Pearson BTEC Levels 4 Higher Nationals in Engineering (RQF)

Unit 19: Electrical and Electronic Principles

Unit Workbook 1

in a series of 4 for this unit

Learning Outcome 1

Fundamental Electrical Quantities

1. Fundamental Electrical Quantities and Concepts

1.1 Charge

Electrical charge is a property of subatomic particles which can cause them to either attract or repel. Like charges repel and opposite charges attract. The electron is deemed to have a negative charge and the proton a positive charge. Not all subatomic particles contain a net charge; the neutron is an example (hence its name).

Electrical charge is given the symbol Q and is measured in Coulombs (C). When examining the electrical charge on an electron or proton it is found that they have the same magnitude of charge, 1.602×10^{-19} C. Since the electron is negatively charged it has a charge of -1.602×10^{-19} C and the proton, being positively charged, has a charge of $+1.602 \times 10^{-19}$ C. It is common to refer to the charge on an electron as '-e' and the charge on a proton as '+e'.

Atoms consist of electrons, protons and neutrons. Usually atoms have an overall charge of zero because they have equal numbers of electrons and protons. However, should an atom lose an electron (perhaps that electron has joined a neighbouring atom) then it will have a net positive charge of +e. You will discover more on this topic when reading workbook 3 for this unit.

1.2 Current

Electrical current in a wire is due to the flow of electrons through the wire. Since electrons are negatively charged they will flow towards a positive destination (perhaps the positive terminal of a battery).

Before electricity and current were properly understood (in the early 1800's) it was wrongly deemed that electrical current flowed from positive to negative. Unfortunately, this convention has stuck around to the present day, and is known as 'conventional current'. You will see conventional current marked on circuit diagrams with an arrow.

To put a figure onto electrical current we must consider how many electrons pass a certain point within 1 second. Put another way, electrical current (I) is given by the number of electrons which have passed by, divided by 1 second…

$$I = \frac{Q}{t}$$

If we now find the reciprocal of the charge on the electron (i.e. 1 over e) we can determine how many electrons need to pass by a point in one second in order to register 1 Amp…

$$1\ Amp = \frac{1}{1.602 \times 10^{19}} \equiv 6.2 \times 10^{18}\ electrons$$

That a lot of electrons; around 6 billion billion electrons per second passing a point within a 1 second timeframe is equivalent to 1 Amp (1 A).

1.3 Electric Field

Since electrons and protons have charge, they produce electric fields. Electric fields are measured in Volts per Metre ($V.m^{-1}$). It is the electric fields emanating from electrons and protons which give rise to the forces of attraction and repulsion between them.

In workbook 2 you will learn that an electric field can also be caused by a varying magnetic field.

1.4 Energy in an Electrical Context

Since the flow of electrons provides a current, and current gives rise to energy, it therefore follows that electrical energy can result from field influences between charges. There is a potential (expectation) that energy will be produced when charges come into close contact.

1.5 Potential and Potential Difference

Electric potential is the amount of work done in moving a unit charge (e) from infinity to a given point in an electric field. A good analogy is the potential for water to flow down from a tap once the tap is opened.

Potential difference is the amount of work done moving a point charge from a point of lower potential to a point of higher potential. There is a potential difference between the positive and negative terminals of a battery, so connecting these with a wire will result in the flow of electrons through the wire (and the battery).

1.6 Resistance

Resistance is the property of materials to block the flow of electrons to some extent. Some atoms have loosely bound outer orbital electrons and can give these up easily when subjected to an electric field (copper, gold for example). Some materials have tightly bound orbital electrons and don't give these up so easily in the presence of an electric field (rubber, ceramic for example).

If a potential difference (voltage) of 1 Volt is applied to a length of material, and, as a result, 1 Amp of current flows, the length of material is said to have a resistance of 1 Ohm (1 Ω).

1.7 Electromotive Force

Electromotive force (e.m.f) is the electrical intensity developed across a device such as a battery, solar cell or generator. It can be considered to be a form of electrical pump which can provide charge (electrons) to circuits, and is measured in Volts.

1.8 Conductors and Insulators

As indicated in section 1.6 above, the nature of a materials' atoms and their orbital outer electrons will dictate the ability of a material to conduct electricity. Conductors have very low resistance, such as silver, iron, copper, gold and mercury, but insulators have very high resistance, such as glass, rubber, Teflon and ceramic.

2. Circuit laws

2.1 Voltage Sources

An *ideal* voltage source (no such thing exists) will deliver a *fixed* voltage across two terminals, regardless of the circuit/load it is delivering the voltage to. In the real world, a voltage source will have a finite internal resistance, so the voltage it delivers will be dependent upon the nature (resistance) of the load. For example, a battery has a finite internal resistance, thus limiting the amount of current it is able to deliver, even if a short (wire) is placed across it (NEVER try this; the battery may explode). Also, very importantly, note; there is no such thing as a short circuit, because even a tiny piece of wire across a battery has some resistance (albeit small).

Of course, batteries are chemical devices, and rely upon human-devised chemical interactions to function. A solar cell can also be considered to be a voltage source – after all, every bit of useful light energy on the earth comes from the Sun. Also, you the reader, are made up of stardust; all of your atoms and energy came from our host star.

The Sun is powerful, yes, but it is not infinitely powerful. If you were to gather all of the energy of the Sun into a battery and place a short circuit across it, you would still not be able to achieve an infinite current (even at absolute zero temperature – for all of you superconductor devotees). Now then, you electrical engineers, listen good, because this point about the finite capacity of an energy (or voltage) source is **infinitely important in your studies of electrical engineering**. There is no such thing as an ideal voltage or current (Norton) source. You heard it here first! However, they are useful concepts when designing circuits, so you must keep them in your designer's box of tricks.

Sometimes you may have heard of voltages being produced by placing rods of different metals inside fruits – a chemical fact. All fruits contain energy, and all this energy was gathered by the fruit as it sunbathed!

2.2 Ohm's Law

I think this was the very first thing I learned in my early studies, and with good reason. It tells us about the relationship between voltage, current and resistance in DC circuits (when considering AC circuits, the topic is somewhat more complicated, but the relationship still holds good once we also consider the frequency involved).

As a student, I was the given the option of learning Ohm's Law via repetition (what an insult), or by fancy triangles (which you may have heard of). I wanted understanding, not poetry, so, after a few decades of getting a feel for Ohm's Law I'd like to present it to you in a nice simple way which you will hopefully never forget…

If you squeeze a lemon (that pressure you exert is analogous to voltage) you get an understanding of the lemon in terms of its softness or hardness (analogous to its resistance). The amount of juice squirting from the lemon (analogous to current) must therefore depend upon how hard you squeeze it and its initial condition (perhaps frozen or ripe). You get more juice by squeezing it harder, but less juice if you are squeezing a much harder lemon with the same force. Therefore, the amount of juice you extract (current, I) is proportional to the squeezing force (voltage, V), but inversely proportional to the hardness of the lemon (resistance, it's a blocker remember).

Enough of the culinary analogy then. Here's Ohm's Law…

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

Understand it, *then* remember it.

2.3 Resistors in Series

Resistors are commonly made of carbon, but can be made of metal, printed, made of polysilicon in integrated circuits, or many other ways. They are still resistors – they block the flow of electrons (see section 1.6). To work out the total resistance of a number of resistors in series we just add their resistance values (simple) – see below…

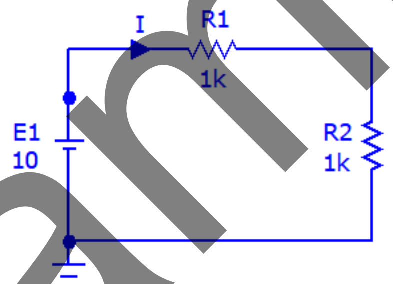


Figure 1: **A simple series resistance circuit**

The total resistance (R_T) seen by the battery in Figure 1 is given by…

$$R_T = R_1 + R_2 = 1k + 1k = 2k \qquad (more\ formally, 2k\Omega)$$

So, whether there are two or twenty-two resistors in series, no matter, just add them all up to find the total equivalent resistance. Figure 1 can then be simplified to a 2k resistor sitting across a 10V battery. From Ohm's Law we may therefore calculate the total current (I) emerging from the battery…

$$I = \frac{E_1}{R_T} = \frac{10}{2000} = 5mA$$

2.4 Resistors in Parallel

The picture is a little more involved when we come to consider resistors in parallel. The parallel arrangement provides 'alternative paths' for the electrons to negotiate. The more alternative paths there are will mean an easier route for the electrons. A good analogy might be to think of multiple hosepipes connected to a single tap: there will be an increased water flow compared to the single hose arrangement.

To evaluate the overall resistance of a parallel arrangement of resistors we need to consider these multiple paths and use the equation…

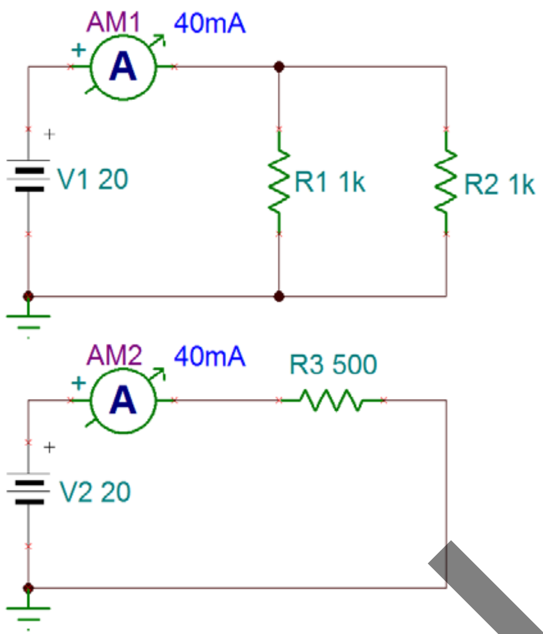
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \quad [S]$$

Notice the units used in the equation. They are Siemens (reciprocal of resistance) which is the unit used for Conductance. This equation must be used for all cases where there are three or more resistors in parallel. When there are only two resistors in parallel then we may take a common denominator, and end up with the product over sum for the overall resistance…

$$R_T = \frac{R_1 R_2}{R_1 + R_2} \quad [\Omega]$$

The first circuit below shows two 1kΩ resistors in parallel, connected to a 20V DC source. Using the product over sum formula for the overall resistance yields…

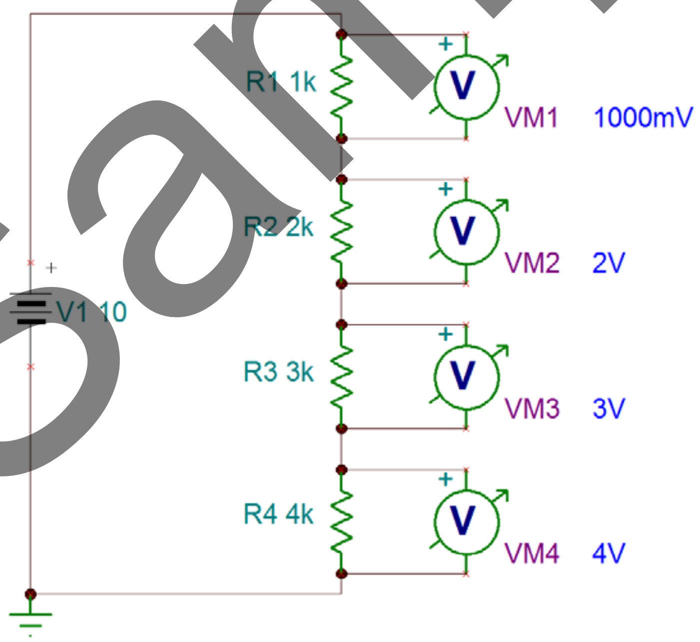
$$R_T = \frac{1000 \times 1000}{1000 + 1000} = \frac{1000000}{2000} = 500\Omega$$



The lower circuit shows that the same current flows using the equivalent resistance of 500Ω.

2.5 The Potential Divider

A voltage (potential) divider 'divides' a supply voltage across series connected resistors according to the proportion of each resistor to the total resistance seen by the voltage source. Here's the picture…

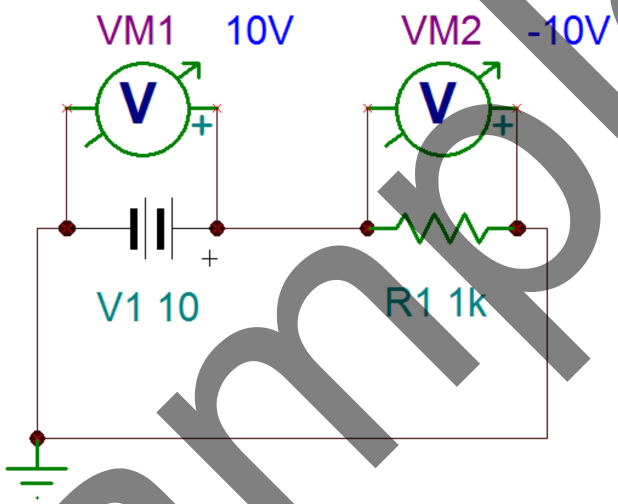


Clearly the total resistance seen by the 10V battery is 10kΩ. This obviously gives a current of 1mA. Since 1mA flows through each resistor it is a simple matter to apply Ohm's Law to each resistor to calculate the voltage across it. For example, R3 is 3kΩ and 1mA flows through it, so it develops a voltage of 1mA x 3000 = 3V, as seen on the simulator.

2.6 Kirchhoff's Laws

Kirchhoff's Voltage Law (KVL)

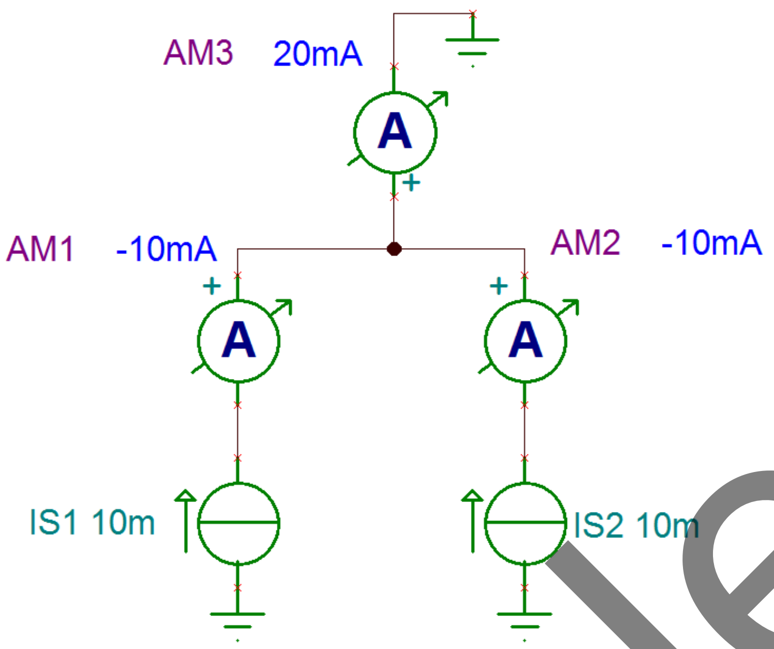
This states that the ***algebraic*** sum of voltages in any closed loop is zero. For a very simple circuit that means that if we place a resistor across a battery then the algebraic sum of voltages in the closed loop will be zero. Let's have a look at this arrangement…



The crucial part in this circuit is that we have connected the voltmeters in such a way that their '+' terminals both face the same way. Adding +10V and -10V gives us zero volts. This proves KVL in this simple case. Perhaps you would like to construct an arrangement with more resistors and prove that KVL still applies?

Kirchhoff's Current Law (KCL)

This states that the ***algebraic*** sum of currents at a junction is zero. Let us again use the TINA simulator to prove this…



Here we have ensured that the Ammeters measure current leaving the junction in each case (notice all the Ammeter '+' terminals are connected to the junction). Adding those three currents gives zero. This proves KCL in a simplistic case. Perhaps you would like to construct a more involved arrangement and prove that KCL still applies?

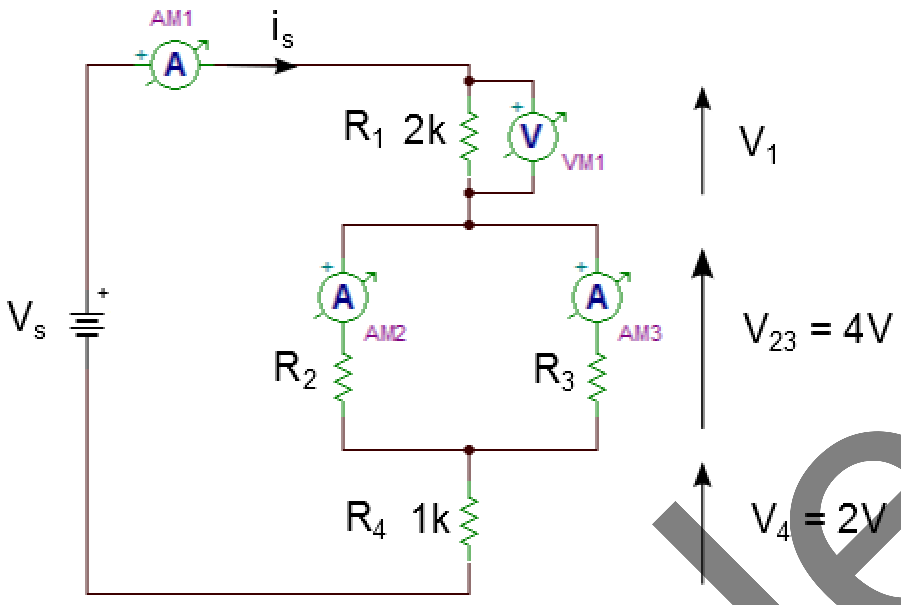
NOTE: *The two symbols at the bottom of the above diagram (marked IS1 and IS2) are constant current generators. They do what their title suggests: provide a constant current.*

Now that KVL and KCL have been reviewed we are in a position to look through a couple or worked examples.

Worked Example 1

For the DC network given below:

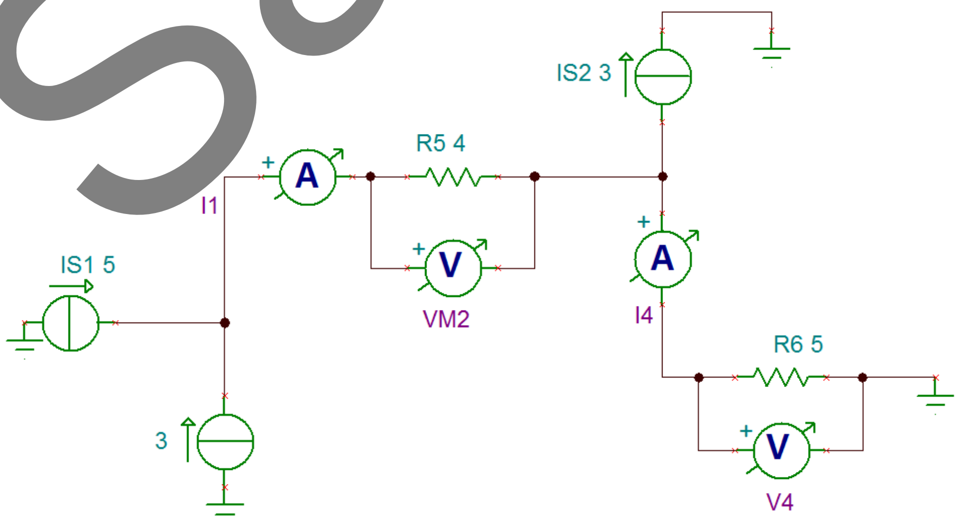
a) **Calculate the value of the supply current (i_s).**
b) **Determine V_1.**
c) **Given that $R_2 = R_3$ calculate the current through each of these two resistors.**
d) **Determine the value of the supply voltage (V_s).**



a) We can see that the value of R_4 is known, as is the voltage across R_4. The current i_s must therefore be $2/1000 = 2mA$.
b) The supply current also flows through R_1 therefore the voltage V_1 must be $2mA \times 2000 = 4V$.
c) Since $R_2 = R_3$ then i_s must split evenly between these two resistors. These currents are therefore 1mA each.
d) Knowledge of KVL tells us that the supply voltage V_s must be equal to the sum of V_1, V_{23} and V_4, which is 10V.

Worked Example 2

Consider the circuit below:



a) Calculate the value of i_1 and hence V_1
b) Calculate the value of i_4 and hence V_4