the battery, that causes this drift of electrons is called an "electromotive force" (E.M.F) or "voltage".

It is important to note that the battery has the voltage or force available without any current flowing, as shown in Figure 4. The voltage available is then referred to as the voltage on an open circuit and has been labelled E.M.F.

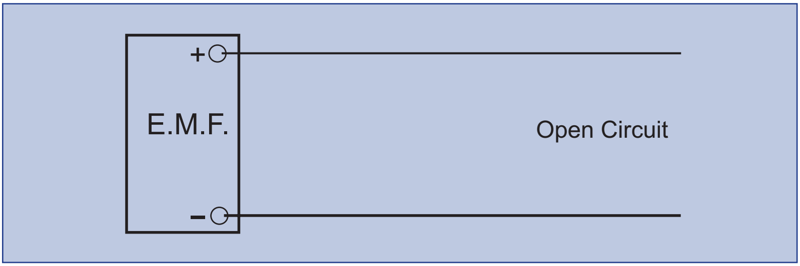


Figure 4. Open circuit

Conductors

Substances such as copper, aluminium and steel, in which the electrons readily move from atom to atom, are known as "good conductors".

Other examples are gold, silver and platinum. Silver is a better conductor than copper, copper better than aluminium and aluminium better than steel.

Insulators

In some materials the electrons are very strongly attached to their atoms and require a very considerable force to dislodge them. Such substances are considered very poor conductors of electricity and are known as "insulators". Examples are porcelain, rubber, glass, dry wood, and the various types of plastic coverings in use today such as polyvinyl chloride (PVC) and polyethylene.

In the best insulators, breakdown of the material takes place before any appreciable current can flow. Good insulators are therefore used to confine the flow of current to its desired path. Typical examples are the insulators used on crossarms to support conductors. Practically no current can flow from the conductor to the crossarm.

Electric circuit

An "electric circuit" is the complete path that the electric current follows from its source of supply through the electric line conductor to the electrical installation or equipment that requires electricity and then back to its source.

Definitions and units

A simple electronic circuit as shown in Figure 3 has:

a. Electromotive force, (E.M.F), voltage, or pressure, being that force that causes the current to flow through the electric circuit. The unit of E.M.F is the volt.

b. Current, being the rate at which electrons flow (or "drift") in the circuit. The unit of current is the ampere.

c. Resistance, being the measure of the opposition offered to the flow of the current by the material of the circuit. The unit of resistance is the ohm.

These units are so related that an E.M.F of one volt causes a current of one amp to flow in a circuit of one ohm resistance.

Difference between voltage and current

It is important to distinguish between voltage and current and also to realise that voltage can exist without a flow of current.

To produce a flow of current two conditions are necessary. There must first be available an electrical pressure or, as it is technically called, a voltage or potential difference.

In addition to the voltage there must be a continuous or complete electric circuit provided for the current to flow through.

For example, when a switch that controls a lamp is open, or set to the "off" position there is a voltage across the switch terminals. But because there is a break in the circuit (the switch being open), there is no flow of current and the lamp does not glow. As soon as the switch is closed, or set to the "on" position, the circuit is completed allowing the current to flow and the lamp glows.

In this case, although there is a voltage present there is no flow of current as long as the switch remains open. The closing of the switch completes the necessary circuit and then the current flows.

Failure to distinguish between voltage and current and understand the condition needed for current to flow has led to a number of accidents that have harmed electrical workers and the public.

Electrical resistance

An E.M.F. must be applied to maintain a steady flow of current in a circuit. This indicates that there must be some opposition to the flow of current and this opposition is known as "resistance".

Under steady voltage conditions, if more resistance is offered, less current flows. On the other hand if less resistance is offered with the same voltage applied, more current will flow. The electrical symbol for resistance is Ω.

Impedance

Impedance is the total opposition to the flow of current in a circuit and comprises three elements – inductance, capacitance and resistance.

Inductance

When current flows in an electric circuit, a magnetic field is set up around the conductor. In some cases this will affect the behaviour of current in the circuit or induce a voltage in a conductor that passes through the magnetic field. The property that causes these effects is known as inductance.

Typical examples where electrical workers may see the effect of inductance are:

a. In the operation of a transformer.

b. When voltage is induced in a de-energised line that runs parallel to, or across, a live line.

A magnetic field stores energy that builds up due to current flow in an electric circuit. When the magnetic field strength changes or collapses, any energy stored is released back into those conductors that pass through the magnetic field. Should this occur, a voltage is induced into these conductors that can present a hazard to electrical workers or equipment.

The properties of magnetic field and inductance are also put to good use in an electric circuit. An example is described under transformers in this section.

Capacitance

When two conductive materials are separated by an insulation material and connected to a voltage source, the circuit builds up an electric charge between the conductors. This charge will be maintained until it is discharged. The property that causes this effect is know as capacitance.

Typical examples of capacitance are:

a. Capacitor devices in street light control circuits and,

b. The charge that is stored in an electric cable after it has been de-energised.

Unlike inductance, the energy stored in the electric charge across a capacitor is not released when the circuit current is removed. Some capacitors can hold their charge of electricity for a long time. For this reason, steps must be taken to discharge any electrical charge before beginning work on equipment (e.g. cables).

3. OHM'S LAW

In 1825, Dr Ohm experimented with the flow of electric current and found that there was a simple relationship between voltage, current and resistance. The relationship is known as "Ohm's law" and is one of the most useful and important laws in the theory of electricity.

Ohm's law is that, if one volt is applied to a circuit with a resistance of one ohm, then one ampere of current will flow.

It is expressed as:

TABLE 1

Electrical Quantity	Unit	Relationship
Current (I) =	Ampere	Voltage ÷ Resistance or E ÷ R
Resistance (R) =	Ohm	Voltage ÷ Current or E ÷ I
Voltage (E) or (V) =	Volt	Current x Resistance or I x R

A method of remembering this law is outlined in Figure 5.

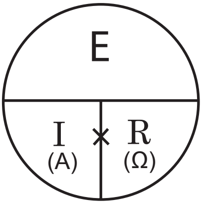


Figure 5. Representation of Ohm's law

Examples of the use of Ohm's law

The following are simple applications of Ohm's law.

Example 1

The resistance of conductors in a circuit is 4 ohms. The resistance of a heater in a circuit is 20 ohms. If the voltage of supply is 240 V what current would flow in the circuit?

Resistance of conductors = 4 ohms

Resistance of heater = 20 ohms

The total resistance (R) = 4 + 20 = 24 ohms

Voltage of supply (V) = 240 V

To find the current using Ohm's law

I = V/R

= 240 / 20 = 10 amps

Figure 6 shows the example set out in a diagram. (In solving electrical problems like this, setting the information out in a diagram often suggests the methods to use. The starting point of this diagram would be the supply, then the conductors connecting the heater to the supply).

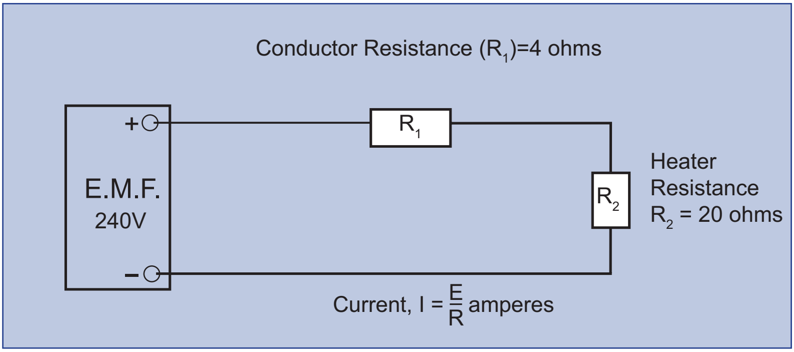


Figure 6. Example 1 set out in a diagram

Example 2

What voltage would cause a current of 20 amperes to flow in a circuit of 12 ohms resistance?

I = 20 amperes

R = 12 ohms

By Ohm's law V = I x R

= 20 x 12

= 240 volts

4. POWER

When an electric motor, lamp or other appliance is connected to a supply of electricity, a voltage is applied across the terminals of the appliance and a current flows. This enables:

a. The motor to run and do work in driving machinery;

b. The lamp to light the room; and

c. The radiator element to become cherry red and heat the room.

In fact, the voltage and the current act together to do useful work.

Power is the rate at which work is done. For example, the motor in a) above drives a water pump that fills a container with water in 2 minutes. If the same amount of water is to be pumped in 1 minute, it is necessary to double the power output of the motor as twice as much work has to be done to pump the water.

In mechanical terms, power is expressed as watts, (W); this is also the unit of electrical power. For example, car engines have their outputs expressed in kilowatts (kW, or thousands of watts), e.g. a 30kW engine's power is equivalent to 30,000 watts.

The usual bar-type domestic radiator is rated at 1,000 watts per bar, so the customer knows that if the radiator is connected to a power outlet of 240V supply, the radiator will deliver 1,000 watts of heat.

Unit of power

The unit of power is the watt and one watt is the power being used where a voltage of one volt causes a current flow of one ampere.

In other words:

Power (P) = Volts x Amperes
= Watts (W)
or P = E x I

Now referring to Ohm's law:

$E = I \times R$
Since $P = E \times I$ then substituting (I x R) in place of E
$P = I \times I \times R$
$P = I^2 R$

The symbol or index "2" means that current is squared or in other words is multiplied by itself once.

The main point to remember is that $P = I^2 R$
$= W$

Power (or watts) used over a period produces heat in conductors or loads so that wherever voltage and current are combined to produce power, heat is produced in some form or other. Examples are:

a. The lamp becomes too hot to handle

b. The frame of the electric motor becomes warm

The heat is produced because the circuit and electrical equipment will also have resistance that has to be overcome by the current flow required to do work in an electric circuit.

5. ENERGY

Energy is the measure of capacity to do work.

To obtain a clear picture of the meaning of energy, assume that two people are each digging a hole of the same size.

One person is big and muscular, but slow in movement; the other person is small, not so muscular but is quick in movement. The larger person uses a large shovel and digs slowly, while the smaller one uses a shovel half the size of the other but shovels twice as fast.

They both dig holes of the same size in the same time and they both have expended the same energy to do the same job.

The larger person puts twice the force into moving but moves half as fast the smaller person.

In both cases:

Energy = Force x Speed x Time

Energy = Power x Time (actual shovelling time)

In electrical terms:

Energy = Power x Time

= Watts x Time

= Watt-hours

Example 3

A 100 watt lamp burning for 10 hours would expend 100 x 10 = 1,000 watt-hours of energy.

Example 4

A motor takes 500 watts to drive a drilling machine and runs on this load for 4 hours.

The energy expended = power x time

= 500 x 4

= 2,000 watt-hours

Unit of energy

The amount of electrical energy (electricity) supplied to a customer is generally measured in terms of the kilowatt-hour (kWh).

The kWh is the energy expended in one hour when the power being drawn is one kilowatt. It is equal to 1,000 watt-hours.

Although this unit is known as the kilowatt-hour (kWh), it is frequently referred to simply as the "unit". This unit is well known to those who pay electricity accounts and in order to measure these units, meters called "kilowatt-hour meters" or "kWh meters" are installed.

6. VOLTAGE DROP

When current flows along the conductors of an overhead electric line, it flows against resistance. The total resistance offered is made up of two parts:

The resistance offered by the connected load, that is the lamps, motors etc. and

a. The resistance of the conductors themselves.

b. Conductor resistance is important because it constrains the capacity of an electric line. The effect of the resistance is to reduce the voltage available to do useful work.

Example 5

Referring to Ohm's law again, $E = I \times R$

If the resistance of an overhead conductor in its entire circuit is 2 ohms and a current of 10 amperes is flowing, then the voltage necessary to cause this current to flow against the resistance of the conductors alone will be $10 \times 2 = 20$ volts; this is the voltage drop in the conductor.

If at the supply end the voltage is 240 volts, then the voltage available to the customer whose appliances are causing 10 amperes to flow will be $(240 - 20) = 220$ volts.

The need for voltage to provide the force for the current to overcome resistance in the conductors from the supply to the load (and return to the source) has reduced the voltage available for the customer's appliance.

If the demand for electricity increased from 10 to 20 amperes, the voltage drop in the conductors would increase from 20 to 40 volts. The voltage drop would reduce the voltage available for the customers appliances to 200 volts. At this level the operation of many appliances will be adversely affected.

In addition to the undesirable effects of excessive voltage drop (eg. fluctuation seen in filament lamps and on television screens), the resistance of the conductors will determine the power lost in the conductors, because work has to be done to overcome the resistance.

In example 5 using the formula

$P = I^2 R$

where P = power in watts

I = current in amps

R = resistance in ohms of the conductors

then P = 10 x 10 x 2 = 200 watts

This power loss for five hours would expend one unit of energy.

watts x hours (Wh) = 200 x 5 = 1,000 watts

= 1kWh (or unit)

It can also be shown that, for the same material and current:

a. Voltage drop increases with the length of the conductor.

b. Voltage drop decreases with the increase in cross-section (thickness) of the conductor.

Since voltage drop is a product of current and resistance, it is essential that the resistance of electric lines is kept to a minimum to obtain the rated value of voltage at the receiving end of a line. The number of joints in a line should be kept down to an absolute minimum and the joints themselves must be clean and well made to have as low a resistance as possible, as every joint or connection introduces some amount of resistance to the flow of current.

When current passes through a resistance, however small, some voltage drop is experienced; these small voltage drops may add up to an appreciable amount where there are a number of joints or any badly made joints.

7. CURRENT SYSTEMS

Electric currents are of three classes: (a) direct, (b) alternating, and (c) pulsating. Distribution & Transmission electrical workers are mainly concerned with alternating currents.

Pulsating currents do not come within the scope of this Handbook, and will not be addressed.

Direct currents

A direct current (d.c.) system is one in which current flows in one direction in the conductors of that system. An everyday example is the car battery, which has two terminals, one positive (+) and the other negative (-).

The accepted convention is that the current flows from the positive terminal to the external circuit and returns to the negative terminal.

High voltage transmission of electricity by direct current has been developed over recent years. In general, however, d.c. distribution is limited to use in:

a. Tramway and traction systems with a voltage of usually 600V;

b. Railway d.c. traction systems with a voltage of 1.5kV between rail and overhead collector wire;

c. Lifts, printing presses and various machines where smooth speed control is desirable;

d. Electroplating; and

e. Battery charging.

Usually d.c. systems are of 2-wire or 3-wire types. In a 2-wire system one wire is positive and the other negative. The difference in potential for tramways is 500V with the rail negative and in the d.c. railway system the difference in potential is 1.5kV, again with the rail negative.

In a 3-wire system the standard voltages are 460 and 230V.

There are three wires, one being at 230V positive (or + 230 volts potential), the second 230V negative (or – 230 volts potential), with the third called the "common" or neutral being at zero potential (see Figure 7).

Supply at 230V is taken from the "outer" (or positive) and the common conductors, or from "inner" (or negative) and the common conductors.

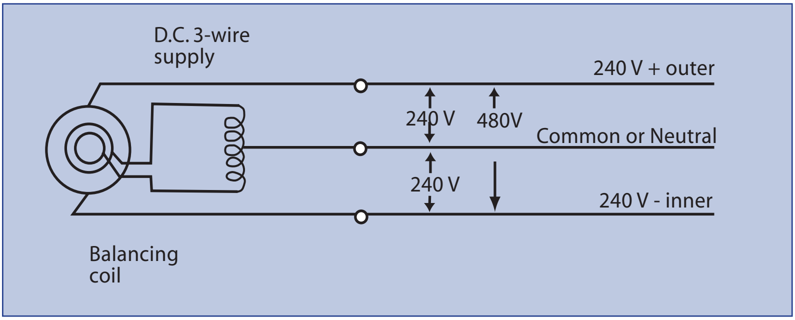


Figure 7. Potential in a 3-wire system

Energy for motors at 480V is taken from the outer and the inner conductors.

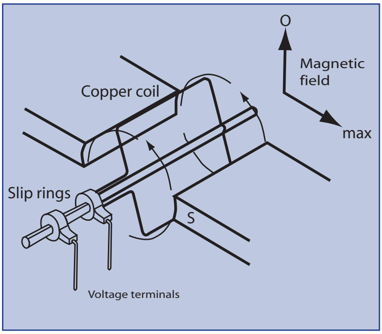
Alternating current

An alternating current (a.c.) flows in an electrical circuit that is energised with an alternating voltage. This voltage is one that reverses its sense of direction in a regular manner, and this is caused by the method by which it is generated.

In simple terms, the generator is a copper coil, which is mounted on a shaft between opposite poles of a magnet. When the shaft spins, the copper cuts the magnetic field and a voltage appears at the ends of the coil.

The generator (or alternator) is shown in Figure 8.

As the coil rotates one revolution the voltage follows the variation shown in Figure 9.



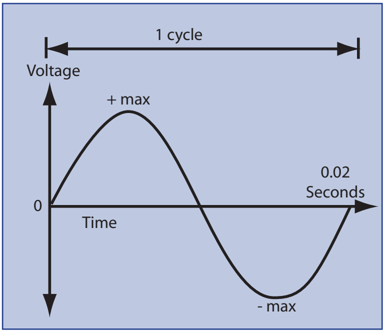


Figure 8. Simple a.c. generator

Figure 9. a.c. voltage wave form

When the coil is at right angles to the magnetic field, it is not cutting the field and the voltage is zero.

The maximum rate of cutting occurs when the coil is in line with the magnetic field and there is a maximum voltage output.

From zero to maximum and beyond maximum back to zero occurs in one half revolution and the voltage rises and falls.

In the next half revolution, the generated voltage is opposite to the first half. One full revolution of the coil produces one "cycle" of variation.

The number of voltage cycles in one second of time is called the frequency of the supply, and is given the name Hertz (Hz). The standard frequency in Australia is 50Hz.

Advantage of a.c. for distribution

Alternating current has an important advantage over direct current in that the voltage can be changed by transformers to a high value for transmission over long distances and then reduced at the customer's point of supply to a lower level suitable for operating lights, motors and other appliances.

As power = volts x amps, for the same power level to transmitted, a high voltage can be used so that the current can be kept to a low level thereby minimising the voltage drop.

Transmission of high power levels therefore requires:

a. Resistance of the transmission line to be as small as possible;

b. The transmission line current to be as low as possible.

The first condition cannot always be met, as it needs conductors of large cross-sectional area. Large conductors are expensive and their great weight would require strong and costly supports.

On the other hand, the second condition can be met by raising the transmission line voltage so that high power levels can be transmitted with relatively small currents. The small currents in turn require relatively small cross-sectional area, lightweight conductors with correspondingly lighter supports. Therefore, when high amounts of power levels are involved, it is general practice to use high transmission voltages and relatively small currents with correspondingly small voltage drops.

This condition is much more efficient than if an equivalent power level were transmitted at low voltage and high current with a relatively high voltage drop.

Transformers are used to provide the high voltages necessary for the transmission of high power levels over long distances.

In keeping with the value of the transmission line voltage employed, it is necessary to insulate the conductors against leakage to earth.

8. VOLTAGE VALUES

In the following, "voltage" means the voltage between the conductors.

The standard voltage values used are:

1. Extra low voltage (ELV) – means any voltage not exceeding 50V a.c. or 120V ripple free d.c.
2. Low voltage – means any voltage exceeding 50V a.c. or 120V ripple free d.c. but not exceeding 1kV a.c. or 1.5kV d.c. Thus the normal voltages of 240V and 415V delivered to most customers are "low voltage".
3. High voltage (HV) – means and voltage exceeding 1kV a.c. or 1.5kV d.c.
4. Extra high voltage (EHV) means any voltage exceeding 220kV.

Standard line voltages

The standard line voltages in use are:

240/415V (3 phase) 240/480V (1 phase)	Used to supply customers installations
6.6kV 11kV 22kV 12.7kV (SWER) 22kV	Used for urban and rural HV distribution
33kV 66kV	Used for sub-transmission of larger power levels in distribution over middle distances[1]
110kV 220V 330kV 500kV	Used for transmission of large power levels over long distances

[1] In some urban areas of Victoria there are pockets of 22kV subtransmission.

Voltage between live conductors and voltage to neutral

The voltage between any two live conductors is often referred to as the "line voltage".

The voltage to neutral, often referred to as the "phase voltage", is the voltage between any live conductor and the neutral point or earth of the system.

Figure 10 shows the line and phase voltages in a three-phase system. The neutral point is usually earthed at the supply end (for protection and safety reasons) and each live conductor is then

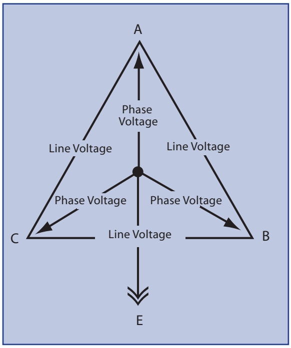


Figure 10. Three-phase system with earthed neutral

at a definite potential to earth. For instance, in an 11kV three-phase system, the voltage between any two live conductors gives a line voltage of 11kV while the voltage between any live conductor and neutral (or earth) gives a phase voltage of 6.35kV.

9. VOLTAGE SYSTEMS

High voltage overhead systems

The two systems most commonly used for transmission and distribution are:

Single-phase
Three-phase

High voltage single-phase system

This system is generally associated with the distribution of low power levels over relatively short distances. Single-phase systems are generally fed from a three-phase line.

The single-phase line consists of two conductors, neither directly earthed to the general mass of earth. In this system there is no neutral conductor (see Figure 11).

It is usual to have the three-phase system earthed (at the neutral point of the transformer or generator supplying the system) either solidly or through some current limiting resistance (for safety and protection purposes). As the single-phase HV system is part of the three-phase HV system, each phase of the single-phase system has a definite voltage to earth.

For safety reasons alone, it is important to remember that each phase is alive to earth and that a definite voltage exists between each phase and the equipment connected to the ground.

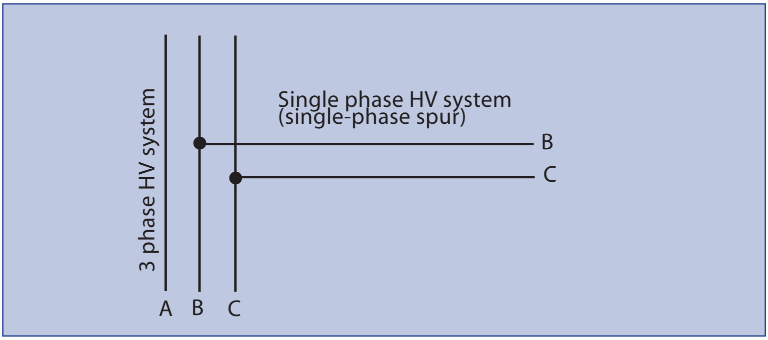


Figure 11. Three-phase high voltage system with single-phase spur

High voltage three-phase system

This system is widely used for the transmission of high power levels and is also the standard system used in distribution and reticulation.

It consists of three conductors, each called a “phase”. To standardise the identification of the phases, they are known as A, B and C phases or red, white and blue phases respectively.

The voltage in each phase alternates, in a similar manner to the alternating voltage shown in Figure 9 but one follows the other in regular order (see Figure 12).

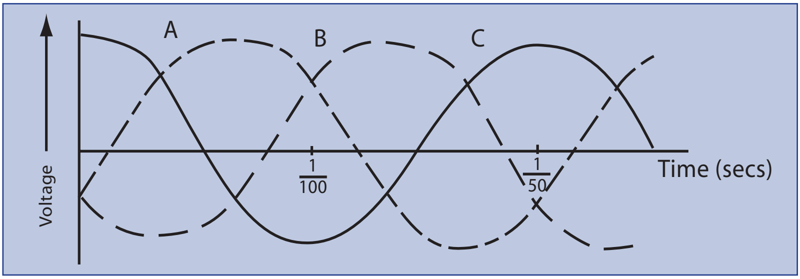


Figure 12. Representation of the three sine waves in a three-phase system

Briefly, phase A reaches its maximum positive value first, then is followed by phase B, then by phase C and so on. The order in which the phases reach their peak is called the phase sequence.

Phase sequence

It is essential that the order of phase sequences and the identity of the A, B and C be known. In the case just cited, the order of phase sequence was from A to B to C because the voltage in phase B reached its maximum value after that in phase A and the voltage in phase C reached its maximum value after that in phase B.

Phase sequence has an important bearing on the direction of rotation of three-phase a.c. motors, which depend on the phase sequence and the relative position of the three-phases connected to the motor terminals.

A reversal in the order of the phase sequence (eg. by interchanging any two of the three wires connected to its main terminals) will cause the motor to run in the reverse direction of rotation. For this reason alone, it is important that electrical workers know what happens if there is an inadvertent change in the position of the phases supplying a factory in which motors are installed.

Low voltage single-phase 2-wire overhead system

In this system there are two conductors, one generally solidly earthed at the transformer and known as the "neutral", while the other is known as the "live", "active" or "phase" conductor.

The voltage between phase and neutral is nominally 240V and the voltage of the phase or active conductor to earth is therefore also 240V (see Figure 13).

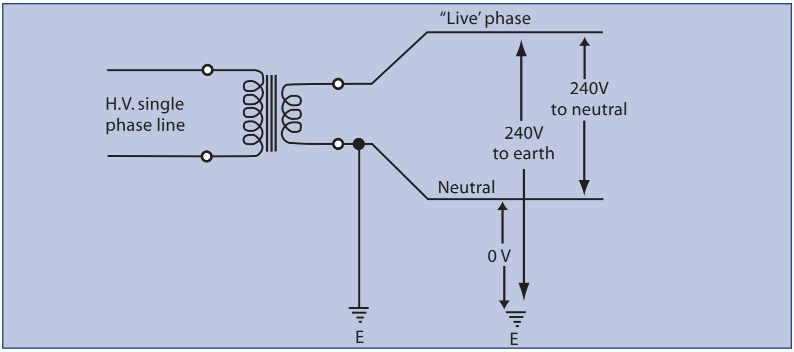


Figure 13. Single-phase 2-wire system

Low voltage single-phase 3-wire system

In certain rural areas, it is often more economical to install a single-phase high voltage line, saving the cost of the third high voltage phase and to supply the load by stepping down through a transformer to a 3-wire system. One conductor is earthed and known as the neutral while the other conductors are both "actives". (see Figure 14).

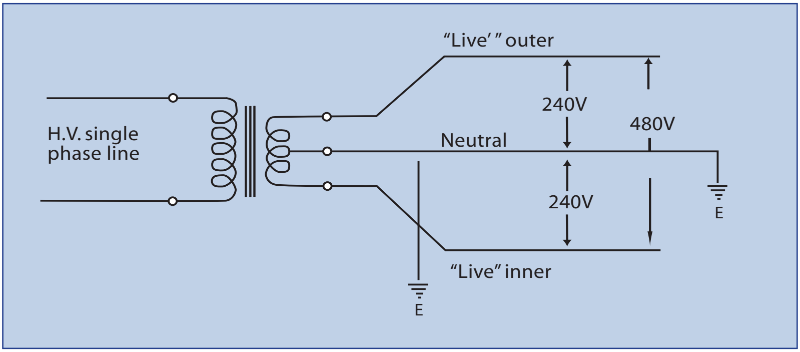


Figure 14. Single-phase 3-wire system

The voltage between either of the actives and the neutral is 240V while the voltage between the two active conductors is 480V. It is the a.c. equivalent of the three-wire d.c. system. It facilitates the supply of larger loads or loads at greater distances from the transformer than the single-phase 2-wire system.

Half of a domestic 240V load is connected between one active and the neutral and the other half between the other active and the neutral. This balances the load on each phase and reduces, if not eliminates, the residual current in the neutral.

Low voltage three-phase 4-wire system

This system employs four conductors and is widely used in all areas where it is considered economical to supply large amounts of energy for industrial and domestic purposes. The system is shown in Figure 15; a, b and c are the active conductors and n is the neutral which is connected to the "star point" of the transformer. It is usual for the "star point" to be earthed as shown.

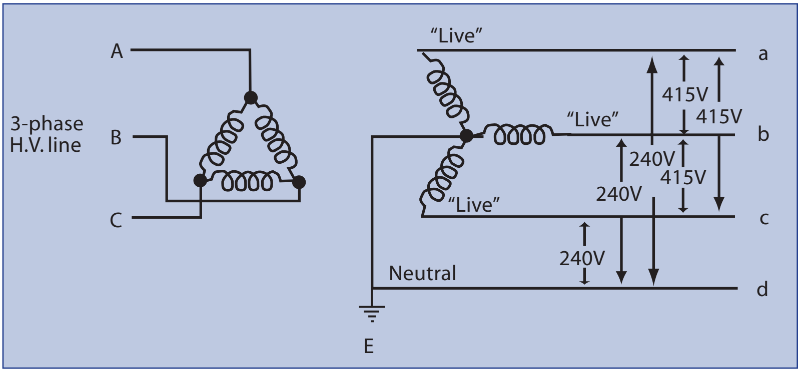


Figure 15. Three-phase system with earthed neutral

The standard voltage between actives is 415V, while the voltage between any one of the actives, (a, b and c respectively) and the neutral is 240V.

The same phase relationship of "phase sequence" exists on the LV as on the HV side of the transformer, so care must be taken when renewing mains to avoid upsetting the phase sequence to the supply of motor loads.

High voltage single-wire earth return (SWER) system

The power system known as the SWER system uses only one HV conductor with the earth being used as the return conductor, (see Figure 16). This system was first developed in New Zealand and is now used in Australia, South Africa and many other countries. It can have great economic advantages in hilly areas where the loading is relatively light, where long distances are involved and where the line can be strung from ridge top to ridge top. Because of the generally lower impedance of the line to earth circuit, it usually has better voltage regulation than a conventional single-phase 2-wire circuit.

To restrict noise interference in telecommunications systems, the amount of earth current allowed to flow in the earth return circuit is limited. Furthermore, there must be a minimum separation between SWER lines and any telecommunication lines.

A special transformer is used to isolate the SWER line from the main distribution line. The SWER line voltage is 12.7kV to earth. The distribution transformers fitted to the SWER line can be either single-phase 2-wire 240V supply or single-phase 3-wire 240/480V supply.

Particular attention must be paid to the good earthing of the transformers on a single-wire line and to the protection of these earth wires from physical damage.

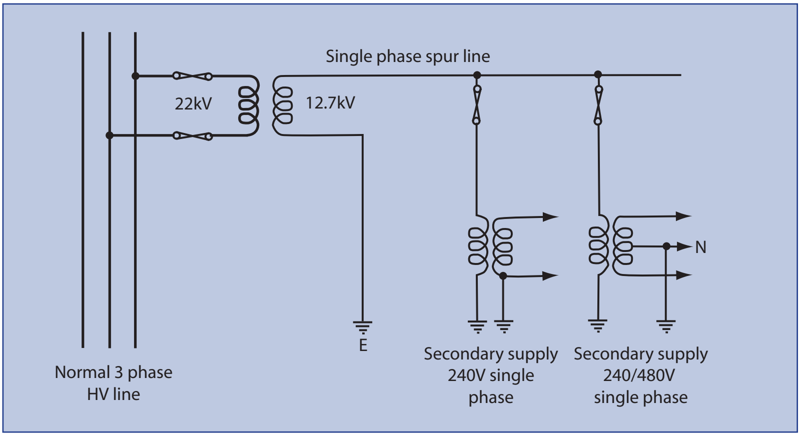


Figure 16. Single wire earth return system

10. THE NEUTRAL CONDUCTOR

In a low voltage single-phase 2-wire system, one conductor is earthed as shown in Figure 13. Both conductors are necessary and the neutral conductor may carry as much current as the active conductor, depending on the earth resistance and other factors.

In the case of the three-phase 4-wire system as shown in Figure 15, a different condition is found. The neutral conductor is necessary to be able to obtain a 240V supply (between any of the three actives and the neutral).

It is found that when each phase is equally loaded, there is no return current in the neutral conductor. This can be easily demonstrated as shown in Figure 17. Three 1kW heaters for example are connected as shown, one on each phase. When heater A for example is switched on, the ammeter records the current taken by the heater, that is 1000/240 = 4.2 or about 4¼ A. On switching on heater B, the current recorded by the ammeter does not increase to 8½ as might be expected but remains unchanged. Finally when heater C is switched on to give a three-phase balanced load, the ammeter reading falls to zero. If there are equal amounts of current in all of the three phases, then there will be no neutral current flowing in the neutral. In practice, the neutral is always required and since, in fact, a perfect balance is very seldom achieved, there is always some current in it. This current is usually considerably less than the current in the active conductors and consequently the size of the neutral can theoretically be smaller than that of the active conductors. In modern practice, the neutral is often left the same size as the active conductors to ensure the lowest possible resistance for the return current.

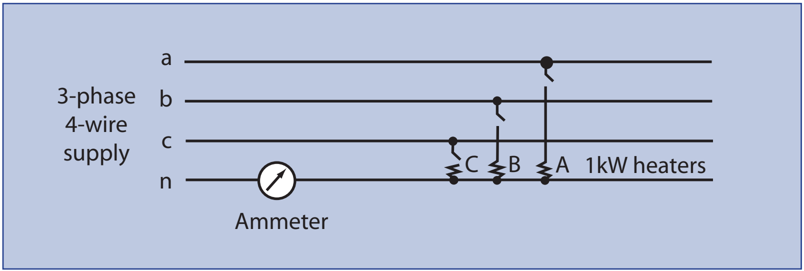


Figure 17. Three-phase 4-wire supply

For example, with 50mm^2 copper active conductors, a 35mm^2 copper neutral is sometimes used. In certain circumstances (for example if one fuse blows), the current in the neutral can be as great as in the active. Neutral current can also be large when transformer neutrals are interconnected. For these reasons, it is usual for the neutral to be the same size as the actives.

A good neutral conductor provides a low-resistance path back to the transformer for out-of-balance currents. If the neutral should be broken under these conditions, quite a considerable voltage can develop between the broken ends and, if both ends are held in the hands, a severe shock will result. Therefore it is as important with the neutral as it is with actives, not to handle both ends of a broken conductor unless supply has been isolated.

The multiple-earthed neutral system

The multiple-earthed neutral (MEN) system is widely used in Australia. Under this system, the neutral, in addition to being connected to earth at the supply end (that is, at the transformer), it is also connected to earth at each customer's premises. In addition, it is frequently earthed at other points and at the ends of distribution lines. From this arises the term "multiple-earthed neutral".

Under the system, the neutral is connected to earth at one point only at each customer's premises. The metal frames of electrical appliances such as ranges, motors and so on are separately earthed, the neutral being kept insulated from the frame of the appliance or apparatus, except at the switchboard where it is connected to the customer's main earth.

For further detail on earthing systems, see Subs, Caps & ACR's.

Active-neutral connection

It is vital to ensure that in connecting the customer's premises, that active and neutral are not reversed. If this happens, the customer's earth main should cause the service fuse to blow but, if the customer's earth is faulty, broken or of high resistance, there may be insufficient current to blow the fuse. In this case, all metal connected to the customer's earthing system, eg. range, water pipes, becomes alive and extremely dangerous, this situation is known as a "reverse polarity".

TRANSFORMERS

11. ELEMENTARY PRINCIPLES OF TRANSFORMERS

A transformer has three principal parts:

a. An iron core, which provides a continuous magnetic circuit

b. A primary winding, which draws current from the supply circuit

c. A secondary winding, which receives energy by electromagnetic induction from the primary winding and delivers it to the secondary circuit

NOTE: The primary winding is always considered to be the winding supplied by the voltage to be changed, whether it is the higher or lower voltage winding. The secondary winding is the one supplying the load.

In its most elementary form, a single phase transformer consists of an iron core with the primary and secondary windings wound on separate limbs of the core as shown in Figure 18.

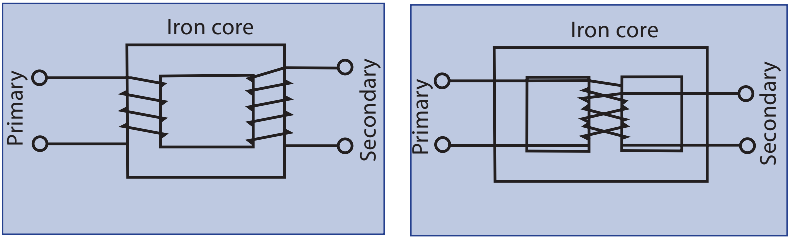


Figure 18. Iron core and windings

The two windings are quite independent of each other. In practice, part of each winding would be wound on each limb of the core.

As with any other piece of electrical equipment, the output from the transformer is equal to the input, less any losses occurring in the transformer. If losses are ignored, then:

Output (kVA) = Input (kVA)

Where kVA = (volts x amps) / 1,000 (volt amps)

This means that the higher the voltage, the smaller the current for the same kVA. For example, if the rating of a single phase transformer is 50kVA, the primary voltage 22kVA and the secondary voltage 240V, then:

$$\text{Primary current} = \frac{(50 \times 1000)}{22000}$$

$$= 2.3 \text{ amps approximately}$$

and

$$\text{Secondary current} = \frac{(50 \times 1000)}{240}$$

$$= 208 \text{ amps approximately}$$

The high voltage winding can therefore be made of fine wire but the low voltage winding will be required to be of much heavier wire.

The number of turns and the voltage of either winding are proportional to one another:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

Where:

E_p is the primary voltage

E_s is the secondary voltage

N_p is the number of turns on the primary winding

N_s is the number of turns on the secondary winding

Taking the transformer in the previous example, the primary voltage was 22kV and the secondary voltage 240V. If then the secondary winding had 23 turns, the number of turns on the primary winding would require to be:

$$\frac{22000}{240} \times 23 = 2108 \text{ turns}$$

12. TRANSFORMER COMPONENTS

Tank

With small distribution transformers, the tank may be quite plain. Heat is radiated from the sides of the tank or carried away by air movement. In large transformers, external cooling tubes or fin-type radiators are fitted and the larger zone substation type transformers may be equipped with separate radiator banks. Fans may be mounted on radiators to increase the rate of heat transfer to air, and oil pumps may force circulation of the insulating oil through the core, windings and radiators where the heat is released to air.

The tank has a tight fitting lid. Others fittings may include a breather or open or silica-gel type (to keep moisture out of the transformer), oil gauge and an oil drain/sampling valve near the bottom of the tank and a thermometer pocket for temperature monitoring purposes. Distribution transformers with a sealed tank are becoming more common. These transformers do not breathe to the outside but have an air space above the oil or flexible sides to permit expansion and contraction of the oil with changing temperatures. The advantage of this design is that, because there is no air movement into or out of the tank, the transformer oil is not exposed to contamination by dirt or moisture laden air.

Smaller transformer tanks may also include termination cubicles either welded or bolted to the tank to enclose the bushings and house items such as low voltage fuses.

Hooks or eyes are fitted to the transformer tank so that it may be lifted with chains or wire slings.

Bushings

The primary and secondary leads have to be brought outside the tank to permit connection to the electricity supply and the load by means of porcelain or cast resin bushings. These may be enclosed in an air-spaced termination cubicle or a cable box or they can be exposed without other protection. Bushings are brittle and easily broken so care must be taken when handling any exposed fittings.

Iron core

The core of a transformer provides the magnetic circuit that permits the transfer of energy between the primary and secondary windings. The core is normally manufactured from a special grade, low resistance, steel sheet cut into laminations and then clamped together to form the core. The purpose of using laminations is to prevent excessive induced currents (eddy) circulating in the core and causing heating of the transformer.

Air gaps between laminations resist the path of the magnetic circuit and assembly techniques have been developed so that the laminations on modern transformers are now assembled with very small air gaps between lamination butt joints.

Advances in the types of material used for the core and in the methods of assembly have greatly improved transformer efficiency and reduced the sizes of the cores required for the same power output.

Windings and connections

Windings around the core can be assembled in a variety of ways. The primary and secondary windings are efficiently magnetically coupled and have low electrical impedance. The windings themselves are of either copper or aluminium and may be either in conventional wire form or long strips of sheet. Normally the aim is to make the length of wire or strip wound on the core as short as possible to reduce losses caused by the winding's resistance.

Star connections

In this method of connection, the "ends" of the windings (shown in the diagram as 2) are connected together and normally connected to earth (or Neutral). The remaining ends (shown in the diagram as 1) are then connected to the phases, a, b, c of a three phase line. The common connection is known as the "neutral" or star point.

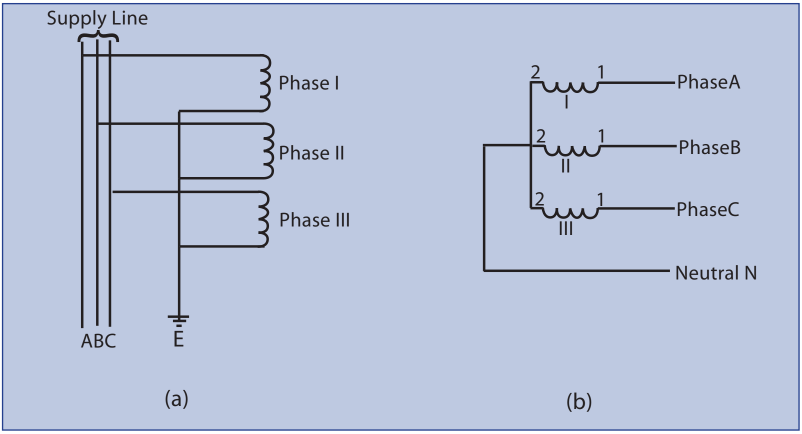


Figure 19. Star connected 3-phase windings

Delta connections

In this method the connections are made as follows; the end of winding I (shown in the diagram as 2) is connected to the beginning of winding II and so on, until the end of winding III is joined to the beginning of winding I. This connection does not give a neutral connection.

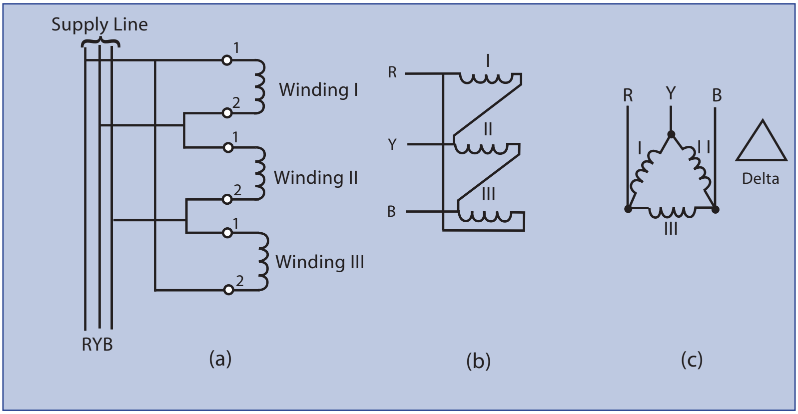


Figure 20. Delta connected 3-phase windings