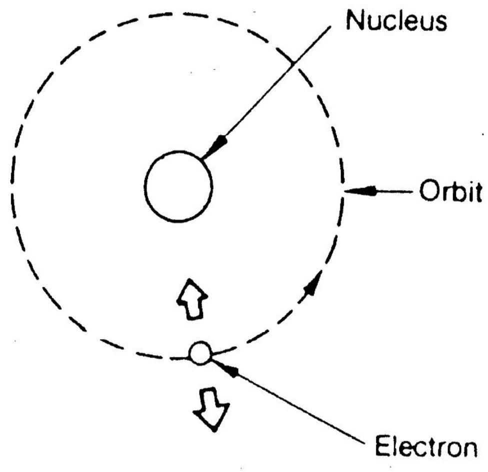
Chapter 1

INTRODUCTION

ATOMIC THEORY - ELECTRICITY

Matter is made up of atoms. Atoms are composed primarily of protons, neutrons and electrons in distinctive combinations for each element. Protons and neutrons of an atom are contained in its nucleus and electrons orbit the nucleus like planets around a sun. Within the structure of all substances, atoms are in a constant state of agitation. The degree of agitation varies according to the substance. This agitation will vary in solids, liquids and gases and there will be further variances in agitation dependent on the temperature of the particular substance.

Unless disturbed by forces external to the atoms, electrons are held in their orbit by a balance between centripetal and centrifugal forces. The centripetal force is attributed to a property of protons and electrons, known as an electric charge.



The attracting force (centripetal) is acting inwards.

The outwards force (centrifugal) is equal and opposite to the centripetal force.

AN ATOM ELECTRICALLY NEUTRAL

A force of attraction acts between an electron and a proton, whilst a force of repulsion acts between individual electrons, similarly, a force of repulsion acts between individual protons. To distinguish the different nature of the electric charges that cause these forces, the charge possessed by protons is said to be of positive polarity, and that of electrons to be of negative polarity. The signs + and - are usually used to identify these respective polarities

This concept of positive and negative electric charges, together with the facts of attraction and repulsion between them, provide the basis for all levels of understanding of the theory of electricity.

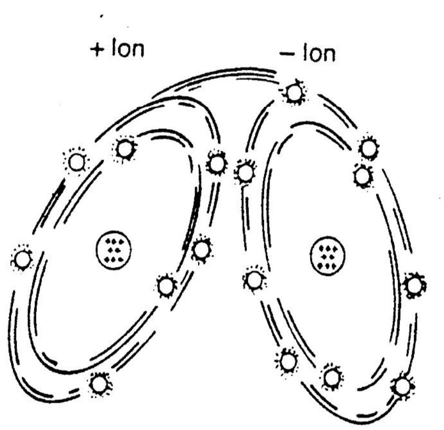
Regardless of the elements or substances to which particular atoms belong, electrons are always negatively charged to the same degree whilst protons are always positively charged to the same degree, and this degree of charge is the same for both electrons and protons. Protons and electrons possess electric charges that are equal in magnitude, but of opposite polarity.

Electrical Charges

As the electric charges of protons and electrons are equal and opposite, an atom with an equal number of each, has a zero net electric charge.

An atom, or a molecule, with one more proton than electrons is electrically unbalanced. Externally it manifests a positive charge equal to one proton. Conversely, an atom or a molecule with one more electron than protons is unbalanced in the opposite sense. Externally it manifests a negative charge equal to one electron.

The net charge of an ion externally manifests itself through the force of repulsion or attraction with which it reacts with other ‘like’ or ‘unlike’ charges.



An atom that loses an electron is positively charged and becomes a positive ion.

An atom that gains an electron is negatively charged and becomes a negative ion

IONS

Electron Movement

Some electrons are continually moving between atoms. They are repeatedly captured and freed to neutralise ions, or to ionise atoms. This random movement of electrons occurs to varying degrees in all substances.

Electric Field

The space surrounding a charged body or particle, in which it can react with some other charged body or particle, is known as an electric field.

Electron Flow

If the ends of a metal wire conductor are put into contact with unlike charged materials, electrons will move through the wire from the negatively charged device to the positively charged one. As the flow of electrons continues, the charges will decrease, unless some type of generation system is available to replace the charge.

Such a transfer of charge through a substance is known as an electric current, and it is said that the substance ‘conducts’ the current.

As is almost always the case with electric current in solid substances, the transfer of charge is by a flow of electrons. In gases and some liquids, the nature of electric current may differ from this in that charge may be transferred by a simultaneous flow of positive ions, negative ions and electrons. Of course, the positive ions would move in the opposite direction to the negative ions and electrons.

ELECTRICITY

Electrical energy relates directly to the flow of an electrical current. This electrical current is a flow of electrons. When current flows, it always travels at the speed of light (3×10^8 meters per second), but the amount of current that flows, depends on :

a) the force or pressure (voltage) encouraging the current flow; and

b) the difficulty (resistance) to the current flow in that circuit.

Current which flows only in one direction is known as Direct Current (DC) and current that continually changes its direction of flow is called Alternating Current (AC). The first section of these notes is intended to cover direct current. However, it is not possible to stay only with DC concepts, so some of the appropriate AC principles will be introduced.

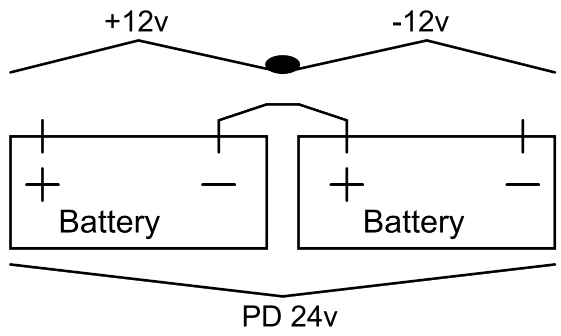
TERMINOLOGY - General & DC

Electromotive Force (EMF)

This is the force which causes current to flow and is measured in Voltage [V]. The unit 'volts' (12v,14v,24v,27.5v) has become the common designator for EMF. The size of this force is a measure of potential energy and is often referred to as electrical potential.

Potential Difference (PD)

A function of EMF, is potential difference, which is the difference between two voltages. The PD between the terminals of two 12 volt batteries connected in series is 24 volts. However, the PD measured from the middle connection would be +12 volts or - 12 volts.



THE PD BETWEEN TWO POINTS ON THE SAME 24 VOLT TERMINAL IS ZERO

Current

Current is the flow of electrons through a conductor and is measured in AMPERES (I).

An ampere is a measure of amount of current flow over a certain period (rate of flow). One ampere is equal to a one coulomb flow in one second.

A coulomb is a specific amount of electricity (a unit of quantity), defined as 6.28×10^{18} electrons.

Resistance

Resistance is the restriction to a flow of current in a circuit. If the circuit resistance is high, the current flow is low and if the circuit resistance is low, the current flow is high. This statement relates to a constant applied voltage and will be qualified on the following pages by applying OHM'S Law. Resistance is measured in ohms [Ω].

Different materials offer different values of resistance to current flow. There are other factors that affect the resistance of materials. Good conductors have fairly low resistance values but this can vary with:

a) increase in length of the conductor (increase resistance),

b) increase in cross-sectional area (decrease resistance) and,

c) increase in temperature (usually increases resistance, however in carbon resistance decreases).

Conductors and Insulators

Conductivity is a measure of the ease with which a substance conducts current. Resistivity is a measure of a substance's opposition to the conduction of current. Each is the reciprocal of the other. High conductivity substances have low resistivity. Substances of high resistivity have low conductivity.

Always for practical engineering reasons, and also frequently for safety reasons, it is necessary to confine current to specific conducting materials or paths. This is done by using high conductivity substances for the conducting paths, and protecting these by surrounding them with substances or materials of very high resistivity. The protection of current-carrying substances or materials in this way is known as electrical insulation, and the materials used for this purpose are known as insulators. Air is a satisfactory insulator in some circumstances, but solid materials are usually used to insulate current-carrying conductors from each other, from non-current-carrying conducting materials.

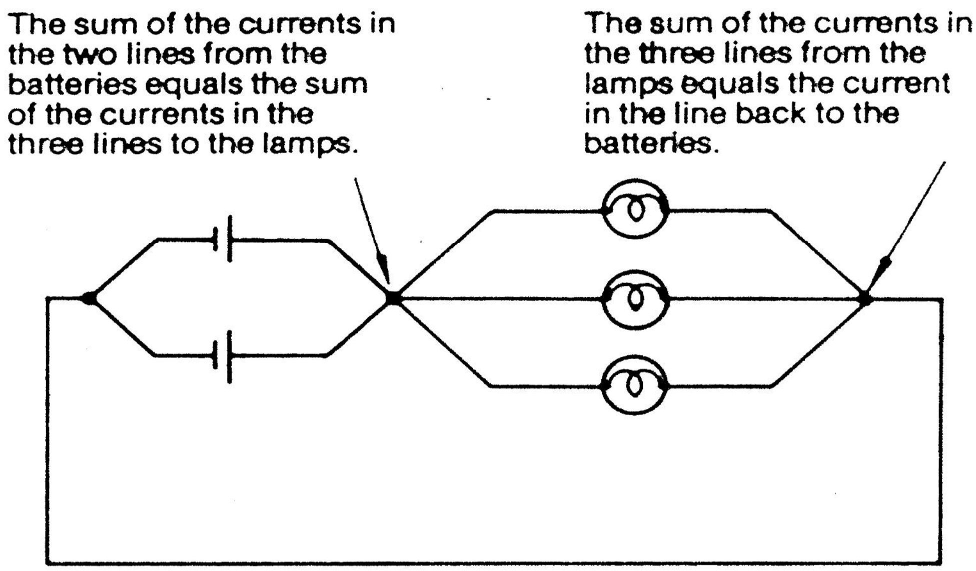
A conductor is a substance, usually a metal, which conducts electricity. Metals such as silver, copper and gold are very good conductors. Water is a fairly poor conductor depending on its mineral salt content. Most plastics, china, bakealite, wood and air are very poor conductors. This last group displays such a high resistance to current flow that they are considered to be insulators. There is a group of materials that are neither good conductors nor good insulators (silicon, germanium). These are known as semi-conductors and are used in solid state devices such as transistors, diodes, integrated circuits, computer chips.

Conductivity in a circuit will vary with the quality of the electrical connections. Dust, corrosion or oxidation on battery terminals causes a high resistance connection which decreases current flow and circuit performance. Gold connectors are used in computers where very small voltages and current flows are normal, because gold does not oxidize and so the connections remain good for very long periods.

Kirchhoff's Voltage and Current Laws

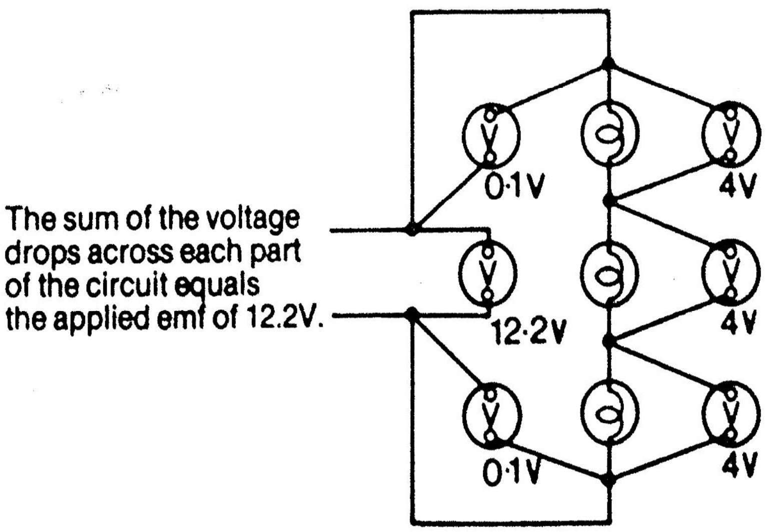
Kirchhoff's **Current Law** states simply that in any circuit the current to a terminal or a junction is equal to the current from that terminal or junction.

This really means that what goes in must come out and is demonstrated by this simple parallel circuit. Note the current values:



KIRCHOFF'S CURRENT LAW

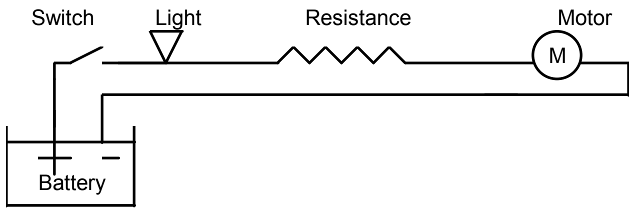
Kirchhoff's **Voltage Law** states that the sum of the voltage drops in a series circuit is equal to the total applied voltage (EMF). The series circuit below shows where the voltage drops occur. This principle is sound for complex circuits (a combination of series and parallel circuits) as each component, depending on its effective resistance, will cause a particular voltage drop.



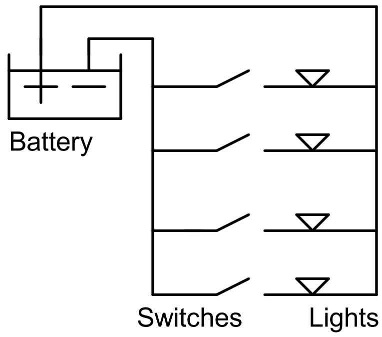
KIRCHOFF'S VOLTAGE LAW

The following diagrams are further examples of the two basic types of circuits. Note that the symbol for resistance is often used to indicate the resistance value of a component or the total resistance value of the circuit and is not necessarily a resistor.

A Series Circuit



A Parallel Circuit



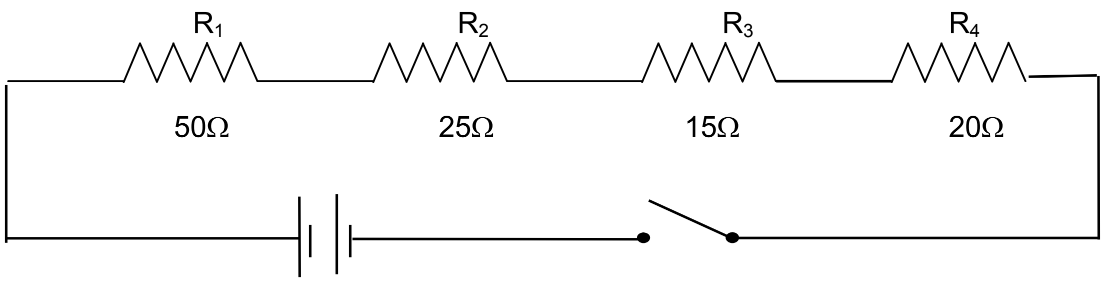
UNDERSTANDING RESISTANCE IN CIRCUITS

The total resistance (R_{TOTAL}) value of a circuit can be calculated by using the following formulae:

Series Circuits

$$R_{TOTAL} = R_1 + R_2 + R_3 \text{ etc.}$$

Example What is the total resistance of this series circuit?



R_T $= R_1 + R_2 + R_3 + R_4$

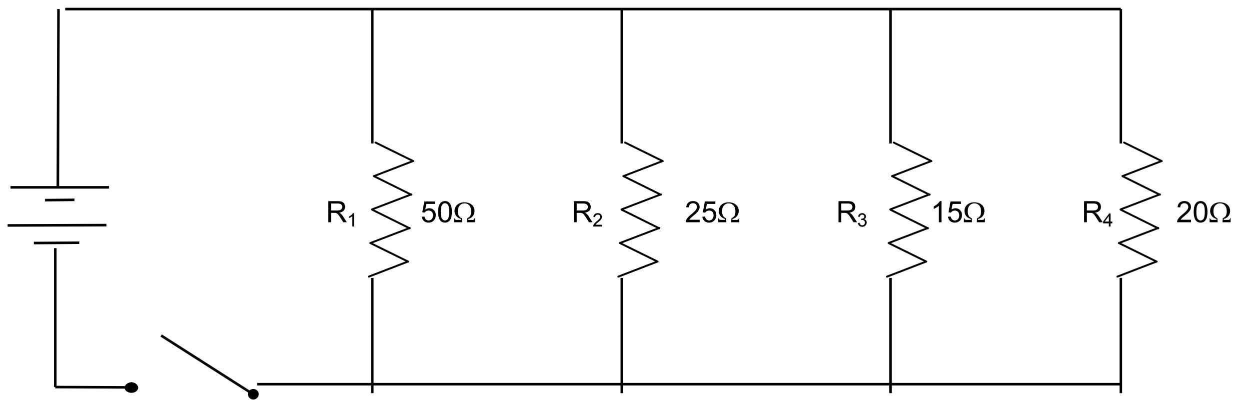
$= 50\Omega + 25\Omega + 15\Omega + 20\ \Omega$

$= 110\Omega$

Parallel Circuits

$$\frac{1}{R_{TOTAL}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R3} \text{ etc.}$$

Example What is the total resistance of this parallel circuit?



$$\frac{1}{R_T} = \frac{1}{50} + \frac{1}{25} + \frac{1}{15} + \frac{1}{20}$$

$$= \frac{6+12+20+15}{300}$$

$$\frac{1}{R_T} = \frac{53}{300}$$

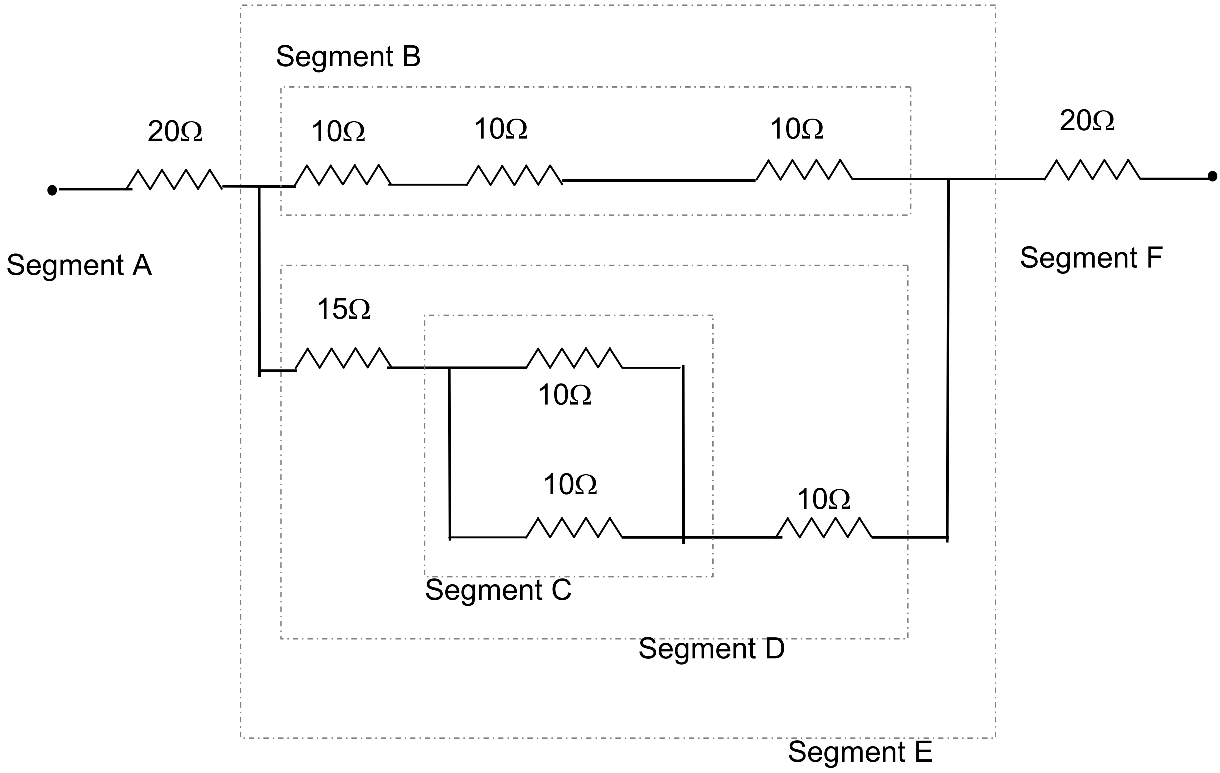
$$\therefore R_T = \frac{300}{53}$$

$$= 5.66\Omega$$

Note this is a very small value of resistance when compared with the same values in a series circuit.

SERIES PARALLEL CIRCUITS

Should a complex circuit be encountered where the resistance value must be calculated, the circuit must be divided into series and parallel segments. When each segment resistance value is determined, it will then be in either series or parallel with its adjacent segment.



A COMPLEX CIRCUIT

In this diagram, resistance of segment A and segment F are in series with the centre section, segment E, so these can be summed later. To determine the resistance of segment E, start from the middle and work outwards.

$$\frac{1}{R_{T(C)}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Segment C $$\frac{1}{R_{T(C)}} = \frac{1}{10\Omega} + \frac{1}{10\Omega}$$

$$= \frac{2}{10}$$

$$= \frac{1}{5}$$

$$\therefore \quad R_{T(C)} = \frac{5}{1} = 5\Omega$$

	$R_{T(D)}$	=	$R_1 + R_2 + R_3$
Segment D	$R_{T(D)}$	=	$15\Omega + 5\Omega + 10\Omega$
		=	30Ω
	$R_{T(B)}$	=	$R_1 + R_2 + R_3$
Segment B	$R_{T(B)}$	=	$10\Omega + 10\Omega + 10\Omega$
		=	30Ω

Segment E = Segments B and D in parallel.

$$\therefore \quad \frac{1}{R_{T(E)}} = \frac{1}{R_{T(B)}} + \frac{1}{R_{T(D)}}$$

$$= \frac{1}{30} + \frac{1}{30}$$

$$= \frac{2}{30} = \frac{1}{15}$$

$$\therefore \quad R_{T(E)} = 15\Omega$$

Looking back at the complex circuit diagrams, we can now sum Segments A, E and F to produce the effective resistance.

R_T	=	Segment A + Segment E + Segment F
	=	$20\Omega + 15\Omega + 20\Omega$
	=	55Ω

Now that the resistance of the circuit is known, if we know the applied voltage, we can determine the current flow. This is the application of Ohm's law.

Ohm’s Law

States - "When current flows in a conductor, the difference in potential between the ends of the conductor, divided by the current flowing, is a constant, provided there is no change in the physical condition of the conductor."

This means that *one* volt applied across a *one* ohm resistor will cause *one* ampere to flow.

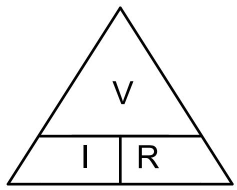
The conductor constant is resistance (R) and is measured in ohms.

The potential difference is measured in volts (V).

The current is measured in Amps (I).

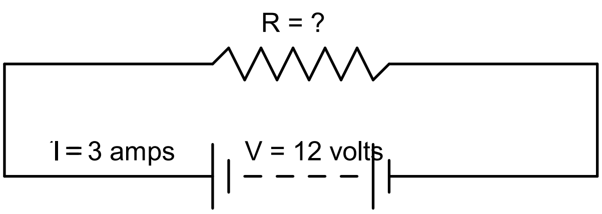
The Ohm's Law formula	V	=	IR (volts)
by transformation is	R	=	$\frac{V}{I}$ (ohms)
and	I	=	$\frac{V}{R}$ (Amps)

To assist in remembering the Ohm’s Law formula use :



Ohm’s Law is particularly useful when two of the three properties are known - the third can be calculated.

Example 1 If an EMF of 12v is applied to a resistance R and the current flowing is 3 amps, what is the value of R?



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

$\therefore R = \frac{12 \text{ volts}}{3 \text{ amps}}$

$\therefore R = 4$ ohms

Example 2 You will see from the printing on its base, that a bulb from the headlight of your car is rated at 12v and 4 amps. What is its resistance?

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

$\therefore R = \frac{12}{4}$

$\therefore R = 3$ ohms

Example 3 An electromagnet draws a current of 1.5 amps and the resistance of the coil is 24 ohms. What voltage must be applied to make it operate?

Since $V = I \times R$

$\therefore V = 1.5 \times 24$

$\therefore V = 36$ volts

This is a fundamental explanation only. An understanding of series and parallel DC circuits is necessary. Impedance in AC circuits is discussed later and is also necessary for a complete understanding of Ohm's law.

POWER

The rate of doing work (power), in electrical circuits is measured in WATTS. The greater the EMF (voltage), the greater the current flow through that resistance and the greater the power produced.

The power formula:

Units EMF (E or V) measured in Volts.
Current (I) measured in Amps.
POWER (P) measured in Watts.
Resistance (R) measured in Ohms.

$\underline{P = VI}$

Substituting for V from Ohms Law.

$P = (IR).I$

$\therefore P = I^2 R$

and substituting for I from Ohm's Law

$$P = V \left(\frac{V}{R} \right)$$

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

Finding the Power Consumed by a Circuit or Component.

A circuit is connected across a supply of 24 volts. How much power is used when a current of 5 amperes flows through this load, which may be a simple resistor or a complex circuit ?

Power = Voltage x Current

$P = VI = 24 \times 5$

Power Used = 120 watts

Note : *This calculation demonstrates the REAL or TRUE power in this 'resistive circuit'. Consideration will be given later to power in AC circuits where factors other than resistance affect current flow.*

To help understand 'power' in electrical circuits we should perhaps look again at the formulae.

$P = VI$ If P is considered constant we can deliver that power by having a very high voltage supply a very small current, conversely a very high current from a small voltage.

$P = I^2R$ Circuits generally demand current in relation to resistance, to complete their function. The amount of current flow is critical when considering circuit power, as its value is square. Current is therefore about the best indicator of power consumption in a circuit or component. The term 'LOAD' is often used to describe actual current flow

POWER RATING OF EQUIPMENT

Most electrical equipment is 'rated' for both voltage and power (volts and watts). Electric lamps for 24 volt systems are also rated in watts and are usually identified by voltage and wattage statements printed on their base.

The power rating of an electric lamp, or any other electrical equipment indicates the rate at which electrical energy is changed into another form of energy, such as heat or light. A 10 watt lamp will give more light than a 5 watt lamp. Similarly the wattage rating of motors, resistors and other electrical devices, indicates they are designed to withstand a specific amount of heat (real power).

When power is consumed in a material having only resistance, electrical energy is changed into heat. If more current is forced to flow, more power is used and the temperature of the material will rise further. If the temperature rises too high the material may change its composition, expand, contract or burn. For this reason, all electrical equipment is rated for a maximum wattage. If operated at less than this power value, the equipment will usually reach or exceed its design life.

The Magnitude of UNITS of Electrical Energy

The fundamental examples in the preceding Ohm's law descriptions show most units as whole numbers.

In reality there may be a need to apply thousands of volts to a circuit. Perhaps 12000 volts, which then becomes 12 kilovolts designated kV which is 12 x 10^3 volts. Similarly, values of current are often expressed in units of less than one amp. For example 1/40th of an amp is 0.025 amps and the standard way to describe this value is 25 milliamps (25mA) which is 25 x 10^{-3} amps. The table below may be helpful.

Name of Prefix	Factor (10^x)	Prefix
tera	10^{12}	T
giga	10^{9}	G
mega	10^{6}	M
kilo	10^{3}	k
'unity'	10^{0}	-
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	η
pico	10^{-12}	ρ

Power expressed as 60 kW is 60 x 10^3 = 60000 watts

Current expressed as 100 mA is 10 x 10^{-3} = 0.1 amps

Frequency expressed as 126.7 MHz is 126.7 x 10^6 = 126,700,000 Hz

A final example of Ohm’s Law;

Find the current flow and resistance of a 6 volt torch (flash light) rated at 3 watts.

$$P = VI$$

$$\therefore \quad I = \frac{P}{V}$$

$$= \frac{3}{6}$$

Current = 0.5 amps or 500mA

$$P = 1^2R$$

$$\therefore \quad R = \frac{P}{I^2}$$

$$R = \frac{3}{0.25}$$

Resistance = 12Ω