EDEXCEL NATIONAL CERTIFICATE/DIPLOMA

UNIT 5 - ELECTRICAL AND ELECTRONIC PRINCIPLES
NQF LEVEL 3

OUTCOME 1 - D.C. CIRCUITS

1 **Be able to use circuit theory to determine voltage, current and resistance in direct current (DC) circuits**

***DC circuit theory*:** voltage e.g. potential difference, electromotive force (e.m.f.); resistance e.g. conductors and insulators, resistivity, temperature coefficient, internal resistance of a DC source; circuit components (power source e.g. cell, battery, stabilised power supply; resistors e.g. function, types, values, colour coding; diodes eg types, characteristics, forward and reverse bias modes); circuit layout (DC power source, resistors in series, resistors in parallel, series and parallel combinations); Ohm's law, power and energy formulae e.g. V = IR, P = IV, W = Pt, application of Kirchhoff's voltage and current laws

***DC networks*:** networks with one DC power source and at least five components e.g. DC power source with two series resistor and three parallel resistors connected in a series parallel arrangement; diode resistor circuit with DC power source, series resistors and diodes

***Measurements in DC circuits*:** safe use of a multimeter e.g. setting, handling, health and safety; measurements (circuit current, voltage, resistance, internal resistance of a DC power source, testing a diode's forward and reverse bias)

1. BASIC ELECTRICAL THEORY

If you have already studied the very basic theory you should skip this section.

Electricity is conducted through a substance by the movement of electrons from one molecule to another. Each electron possesses energy so the flow of electricity transfers energy from one place to another rather like how a flow of liquid can transport energy from one place to another.

Some materials such as copper have atoms with a large number of orbiting electrons so electrons jump easily from one to another. Other materials have few electrons (e.g. polymers and glass) so they do not conduct electricity very well. In order to make electricity flow along a conductor, a force is needed to make them jump from one atom to another. This is the voltage or potential difference. Voltage is rather like pressure in a pipe which is needed to make a liquid flow along it.

Fluids do not flow easily through a pipe because of the frictional resistance. If you wish to make a fluid flow faster, the pressure behind it must be increased. If the pipe is long and narrow the pressure required is much larger than if it was short and wide. In the same way, if an electrical conductor has lots of free electrons, a smaller voltage is needed to make them flow than for a conductor with few free electrons.

Wherever friction is present, a force is needed to cause movement and energy is lost as heat as a result. This is true when you slide an object on a rough surface or if you force fluid through a restriction. The same is also true of conductors. A large voltage is needed to make the electrons flow through a poor conductor and it heats up as a result and loses energy. The property which governs how easily the electrons flow is called RESISTANCE (R).

Note the analogy between	Voltage	Force	Pressure.
also between	Current	movement	Flow rate.
also between	Resistance	Friction	Restriction.

Each electron carries a small amount of energy equal to 160.25×10^{-21} Joules per Volt. The greater the voltage, the greater this energy becomes. The total energy per volt is called the CHARGE (Q) and this is measured in Coulombs.

Electrical energy = Charge x Volts = Q V

The charge transferred per second is called the CURRENT (I) and this is measured in Amperes (A).

Current = Charge/second = Q/time = I Amps.
1 Amp = 1 Coulomb per second.

SELF ASSESSMENT EXERCISE No. 1

1. A charge of 500 Coulombs flows through a conductor in 200 seconds. What is the average current?

   (2.5 A)

2. A Battery holds a charge of 2000 Coulombs at a potential of 12 Volts. What is the energy stored?

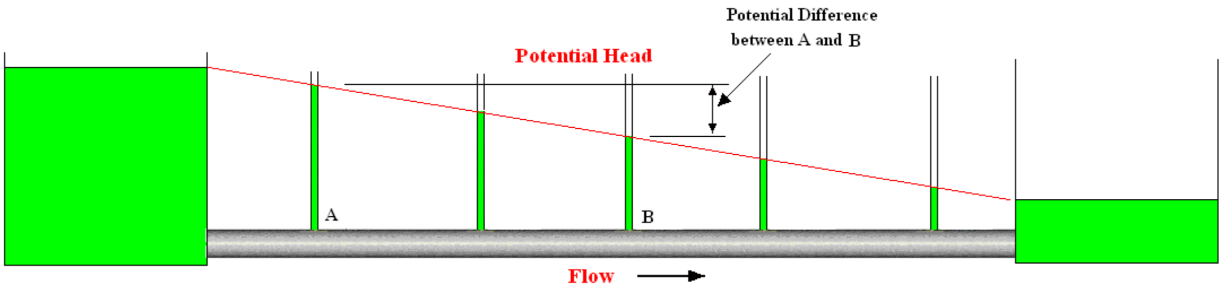
   (24000 Joules)

3. A light bulb consumes 100 Watts of power at 24 Volts. What is the current?

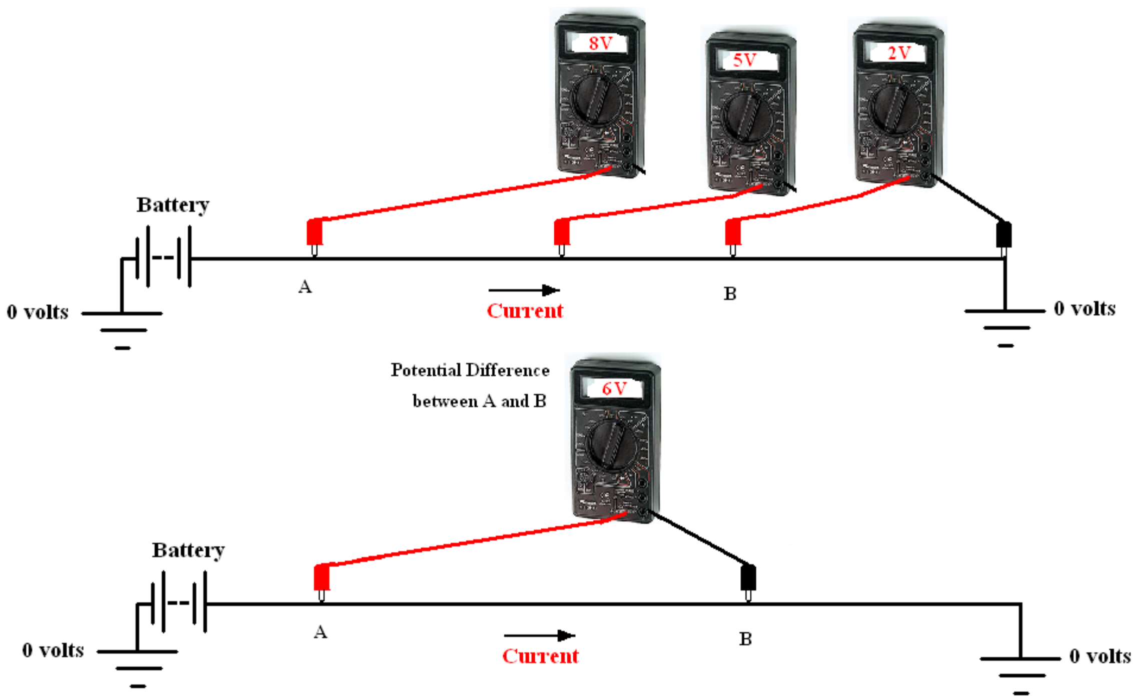
   (4.17 A)

POTENTIAL DIFFERENCE

This is another term for voltage difference and it comes about by analogy with a hydraulic system. The diagram illustrates a liquid such as water flowing through a horizontal pipe from the tank on the left with a high level to a tank on the right with a low level. If we inserted vertical tubes at various places along the pipe, water would rise to a height in that tube as shown. The height of the liquid is called the PRESSURE HEAD and represents the pressure in the pipe. Because of the resistance in the pipe, the pressure falls as shown. The height of the column of liquid represents potential energy and so the pressure head is also called POTENTIAL HEAD. The difference in height between points A and B is called the POTENTIAL DIFFERENCE.



The next diagram shows the electrical circuit analogous to the hydraulic circuit. A wire conducts electric current from the positive terminal of the battery to the earth terminal at the other end. The negative terminal of the battery is also earthed. Due to the resistance of the wire, the voltage falls along the length as indicated by a voltmeter connected to various points along the length. Because of the similarity with the hydraulic system, we call the voltage difference between two points such as A and B the POTENTIAL DIFFERENCE or P.D. Remember that whenever you come across a potential difference, it simply means the voltage difference.



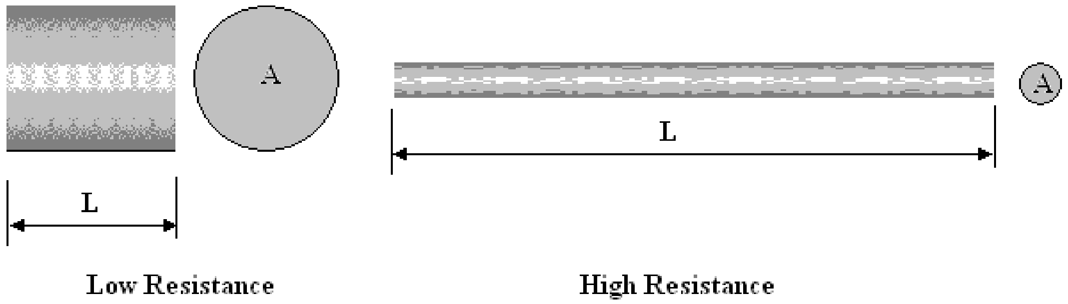
2. RESISTANCE AND CONDUCTION

Some materials such as copper have atoms with a large number of orbiting electrons so electrons jump easily from one to another. Silver is the best conductor but too expensive to use for wires. Other materials have few electrons (e.g. polymers and glass) so they do not conduct electricity very well. In order to make electricity flow along a conductor, a force is needed to make them jump from one atom to another. This is the voltage or potential difference.

The resistance of a conductor increases with length L and decreases with cross sectional area A so we may say R is directly proportional to L and inversely proportional to A.

R = Constant x L/A measured in Ohms Ω
The constant is the resistivity of the material ρ hence:- **$R = \rho L/A$ Ohms.**
The diagram illustrates the difference between a short fat conductor and a long thin conductor.
In terms of conductance
G = Constant x A/L measured in Siemens (S)
The constant is the conductivity of the material σ hence:- **$G = \sigma A/L$ Siemens.**
It follows that $G = 1/R$ and $\sigma = 1/\rho$

The diagram illustrates the difference between a short fat conductor and a long thin conductor.



WORKED EXAMPLE No. 1

Calculate the resistance of an Aluminium wire 0.2 mm diameter and 20 m long given the resistivity is 2.65×10^{-8} Ω m

SOLUTION

$A = \pi D^2/4 = \pi \times 0.0002^2/4 = 31.42 \times 10^{-9}\ m^2$
$L = 20$ m
$\rho = 2.65 \times 10^{-8}$ Ω m

$R = \rho L/A = 2.65 \times 10^{-8} \times 20/31.42 \times 10^{-9} = 16.87\ \Omega$

SELF ASSESSMENT EXERCISE No. 2

1. Calculate the resistance of a copper wire 5 m long and 0.3 mm diameter.
   The resistivity is 1.7×10^{-8} Ohm metre. (Answer 1.202 Ω)

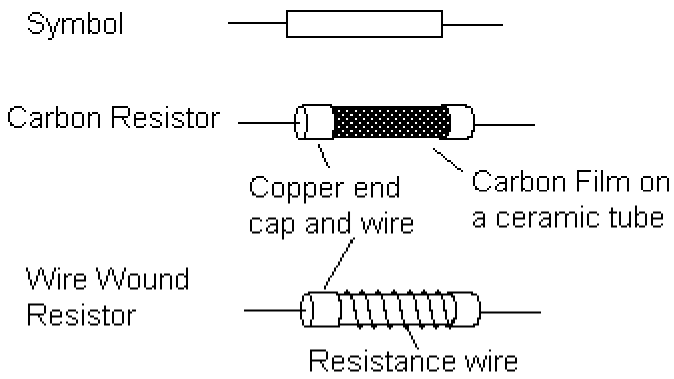
2. Calculate the resistance of a nichrome wire 2 m long and 0.2 mm diameter given $\rho = 108 \times 10^{-8}$
   (Answer 68.75 Ω)

3. RESISTORS

If you are already familiar with the various types of resistors, you should skip section 2

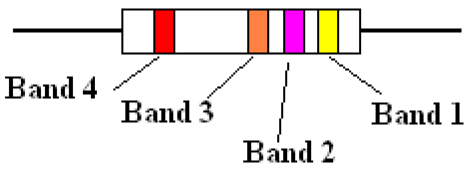
A resistor is an electrical component specifically designed to resist the flow of electric current. The resistance is measured in Ohms (Ω). Resistors may be fixed in value or designed to have the resistance varied. In order to resist the flow of current they produce heat so they are made to dissipate different heat rates (the Wattage value).

FIXED RESISTORS



The most common form of construction is a ceramic tube coated in a resistor material. This may be a carbon film, a metal oxide film or a metal film. The resistors are generally larger for higher wattage ratings. The wire wound resistor is generally used for high heat dissipation rates. The heat produced by resistors may cause the resistance value to change and affect the electronic circuit of which it is a part. The type and size must be chosen carefully to suit the application.

COLOUR CODE



Band 1 represents the first digit.
Band 2 represents the second digit.
Band 3 represents the number of zeros following the second digit.
Band 4 represents the tolerance and has the following codes.

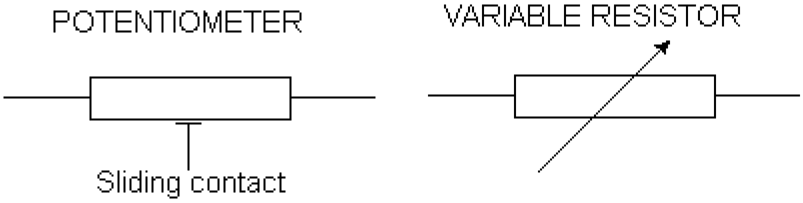
Black	0	Green	5
Brown	1	Blue	6
Red	2	Violet	7
Orange	3	Grey	8
Yellow	4	White	9

None ±20% Silver ±10% Gold ±5% Red ±2%

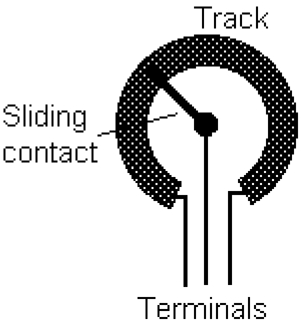
For example a colour code of yellow, Violet and Orange would translate into 47000 Ω or 47 kΩ.

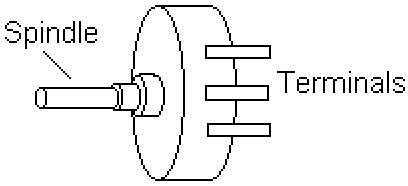
VARIABLE RESISTORS

A variable resistor is a two terminal device and the resistance value between them may be adjusted. A potentiometer is a three terminal device and the resistance between one end the sliding contact may be varied to produce different voltages (potentials).

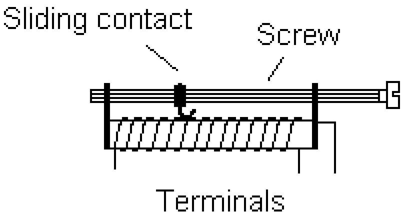


The diagram shows the construction of a typical rotary potentiometer. The track is made from a film or from resistance wire. When the spindle is rotated, the sliding contact moves along the track and the resistance value between the middle and end terminals change.

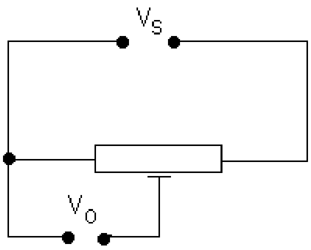




The construction of a simple wire wound linear potentiometer is shown below.

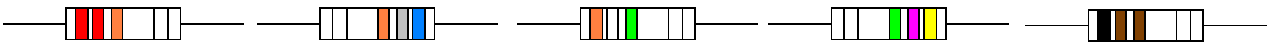


A typical circuit for a potentiometer is shown below. The supply voltage Vs is usually constant and the output voltage Vo is varied by moving the contact. This is often used to control electronic circuits.



SELF ASSESSMENT EXERCISE No. 3

Identify the resistance value of the resistors shown below.



A **B** **C** **D** **E**

4. TEMPERATURE COEFFICIENT OF RESISTANCE

The resistance of conductors changes with temperature. This is a problem in many electrical circuits because resistors generate heat and so change in value as they warm up. The extreme example is a filament light bulb that has a much lower resistance when cold than when it glows. Usually the resistance increases with temperature but there are some special conductors that do the opposite.

The amount by which the resistance changes per degree per ohm of the original resistance is called the temperature coefficient of resistance and it is denoted with the symbol α. The units are Ohms per Ohm per degree or more often simply $^{o}C^{-1}$ or K^{-1}.

Let the resistance of a conductor be R_o at 0^oC.

Let the resistance be R_1 at θ_1 ^oC. The change in resistance = $\alpha\theta_1 R_o$

The new resistance is $R_1 = R_o + \alpha\theta_1 R_o$

Let the resistance be R_2 at θ_2 ^oC. The change in resistance = $\alpha\theta_2 R_o$

The new resistance is $R_2 = R_o + \alpha\theta_2 R_o$

If the temperature changes from θ_1 to θ_2 the resistance changes by

$\Delta R = R_2 - R_1 = (R_o + \alpha\theta_2 R_o) - (R_o + \alpha\theta_1 R_o)$ $\qquad$ $\mathbf{\Delta R = R_o\, \alpha\Delta\theta}$

Typical values of α are found on the data sheets on the home page of www.freestudy.co.uk.

WORKED EXAMPLE No. 2

A long thin aluminium wire has a resistance 0.250 Ω at 0^oC. Find the resistance at 200^oC given that $\alpha = 4 \times 10^{-3}\ K^{-1}$

SOLUTION

$\Delta R = R_o\, \alpha\, \Delta\theta = 0.25 \times 4 \times 10^{-3} \times (200 - 0) = 0.2\ \Omega$

The resistance at $200\ ^oC$ is $0.25 + 0.2 = 0.45\ \Omega$

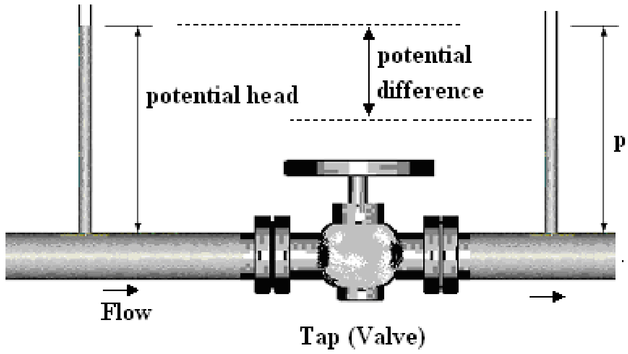
SELF ASSESSMENT EXERCISE No.4

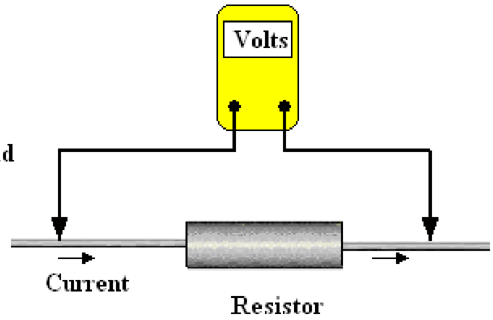
1. A resistor has a nominal resistance of 120 Ω at 0 ^oC. Calculate the resistance at 20^oC. Calculate the change in resistance when the temperature drops by 5 degrees. $\alpha = 6 \times 10^{-3}\ K^{-1}$

(Answers 134.4 Ω and - 3.6Ω)

4 OHM'S LAW

The next diagram shows how a restriction causes a pressure drop in a pipe and in a similar way a resistor creates a potential difference in a circuit.

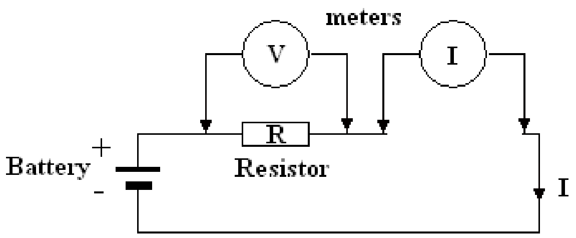




Ohm discovered that the current ‘I’ flowing through a resistance is directly proportional to the voltage across it. The circuit shows how a voltmeter and ammeter may be used to prove this.

If the voltage V is varied and the current is I measured, it is found that $V/I = \text{constant}$

The constant is the resistance R and has units of Volts per Ampere but this is commonly known as the Ohm (Ω).



$$\mathbf{V/I = R}$$

5 ELECTRIC POWER

Electrons carry energy and this is given by Energy = Volts x Charge = VQ
Power is energy per second so the electric power is

$$P = E/\text{second} = V\,Q/\text{Second}$$

Charge per second is the current I Amperes. It follows that the power contained in an electric current is

$$\mathbf{P = VI}$$

The formula may be presented in other ways by substituting Ohm's law into it. from Ohm's law we have V = IR and I = V/R.

Substituting for V gives $\mathbf{P = I^2R}$

Substituting for I gives $\mathbf{P = V^2/R}$

<u>WORKED EXAMPLE No. 3</u>

A resistance of 5 Ω has a potential difference of 24 V applied across it. Calculate the current and the and the power dissipated as heat.

<u>SOLUTION</u>

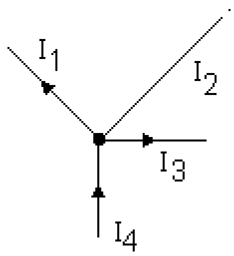
$I = V/R = 24/5 = 4.8\text{ A}$

$P = I\,V = 4.8 \times 24 = 115.2\text{ W}$

Check $P = I^2R = 4.8^2 \times 5 = 115.2\text{ W}$

6 KIRCHOFF'S RULES

CURRENT RULE



This rule concerns the currents flowing in and out of a junction. It simply states that the total current entering a junction equals the total current leaving the junction. Consider 4 conductors carrying currents into and out of a junction as shown.

Let current entering the junction be positive and currents leaving be negative. The rule then becomes

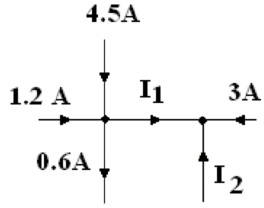
$$I_1 + I_2 + I_3 + I_4 = 0$$

Suppose $I_1 = -2$ Amps, $I_3 = -4$ Amps and $I_4 = 7$ Amps. Determine I_2 .

$$I_1 + I_2 + I_3 + I_4 = 0$$
$$-2 + I_2 - 4 + 7 = 0$$
$I_2 = -1$ Amp (i.e. leaving)

WORKED EXAMPLE No. 4

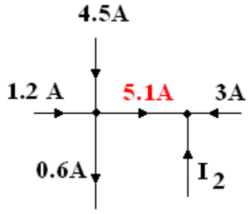
Calculate the currents I_1 and I_2 in the network below.



SOLUTION

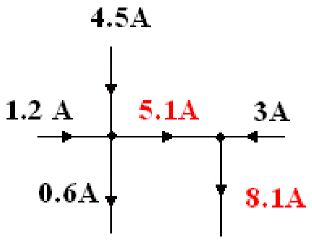
Starting at the first solvable junction we have:

$4.5 + 1.2 - 0.6 + I_1 = 0$ $\qquad$ $I_1 = -5.1$A so it is leaving the junction as shown.



Moving to the next junction we have:

$5.1 + 3 + I_2 = 0$ $\qquad$ $I_2 = -8.1$A so it is leaving the junction as shown.

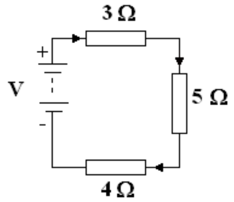


VOLTAGE RULE

This law states that all the potential differences that make up a closed loop must add up to zero. For this to make sense we need a sign convention. In the following the p.d. is negative if the current is flowing clockwise.

WORKED EXAMPLE No. 5

The battery drives 0.5 A around the circuit as shown. What is the voltage of the battery?

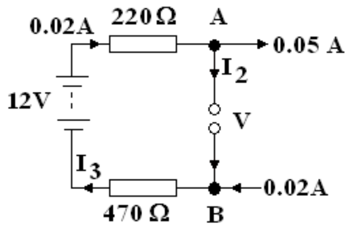


SOLUTION

Noting that the positive terminal of the battery is at the top, the current must be clockwise.
The p.d. across each resistor is - I R
V - (3 x 2) - (5 x 2) - (4 x 2) = 0   V - 6 - 10 - 8 = 0   V = 24V

WORKED EXAMPLE No. 6

Calculate the currents I_2 and I_3 in the circuit below and the voltage V. The currents are not necessarily in the direction indicated.

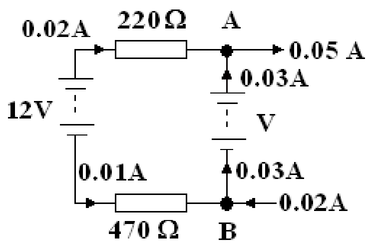


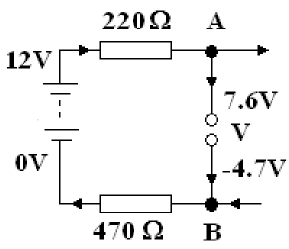
SOLUTION

Applying Kirchoff's law to junction A: $0.02 - 0.05 + I_2 = 0$ $I_2 = 0.03$A (into junction)

Applying Kirchoff's current law to junction B (I_2 is into the junction):
$I_2 + 0.02 + I_3 = 0$ $-0.03 + 0.02 + I_3 = 0$ $I_3 = 0.01$A

Apply Kirchoff's voltage law to the loop.
$1_2 - I_1 \times 220 - V - I_3 \times 470 = 0$
$1_2 - 0.02 \times 220 + V + 0.01 \times 470 = 0$ $12 - 4.4 + V + 4.7 = 0$ $V = -12.3$ V
The voltage and currents at the nodes are shown on the diagram.





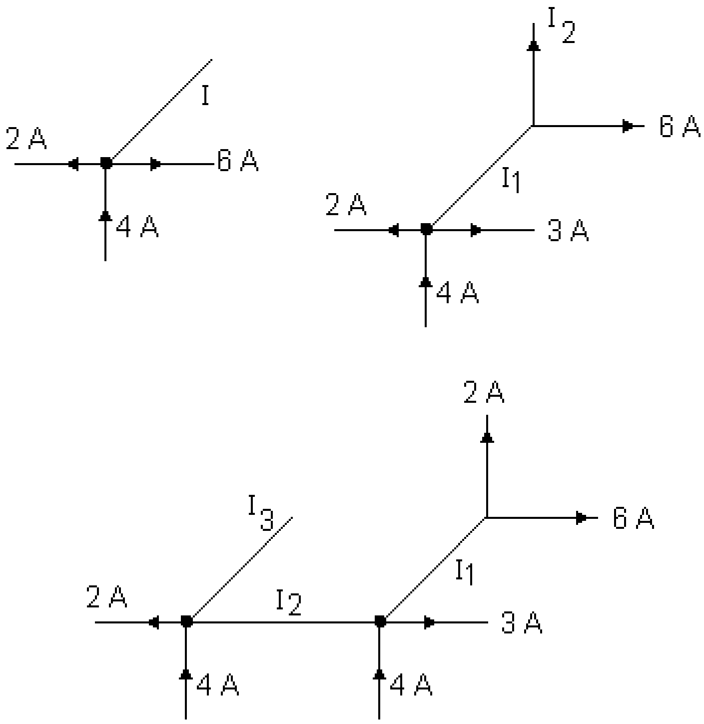
SELF ASSESSMENT EXERCISE No. 5

1. Calculate the resistance if a voltage of 10 V produces a current of 0.2 Amperes. Also calculate the power dissipated. (50 Ω)

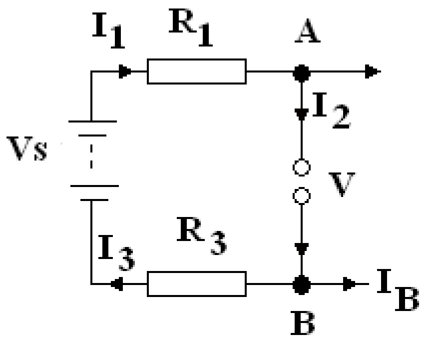
2. Calculate the current which flows in a resistor 5Ω when 240 V is applied to it. Also calculate the power dissipated. (48 A and 11520 W)

3. Calculate the voltage needed to make 20 mA flows in a resistor of 470kΩ . (9400 V)

4. Find the unknown current for each case shown.



5. Given the following values, calculate the voltage V and currents I_2 and I_3 in the circuit below.

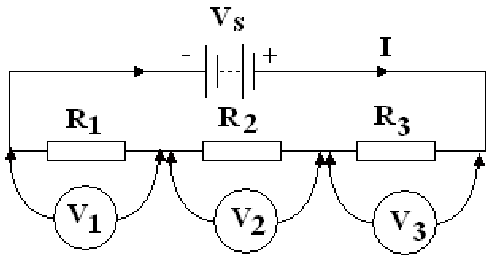


Vs = 10V	$R_1 = 50\Omega$	$R_2 = 70\Omega$
$I_1 = 0.2$ (clockwise)	$I_A = 0.15$ A into the junction	
$I_B = 0.25$A out of junction		

(Answers V = -7V, $I_2 = 0.35$A clockwise, $I_3 = 0.1$A Anticlockwise)

7 RESISTORS IN SERIES –VOLTAGE DIVIDERS

Consider 3 resistors in series as shown.



The same current I flow through each of them. The voltage drop on each is given by Ohms' Law as follows.

$$V_1 = I\,R_1 \qquad V_2 = I\,R_2 \qquad V_3 = I\,R_3$$

In other words the voltage is divided according to the resistors. If the resistors were all equal, the voltage would be divided equally across each. The three voltages must add up to the supply voltage V_s.

$V_s = V_1 + V_2 + V_3$
$V_s = I\,R_1 + I\,R_2 + IR_3$
$V_s = I\,(R_1 + R_2 + R_3)$

If the 3 resistors were replaced by a single total resistor R_T then the supply voltage would be

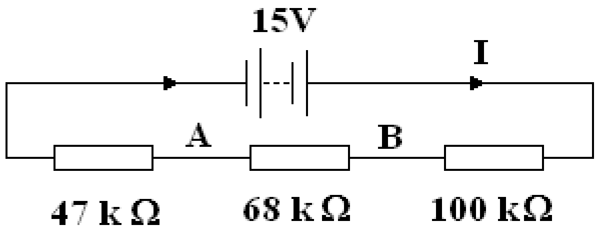
$$V_s = I\,R_T$$

Comparing the two equations it is apparent that $\mathbf{R_T = R_1 + R_2 + R_3}$

Resistors in series may be added to give one equivalent value.

WORKED EXAMPLE No. 7

Calculate the current drawn from the battery and the voltage at A, and B in the circuit below.

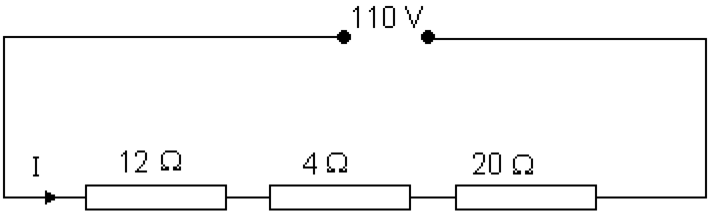


SOLUTION

$R_T = 47 + 68 + 100 = 215$ kΩ
$I = V/\,R_T = 15/215 = 0.0697674$ mA
p.d. across the 47 KΩ resistor is 47 x 0.0697674 = 3.279 V
p.d. across the 68 kΩ resistor is 68 x 0.0697674 = 4.744 V
p.d. across the 100 kΩ resistor is 100 x 0.0697674 = 6.976 V
Check total p.d. = 3.279 +4.744 + 6.976 = 15 V
The voltage at A is 3.279 V
The voltage at B is 3.279 + 4.744 = 8.023 V

SELF ASSESSMENT EXERCISE No. 6

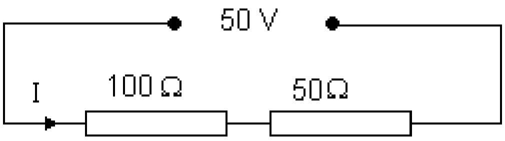
1. Calculate the current flowing in the circuit below and the voltage drop over the middle resistor.



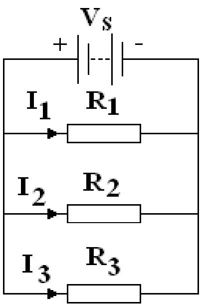
(3.055 A and 12.22 V)

2. Calculate the total resistance of the circuit shown. Determine the current and the voltage drop over each resistor.

(150 W), 0.333 A, 33.3 V and 16.67 V)



8 RESISTORS IN PARALLEL – CURRENT DIVIDERS



Consider 3 resistors in parallel as shown.

The voltage across each is the supply voltage V. The current flowing in each is given by Ohms' Law as

$I_1 = V/R_1$ $\qquad$ $I_2 = V/R_2$ $\qquad$ $I_3 = V/R_3$

In other words the current is divided according to the resistance. If the resistors were all the same, the same current would flow in each. The total current drawn from the supply is

$I = I_1 + I_2 + I_3$

$I = V/R_1 + V/R_2 + V/R_3$

$I = V(1/R_1 + 1/R_2 + 1/R_3)$

If the same current was drawn from the supply by a single resistor R_T the current would be

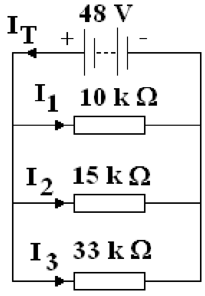
$I = V/R_T$

Comparing the two equations it is apparent that

$1/R_T = 1/R_1 + 1/R_2 + 1/R_3$ $\qquad$ $R_T = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$

WORKED EXAMPLE No. 8

Calculate the total resistance and all the currents in the circuit below.



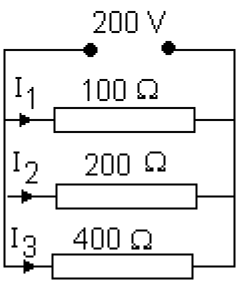
SOLUTION

$$R_T = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}} = \frac{1}{\frac{1}{10}+\frac{1}{15}+\frac{1}{33}} = \frac{1}{0.19696} = 5.077\ \text{k}\Omega$$

I_T = 48/5.077 = 9.455 mA
I_1 = 48/10 = 4.800 mA
I_2 = 48/15 = 3.200 mA
I_3 = 48/33 = 1.455 mA
Check total = 9.455 mA

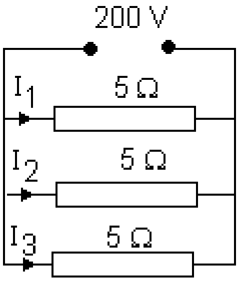
SELF ASSESSMENT EXERCISE No. 7

1. Calculate the total resistance for the circuit shown. Determine the total current drawn from the supply.



2. Calculate the total resistance for the circuit shown. Determine the current in each resistor and the total current drawn from the supply.

(1.66Ω, 40 A 120 A)

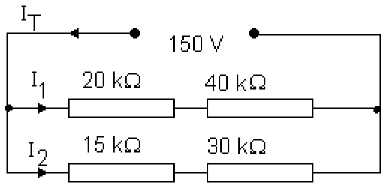


9 RESISTANCE NETWORKS

A network is a combination of parallel and series circuits. In order to find the total resistance, the circuit must be broken down step by step by identifying the series and parallel circuits and replacing them with a single resistor. The following example shows this.

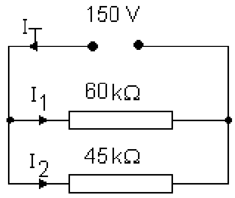
WORKED EXAMPLE No. 9

Find the total resistance for the network shown and calculate the currents I_1 and I_2



SOLUTION

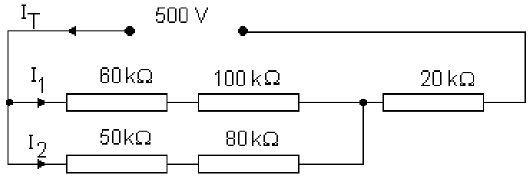
First identify two series circuits and replace them by single resistors.
20 + 40 = 60 15 + 30 = 45



Next solve the parallel circuit. $R_T = 1/\{1/60 + 1/45\} = 25.71$ kΩ.
The total current is $I_T = V/R_T = 150/25710 = 0.00583$ Amps or 5.83 mA.

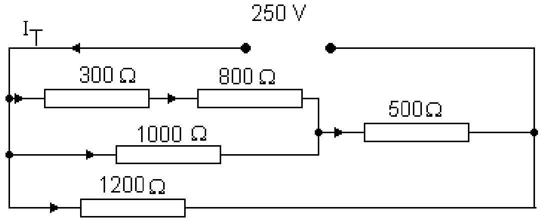
SELF ASSESSMENT EXERCISE No. 8

1. Solve the total resistance and current. Determine the voltage over the 20 K resistor.



(Answers 91.72 Ω, 5.45 mA and 109 V)

2. Solve the total resistance and current. Determine the voltage over the 800Ω resistor.



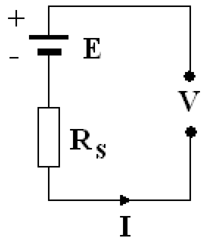
(Answers 552.46 Ω, 0.452 A and 93 V)

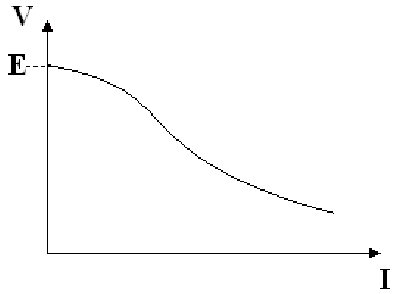
10 D.C. POWER SOURCE - ELECTRO-MOTIVE FORCE

When direct current is supplied to a circuit, it must come from a source. This will be a battery, mains power supply or a generator. The current flowing from the terminals must pass through the internal parts of the source and this will have a resistance called the internal resistance R_s. When a current I flows, there will be a voltage drop inside the source given by I R_s.

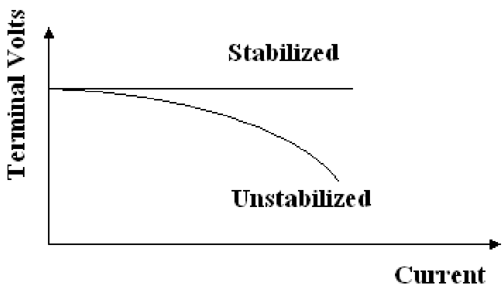
When the current is zero, the terminal voltage will be the maximum possible from the source and this is the Electro-Motive Force (e.m.f). We define the e.m.f. as the ideal voltage of the source. We can measure the e.m.f. by measuring the terminal voltage with a volt meter that draws negligible current.

If the e.m.f. is E then the terminal voltage will be $V = E - I R_s$. If we measure the terminal voltage of a battery for various currents and plot the results we get something like the graph shown. E is the value at zero current. The graph may not be straight and this indicates that the internal resistance is not constant. A good quality battery will have a low internal resistance and is capable of delivering high currents.





This theory applies to any source of electric current such as an electric generator or a mains power supply. The internal resistance is due to partly to the copper wire inside the generator or power supply and other reasons not covered here. A good quality power supply should maintain the voltage at all operating currents and these are called stabilized power supplies.



WORKED EXAMPLE No. 10

A power source has a terminal voltage of 24 V when no current is being drawn. When 8 A of current is used, the terminal voltage falls to 19 V. What is the internal resistance?

SOLUTION

E = 24 V = 19 I = 8 A

$R_s = (24 - 19)/8 = 0.625\ \Omega$

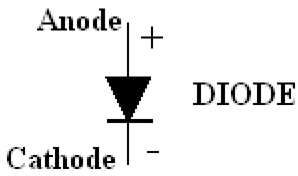
SELF ASSESSMENT EXERCISE No. 9

1. A battery has an internal resistance of 0.15 Ω. When supplying 2 A the terminal volts are 4.8V. What is the E.M.F?

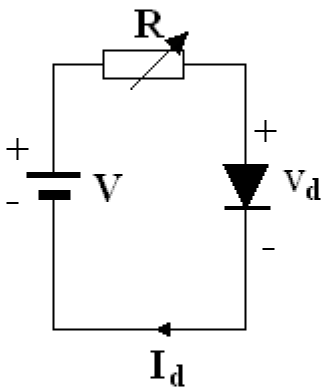
(5.1 V)

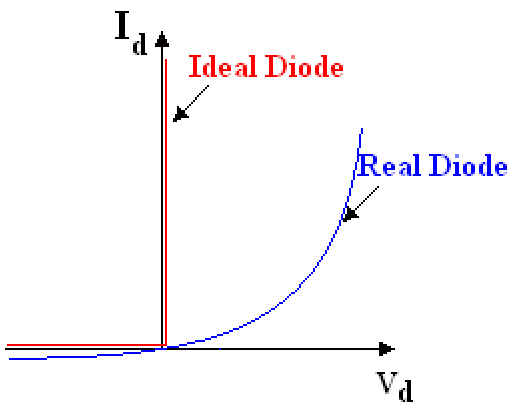
11 DIODES

A diode is an electronic component that ideally only passes current in one in one direction. The symbol is shown. Current flows from the anode to the cathode (forward bias) but not in the reverse direction (reverse bias).



An ideal diode behaves like a one way valve. In reality a small current may flow in reverse bias. In forward bias it has some resistance so there is a small voltage drop over the diode.



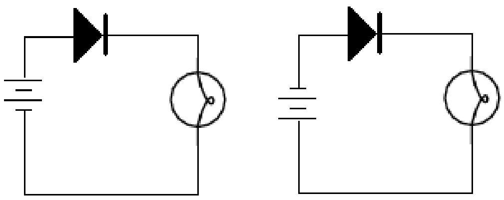


Diodes have many applications such as rectification of alternating electricity.

Here is a great web site to find out all about diodes.
http://www.allaboutcircuits.com/vol_3/chpt_3/1.html

SELF ASSESSMENT EXERCISE No. 9

1. In which of the two circuits will the light be on?



A **B**