CHAPTER 1

Electrical and electronic principles

1.1 Safe working practices

1.1.1 Introduction

Safe working practices in relation to electrical and electronic systems are essential, for your safety as well as that of others. You only have to follow two rules to be safe.

- Use your common sense – don't fool about.
- If in doubt – seek help.

The following section lists some particular risks when working with electricity or electrical systems, together with suggestions for reducing them. This is known as risk assessment.

Safety first

The key to safe working: Common sense.

1.1.2 Risk assessment and reduction

Table 1.1 lists some identified risks involved with working on vehicles, in particular the electrical and electronic systems. The table is by no means exhaustive but serves as a good guide.

1.2 Basic electrical principles

1.2.1 Introduction

To understand electricity properly we must start by finding out what it really is. This means we must think very small (Figure 1.1 shows a representation of an atom). The molecule is the smallest part of matter that can be recognized as that particular matter. Sub-division of the molecule results in atoms, which are the smallest part of matter. An element is a substance that comprises atoms of one kind only.

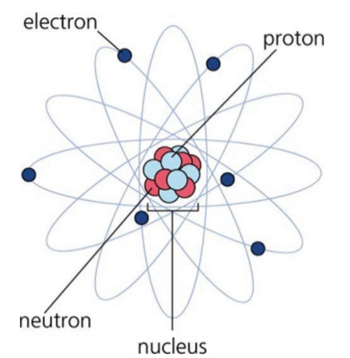

Figure 1.1 The atom

Table 1.1 Risks and risk reduction

Identified risk	Reducing the risk
Electric shock	Ignition HT is the most likely place to suffer a shock, up to 40 000 volts is quite normal. Use insulated tools if it is necessary to work on HT circuits with the engine running. Note that high voltages are also present on circuits containing windings due to back emf as they are switched off, a few hundred volts is common. Mains supplied power tools and their leads should be in good condition and using an earth leakage trip is highly recommended. Only work on HEV and EVs if training in the high voltage systems.
Battery acid	Sulphuric acid is corrosive so always use good PPE. In this case, overalls and if necessary rubber gloves. A rubber apron is ideal, as are goggles if working with batteries a lot.
Raising or lifting vehicles	Apply brakes and/or chock the wheels and when raising a vehicle on a jack or drive on lift. Only jack under substantial chassis and suspension structures. Use axle stands in case the jack fails.
Running engines	Do not wear loose clothing, good overalls are ideal. Keep the keys in your possession when working on an engine to prevent others starting it. Take extra care if working near running drive belts.
Exhaust gases	Suitable extraction must be used if the engine is running indoors. Remember it is not just the CO that might make you ill or even kill you, other exhaust components could cause asthma or even cancer.
Moving loads	Only lift what is comfortable for you; ask for help if necessary and/or use lifting equipment. As a general guide, do not lift on your own if it feels too heavy!
Short circuits	Use a jump lead with an in-line fuse to prevent damage due to a short when testing. Disconnect the battery (earth lead off first and back on last) if any danger of a short exists. A very high current can flow from a vehicle battery; it will burn you as well as the vehicle.
Fire	Do not smoke when working on a vehicle. Fuel leaks must be attended to immediately. Remember the triangle of fire – (Heat/Fuel/Oxygen) – don't let the three sides come together.
Skin problems	Use a good barrier cream and/or latex gloves. Wash skin and clothes regularly.

The atom consists of a central nucleus made up of protons and neutrons. Around this nucleus orbit electrons, like planets around the sun. The neutron is a very small part of the nucleus. It has equal positive and negative charges and is therefore neutral and has no polarity. The proton is another small part of the nucleus, it is positively charged. The neutron is neutral and the proton is positively charged, which means that the nucleus of the atom is positively charged. The electron is an even smaller part of the atom, and is negatively charged. It orbits the nucleus and is held in orbit by the attraction of the positively charged proton. All electrons are similar no matter what type of atom they come from.

When atoms are in a balanced state, the number of electrons orbiting the nucleus equals the number of protons. The atoms of some materials have electrons that are easily detached from the parent atom and can therefore join an adjacent atom. In so doing these atoms move an electron from the parent atom to another atom (like polarities repel) and so on through material. This is a random movement and the electrons involved are called free electrons.

Materials are called conductors if the electrons can move easily. In some materials it is extremely difficult to move electrons from their parent atoms. These materials are called insulators.

1.2.2 Electron flow and conventional flow

If an electrical pressure (electromotive force or voltage) is applied to a conductor, a directional movement of electrons will take place (for example,

Figure 1.2 Electronic components have made technology such as the 200+ km/h Tesla Roadster possible (Source: Tesla Motors)

when connecting a battery to a wire). This is because the electrons are attracted to the positive side and repelled from the negative side.

Certain conditions are necessary to cause an electron flow:

- A pressure source, e.g. from a battery or generator.
- A complete conducting path in which the electrons can move (e.g. wires).

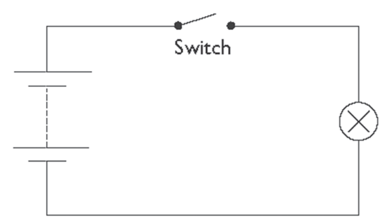

Figure 1.3 A simple electrical circuit

An electron flow is termed an electric current. Figure 1.3 shows a simple electric circuit where the battery positive terminal is connected, through a switch and lamp, to the battery negative terminal. With the switch open the chemical energy of the battery will remove electrons from the positive terminal to the negative terminal via the battery. This leaves the positive terminal with fewer electrons and the negative terminal with a surplus of electrons. An electrical pressure therefore exists between the battery terminals.

With the switch closed, the surplus electrons at the negative terminal will flow through the lamp back to the electron-deficient positive terminal. The lamp will light and the chemical energy of the battery will keep the electrons moving in this circuit from negative to positive. This movement from negative to positive is called the electron flow and will continue whilst the battery supplies the pressure – in other words, whilst it remains charged.

- Electron flow is from negative to positive.

It was once thought, however, that current flowed from positive to negative and this convention is still followed for most practical purposes. Therefore, although this current flow is not correct, the most important point is that we all follow the same convention.

- Conventional current flow is said to be from positive to negative.

Key fact

Conventional current flow is said to be from positive to negative.

1.2.3 Effects of current flow

When a current flows in a circuit, it can produce only three effects:

- Heat
- Magnetism
- Chemical.

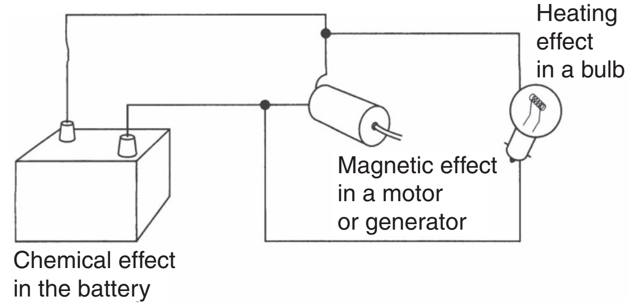

Figure 1.4 A bulb, motor and battery – heat, magnetic and chemical effects

Key fact

The three electrical effects are reversible.

The heating effect is the basis of electrical components such as lights and heater plugs. The magnetic effect is the basis of relays and motors and generators. The chemical effect is the basis for electroplating and battery charging.

In the circuit shown in Figure 1.4 the chemical energy of the battery is first converted to electrical energy, and then into heat energy in the lamp filament.

The three electrical effects are reversible. Heat applied to a thermocouple will cause a small electromotive force and therefore a small current to flow. Practical use of this is mainly in instruments. A coil of wire rotated in the field of a magnet will produce an electromotive force and can cause current to flow. This is the basis of a generator. Chemical action, such as in a battery, produces an electromotive force, which can cause current to flow.

1.2.4 Fundamental quantities

In Figure 1.5, the number of electrons through the lamp every second is described as the rate of flow. The cause of the electron flow is the electrical pressure. The lamp produces an opposition to the rate of flow set up by the electrical pressure. Power is the rate of doing work, or changing energy from one form to another. These quantities, as well as several others, are given names as shown in Table 1.2 on page 28.

If the voltage pressure applied to the circuit was increased but the lamp resistance stayed the same, then the current would also increase. If the voltage was maintained constant but the lamp was changed for one with a higher resistance the current would decrease. Ohm's law describes this relationship.

Ohm's law states that in a closed circuit 'current is proportional to the voltage and inversely proportional to the resistance'. When 1 volt causes 1 ampere to flow the power used (P) is 1 watt.

Using symbols this means:

Voltage = Current × Resistance

$(V = IR)$ or $(R = V/I)$ or $(I = V/R)$

Power = Voltage × Current

$(P = VI)$ or $(I = P/V)$ or $(V = P/I)$

1.2.5 Describing electrical circuits

Three descriptive terms are useful when discussing electrical circuits.

- **Open circuit.** This means the circuit is broken therefore no current can flow.
- **Short circuit.** This means that a fault has caused a wire to touch another conductor and the current uses this as an easier way to complete the circuit.

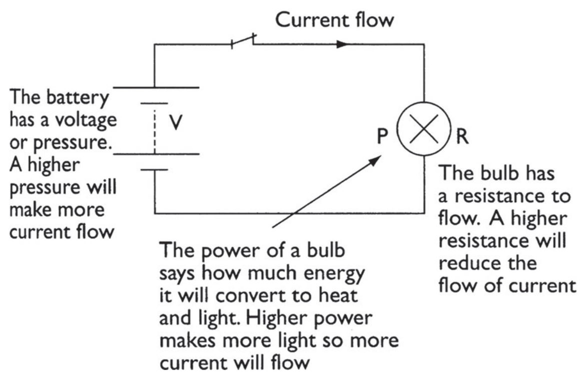

Figure 1.5 An electrical circuit demonstrating links between voltage, current, resistance and power

- **High resistance.** This means a part of the circuit has developed a high resistance (such as a dirty connection), which will reduce the amount of current that can flow.

1.2.6 Conductors, insulators and semiconductors

All metals are conductors. Silver, copper and aluminium are among the best and are frequently used. Liquids that will conduct an electric current are called electrolytes. Insulators are generally non-metallic and include rubber, porcelain, glass, plastics, cotton, silk, wax paper and some liquids. Some materials can act as either insulators or conductors depending on conditions. These are called semiconductors and are used to make transistors and diodes.

1.2.7 Factors affecting the resistance of a conductor

In an insulator, a large voltage applied will produce a very small electron movement. In a conductor, a small voltage applied will produce a large electron flow or current. The amount of resistance offered by the conductor is determined by a number of factors (Figure 1.6).

- Length – the greater the length of a conductor the greater is the resistance.
- Cross-sectional area (CSA) – the larger the cross-sectional area the smaller the resistance.
- The material from which the conductor is made – the resistance offered by a conductor will vary according to the material from which it is made. This is known as the resistivity or specific resistance of the material.
- Temperature – most metals increase in resistance as temperature increases.

1.2.8 Resistors and circuit networks

Good conductors are used to carry the current with minimum voltage loss due to their low resistance. Resistors are used to control the current flow in a circuit or to set voltage levels. They are made of materials that have a high resistance. Resistors intended to carry low currents are often made of carbon. Resistors for high currents are usually wire wound.

Key fact

Resistors are used to control the current flow in a circuit or to set voltage levels.

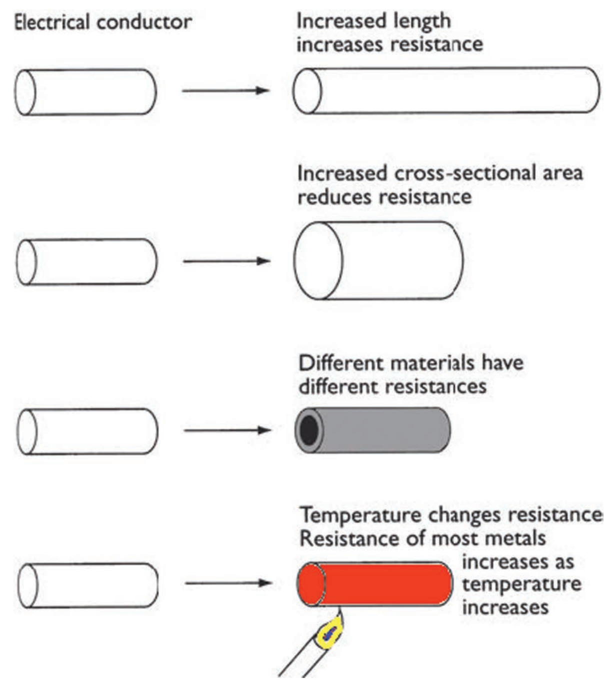

Figure 1.6 Factors affecting electrical resistance

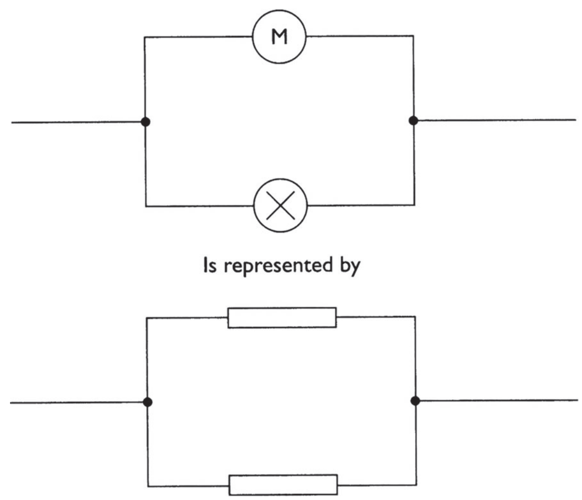

Figure 1.7 An equivalent circuit

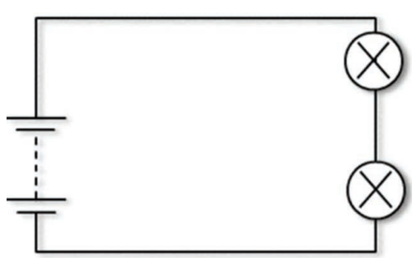

Figure 1.8 Series circuit

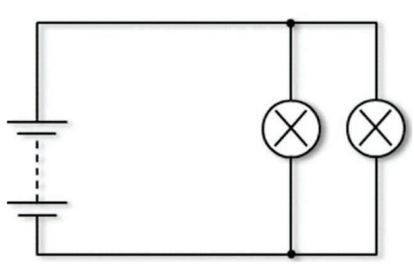

Figure 1.9 Parallel circuit

Resistors are often shown as part of basic electrical circuits to explain the principles involved. The circuits shown as Figure 1.7 are equivalent. In other words, the circuit just showing resistors is used to represent the other circuit.

When resistors are connected so that there is only one path (Figure 1.8), for the same current to flow through each bulb they are connected in series and the following rules apply.

- Current is the same in all parts of the circuit.
- The applied voltage equals the sum of the volt drops around the circuit.
- Total resistance of the circuit (RT) equals the sum of the individual resistance values ($R_1 + R_2$ etc.).

When resistors or bulbs are connected such that they provide more than one path (Figure 1.9 shows two paths) for the current to flow through and have the same voltage across each component they are connected in parallel and the following rules apply.

- The voltage across all components of a parallel circuit is the same.
- The total current equals the sum of the current flowing in each branch.
- The current splits up depending on each component resistance.
- The total resistance of the circuit (RT) can be calculated by

$1/R_T = 1/R_1 + 1/R_2$ or
$R_T = (R_1 \times R_2)/(R_1 + R_2)$

1.2.9 Magnetism and electromagnetism

Magnetism can be created by a permanent magnet or by an electromagnet (it is one of the three effects of electricity remember). The space around a magnet in which the magnetic effect can be detected is called the magnetic field. The shape of magnetic fields in diagrams is represented by flux lines or lines of force.

Some rules about magnetism:

- Unlike poles attract. Like poles repel.
- Lines of force in the same direction repel sideways, in the opposite direction they attract.
- Current flowing in a conductor will set up a magnetic field around the conductor. The strength of the magnetic field is determined by how much current is flowing.
- If a conductor is wound into a coil or solenoid, the resulting magnetism is the same as a permanent bar magnet.

Electromagnets are used in motors, relays and fuel injectors, to name just a few applications. Force on a current-carrying conductor in a magnetic field is caused because of two magnetic fields interacting. This is the basic principle of how a motor works. Figure 1.10 shows a representation of these magnetic fields.

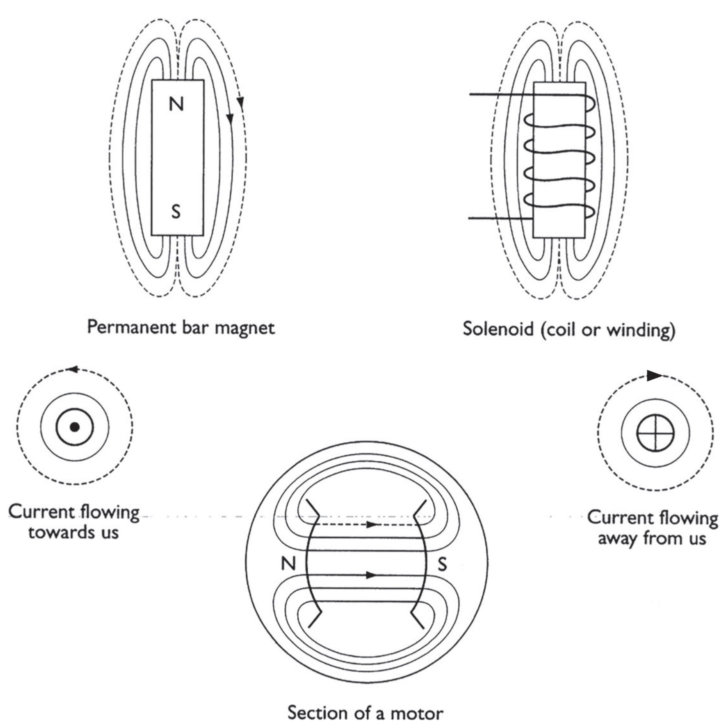

Figure 1.10 Magnetic fields

1.2.10 Electromagnetic induction

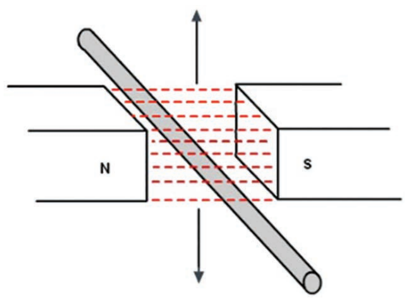

Figure 1.11 Induction

Basic laws:

- When a conductor cuts or is cut by magnetism, a voltage is induced in the conductor.
- The direction of the induced voltage depends upon the direction of the magnetic field and the direction in which the field moves relative to the conductor.
- The voltage level is proportional to the rate at which the conductor cuts or is cut by the magnetism.

This effect of induction, meaning that voltage is made in the wire, is the basic principle of how generators such as the alternator on a car work. A generator is a machine that converts mechanical energy into electrical energy. Figure 1.11 shows a wire moving in a magnetic field.

Definition

A generator is a machine that converts mechanical energy into electrical energy.

1.2.11 Mutual induction

If two coils (known as the primary and secondary) are wound on to the same iron core then any change in magnetism of one coil will induce a voltage in to the other. This happens when a current to the primary coil is switched on and off. If the number of turns of wire on the secondary coil is more than the primary, a higher voltage can be produced. If the number of turns of wire on the secondary coil is less than the primary a lower voltage is obtained. This is called 'transformer action' and is the principle of the ignition coil. Figure 1.12 shows the principle of mutual induction. The value of this 'mutually induced' voltage depends on:

- The primary current.
- The turns ratio between primary and secondary coils.
- The speed at which the magnetism changes.

Key fact

Transformer action is the principle of the ignition coil.

1.2.12 Definitions and laws

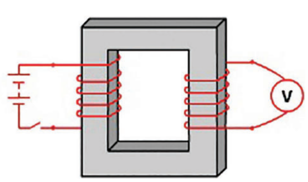

Figure 1.12 Mutual induction

Ohm's law

- For most conductors, the current which will flow through them is directly proportional to the voltage applied to them.

The ratio of voltage to current is referred to as resistance. If this ratio remains constant over a wide range of voltages, the material is said to be 'ohmic'.

$$V = I/R$$

where: I = Current in amps, V = Voltage in volts, R = Resistance in ohms.

Georg Simon Ohm was a German physicist, well known for his work on electrical currents.

Lenz's law

- The emf induced in an electric circuit always acts in a direction so that the current it creates around the circuit will oppose the change in magnetic flux which caused it.

Lenz's law gives the direction of the induced emf resulting from electromagnetic induction. The 'opposing' emf is often described as a 'back emf'.

The law is named after the Estonian physicist Heinrich Lenz.

Kirchhoff's laws

Kirchhoff's 1st law:

- The current flowing into a junction in a circuit must equal the current flowing out of the junction.

This law is a direct result of the conservation of charge; no charge can be lost in the junction, so any charge that flows in must also flow out.

Kirchhoff's 2nd law:

- For any closed loop path around a circuit the sum of the voltage gains and drops always equals zero.

This is effectively the same as the series circuit statement that the sum of all the voltage drops will always equal the supply voltage.

Gustav Robert Kirchhoff was a German physicist; he also discovered caesium and rubidium.

Faraday's law

- Any change in the magnetic field around a coil of wire will cause an emf (voltage) to be induced in the coil.

It is important to note here that no matter how the change is produced, the voltage will be generated. In other words, the change could be produced by changing the magnetic field strength, moving the magnetic field towards or away from the coil, moving the coil in or out of the magnetic field, rotating the coil relative to the magnetic field and so on!

Michael Faraday was a British physicist and chemist, well known for his discoveries of electromagnetic induction and of the laws of electrolysis.

Fleming's rules

- In an electrical machine, the First Finger lines up with the magnetic Field, the seCond finger lines up with the Current and the thuMb lines up with the Motion.

Fleming's rules relate to the direction of the magnetic field, motion and current in electrical machines. The left hand is used for motors, and the right hand for generators (remember gener-righters).

The English physicist John Fleming devised these rules.

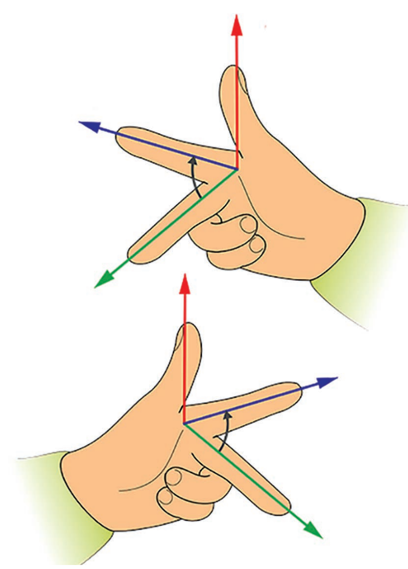

Figure 1.13 Fleming's rules

Ampère's law

- For any closed loop path, the sum of the length elements times the magnetic field in the direction of the elements is equal to the permeability times the electric current enclosed in the loop.

In other words, the magnetic field around an electric current is proportional to the electric current which creates it and the electric field is proportional to the charge which creates it.

André Marie Ampère was a French scientist, known for his significant contributions to the study of electrodynamics.

Summary

It was tempting to conclude this section by stating some of Murphy's laws, for example:

- If anything can go wrong, it will go wrong …
- You will always find something in the last place you look …

- In a traffic jam, the lane on the motorway that you are not in always goes faster …

… but I decided against it!

Table 1.2 Quantities, symbols and units

Name	Definition	Symbol	Common formula	Unit name	Abbreviation
Electrical charge	One coulomb is the quantity of electricity conveyed by a current of one ampere in one second.	Q	$Q = It$	coulomb	C
Electrical flow or current	The number of electrons past a fixed point in one second	I	$I = V/R$	ampere	A
Electrical pressure	A pressure of 1 volt applied to a circuit will produce a current flow of 1 amp if the circuit resistance is 1 ohm.	V	$V = IR$	volt	V
Electrical resistance	This is the opposition to current flow in a material or circuit when a voltage is applied across it.	R	$R = V/I$	ohm	Ω
Electrical conductance	Ability of a material to carry an electrical current. One siemens equals one ampere per volt. It was formerly called the mho or reciprocal ohm.	G	$G = 1/R$	siemens	S
Current density	The current per unit area. This is useful for calculating the required conductor cross sectional areas	J	$J = I/A$ (A = area)		$A\,m^{-2}$
Resistivity	A measure of the ability of a material to resist the flow of an electric current. It is numerically equal to the resistance of a sample of unit length and unit cross-sectional area, and its unit is the ohmmeter. A good conductor has a low resistivity ($1.7 \times 10^{-8}\,\Omega\,m$ copper); an insulator has a high resistivity ($10^{15}\,\Omega\,m$ polyethane)	ρ (*rho*)	$R = \rho L/A$ (L = length A = area)	ohm meter	Ω m
Conductivity	The reciprocal of resistivity	σ (*sigma*)	$\sigma = 1/\rho$	ohm^{-1} $meter^{-1}$	$\Omega^{-1}\,m^{-1}$
Electrical power	When a voltage of 1 volt causes a current of 1 amp to flow the power developed is 1 watt.	P	$P = IV$ $P = I^2R$ $P = V^2/R$	watt	W
Capacitance	Property of a capacitor that determines how much charge can be stored in it for a given potential difference between its terminals	C	$C = Q/V$ $C = \varepsilon A/d$ (A = plate area, d = distance between, ε = permittivity of dielectric)	farad	F
Inductance	Where a changing current in a circuit builds up a magnetic field which induces an electromotive force either in the same circuit and opposing the current (self-inductance) or in another circuit (mutual inductance)	L	$i = \frac{V}{R}\left(1 - e^{-Rt/L}\right)$ (i = instantaneous current, R = resistance, L = inductance, t = time, e = base of natural logs)	henry	H

(Continued)

Table 1.2 *(Continued)*

Name	Definition	Symbol	Common formula	Unit name	Abbreviation
Magnetic field strength or intensity	Magnetic field strength is one of two ways that the intensity of a magnetic field can be expressed. A distinction is made between magnetic field strength H and magnetic flux density B.	*H*	$H = B/\mu_0$ (μ_0 being the magnetic permeability of space)	amperes per metre	A/m (An older unit for magnetic field strength is the oersted: 1 A/m = 0.01257 oersted)
Magnetic flux	A measure of the strength of a magnetic field over a given area.	Φ (*phi*)	$\Phi = \mu HA$ (μ = magnetic permeability, *H* = magnetic field intensity, A = area)	weber	Wb
Magnetic flux density	The density of magnetic flux, one tesla is equal to one weber per square metre. Also measured in Newton-metres per ampere (Nm/A)	*B*	$B = H/A$ $B = H \times \mu$ (μ = magnetic permeability of the substance, *A* = area)	tesla	T

1.3 Electronic components and circuits

1.3.1 Introduction

This section, describing the principles and applications of various electronic circuits, is not intended to explain their detailed operation. The intention is to describe briefly how the circuits work and, more importantly, how and where they may be utilized in vehicle applications.

The circuits described are examples of those used and many pure electronics books are available for further details. Overall, an understanding of basic electronic principles will help to show how electronic control units work, ranging from a simple interior light delay unit, to the most complicated engine management system.

1.3.2 Components

The main devices described here are often known as discrete components. Figure 1.14 shows the symbols used for constructing the circuits shown later in this section. A simple and brief description follows for many of the components shown.

Resistors are probably the most widely used component in electronic circuits. Two factors must be considered when choosing a suitable resistor, namely the ohms value and the power rating. Resistors are used to limit current flow and provide fixed voltage drops. Most resistors used in electronic circuits are made from small carbon rods, and the size of the rod determines the resistance. Carbon resistors have a negative temperature coefficient (NTC) and this must be considered for some applications. Thin film resistors have more stable temperature properties and are constructed by depositing a layer of carbon onto an insulated former such as glass. The resistance value can be manufactured very accurately by spiral grooves cut into the carbon film.

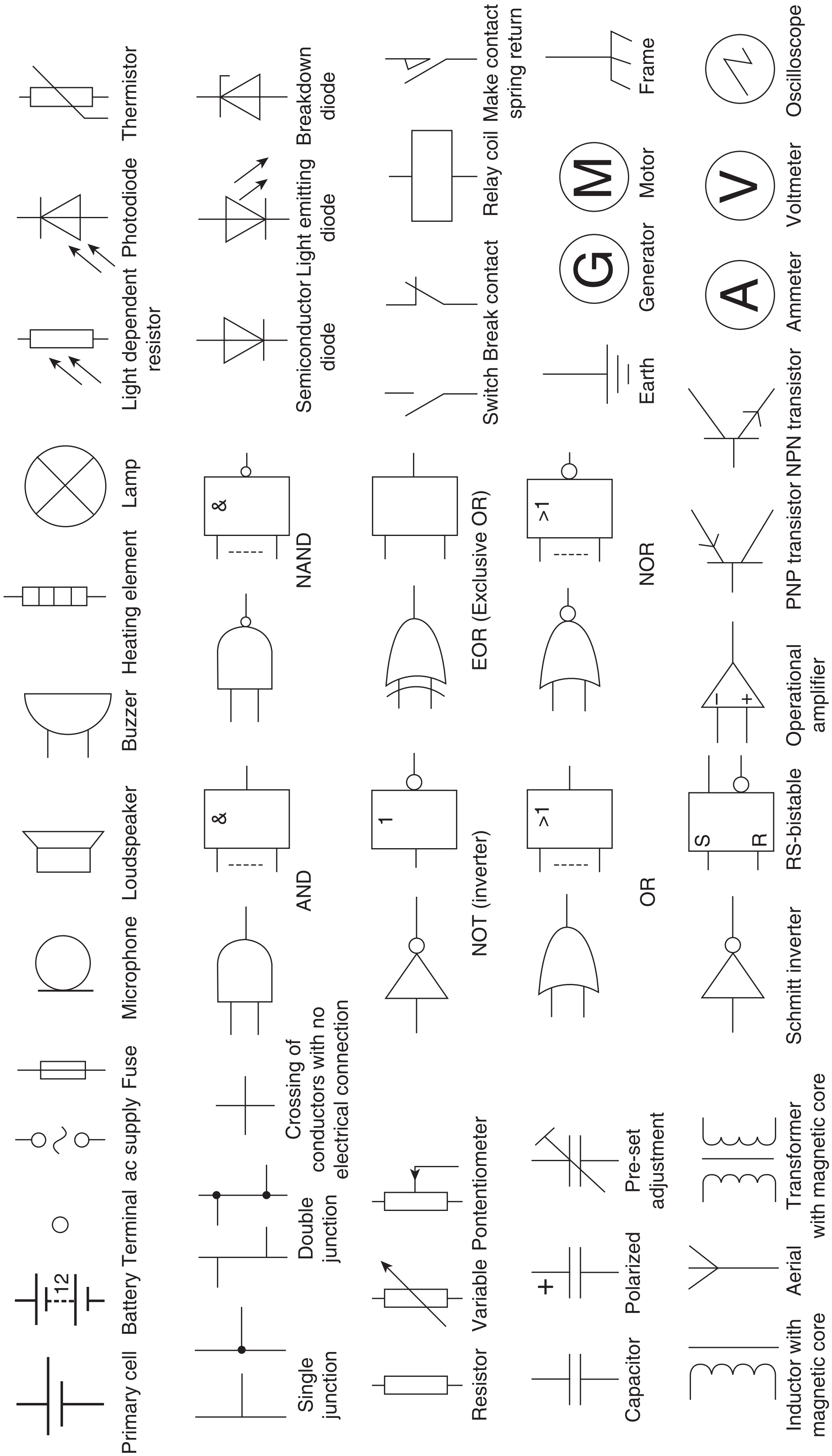

Figure 1.14 Circuit symbols

For higher power applications, resistors are usually wire wound. This can, however, introduce inductance into a circuit. Variable forms of most resistors are available in either linear or logarithmic forms. The resistance of a circuit is its opposition to current flow.

A capacitor is a device for storing an electric charge. In its simple form it consists of two plates separated by an insulating material. One plate can have excess electrons compared to the other. On vehicles, its main uses are for reducing arcing across contacts and for radio interference suppression circuits as well as in electronic control units. Capacitors are described as two plates separated by a dielectric. The area of the plates A, the distance between them d, and the permittivity (ε), of the dielectric, determine the value of capacitance. This is modelled by the equation:

$$C = \varepsilon A / d$$

Metal foil sheets insulated by a type of paper are often used to construct capacitors. The sheets are rolled up together inside a tin can. To achieve higher values of capacitance it is necessary to reduce the distance between the plates in order to keep the overall size of the device manageable. This is achieved by immersing one plate in an electrolyte to deposit a layer of oxide typically 104 mm thick, thus ensuring a higher capacitance value. The problem, however, is that this now makes the device polarity conscious and only able to withstand low voltages. Variable capacitors are available that are varied by changing either of the variables given in the previous equation. The unit of capacitance is the farad (F). A circuit has a capacitance of one farad (1 F) when the charge stored is one coulomb and the potential difference is 1 V. Figure 1.15 shows a capacitor charged up from a battery.

Diodes are often described as one-way valves and, for most applications, this is an acceptable description. A diode is a simple PN junction allowing electron flow from the N-type material (negatively biased) to the P-type material (positively biased). The materials are usually constructed from doped silicon. Diodes are not perfect devices and a voltage of about 0.6 V is required

Definition

Negative temperature coefficient (NTC): As temperature increases, resistance decreases.

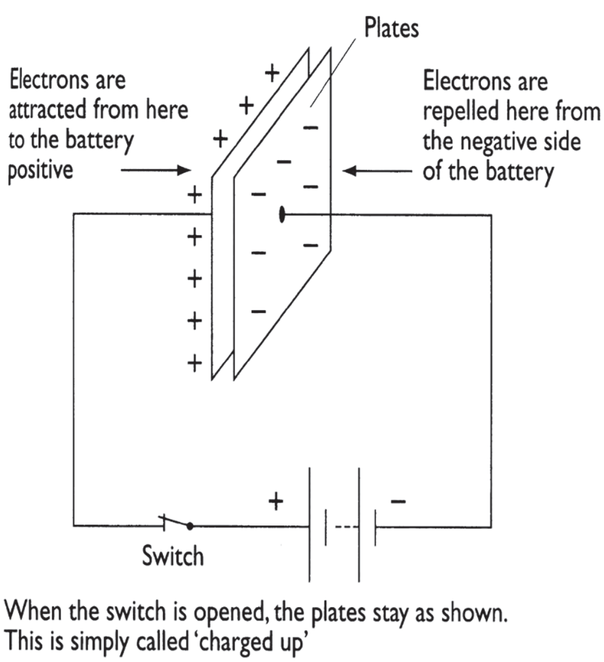

Figure 1.15 A capacitor charged up

to switch the diode on in its forward biased direction. Zener diodes are very similar in operation, with the exception that they are designed to breakdown and conduct in the reverse direction at a pre-determined voltage. They can be thought of as a type of pressure relief valve.

Transistors are the devices that have allowed the development of today's complex and small electronic systems. They replaced the thermal-type valves. The transistor is used as either a solid-state switch or as an amplifier. Transistors are constructed from the same P- and N-type semiconductor materials as the diodes, and can be either made in NPN or PNP format. The three terminals are known as the base, collector and emitter. When the base is supplied with the correct bias the circuit between the collector and emitter will conduct. The base current can be of the order of 200 times less than the emitter current. The ratio of the current flowing through the base compared with the current through the emitter (I_e/I_b), is an indication of the amplification factor of the device and is often given the symbol.

Another type of transistor is the FET or field effect transistor. This device has higher input impedance than the bipolar type described above. FETs are constructed in their basic form as n-channel or p-channel devices. The three terminals are known as the gate, source and drain. The voltage on the gate terminal controls the conductance of the circuit between the drain and the source.

A further and important development in transistor technology is the insulate gate bipolar transistor (IGBT). The insulated gate bipolar transistor (Figure 1.16) is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

Inductors are most often used as part of an oscillator or amplifier circuit. In these applications, it is essential for the inductor to be stable and to be of reasonable size. The basic construction of an inductor is a coil of wire wound on a former. It is the magnetic effect of the changes in current flow that gives this device the properties of inductance. Inductance is a difficult property to control, particularly as the inductance value increases due to magnetic coupling with other devices. Enclosing the coil in a can will reduce this, but eddy currents are then induced in the can and this affects the overall inductance value. Iron cores are used to increase the inductance value as this changes the permeability of the core. However, this also allows for adjustable devices by moving the position of the core. This only allows the value to change by a few per cent but is useful for tuning a circuit. Inductors, particularly

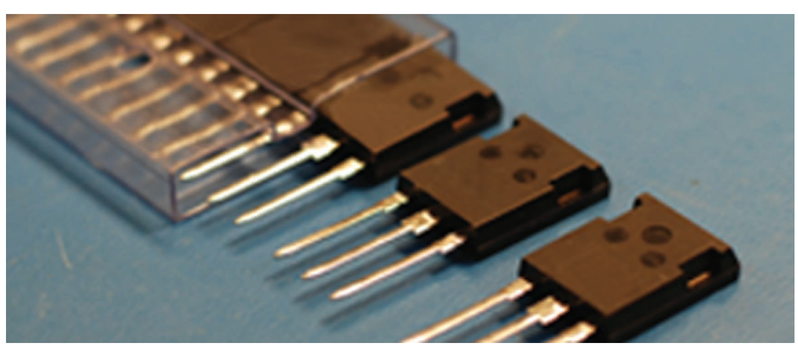

Figure 1.16 IGBT packages (Source: Telsa Motors)

of higher values, are often known as chokes and may be used in DC circuits to smooth the voltage. The value of inductance is the henry (H). A circuit has an inductance of one henry (1 H) when a current, which is changing at one ampere per second, induces an electromotive force of one volt in it.

1.3.3 Integrated circuits

Integrated circuits (ICs) are constructed on a single slice of silicon often known as a substrate. In an IC, Some of the components mentioned previously can be combined to carry out various tasks such as switching, amplifying and logic functions. In fact, the components required for these circuits can be made directly on the slice of silicon. The great advantage of this is not just the size of the ICs but the speed at which they can be made to work due to the short distances between components. Switching speeds in excess of 1 MHz is typical.

There are four main stages in the construction of an IC. The first of these is oxidization by exposing the silicon slice to an oxygen stream at a high temperature. The oxide formed is an excellent insulator. The next process is photo-etching where part of the oxide is removed. The silicon slice is covered in a material called a photoresist which, when exposed to light, becomes hard. It is now possible to imprint the oxidized silicon slice, which is covered with photoresist, by a pattern from a photographic transparency. The slice can now be washed in acid to etch back to the silicon those areas that were not protected by being exposed to light. The next stage is diffusion, where the slice is heated in an atmosphere of an impurity such as boron or phosphorus, which causes the exposed areas to become p- or n-type silicon. The final stage is epitaxy, which is the name given to crystal growth. New layers of silicon can be grown and doped to become n- or p-type as before. It is possible to form resistors in a similar way and small values of capacitance can be achieved. It is not possible to form any useful inductance on a chip. Figure 1.18 shows a representation of the 'packages' that integrated circuits are supplied in for use in electronic circuits.

The range and types of integrated circuits now available are so extensive that a chip is available for almost any application. The integration level of chips has now reached, and in many cases is exceeding, that of VLSI (very large scale

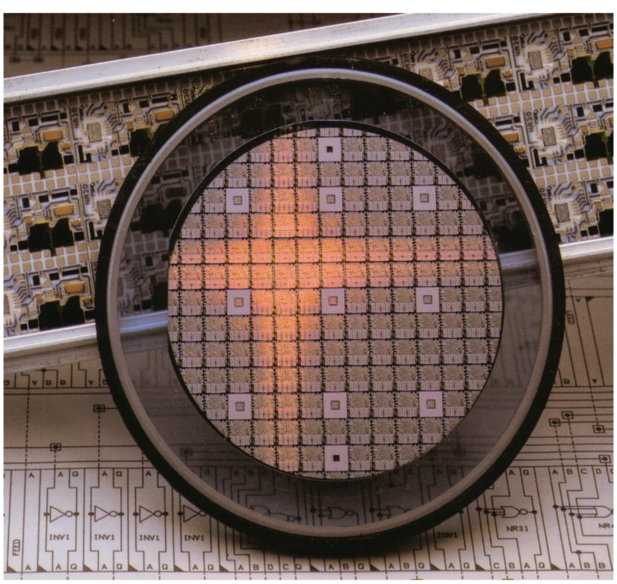

Figure 1.17 Integrated circuit components

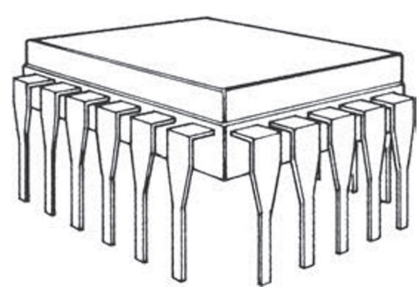

Figure 1.18 Typical integrated circuit package

Key fact

Today's microprocessors have many millions of gates and billions of individual transistors (well in excess of VLSI).

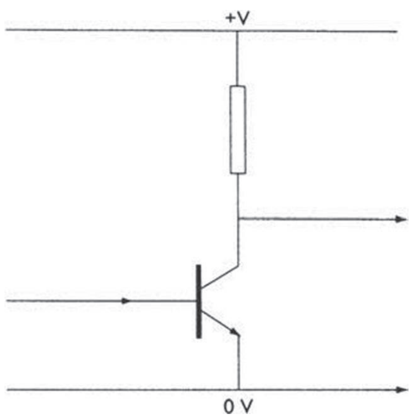

Figure 1.19 Simple amplifier circuit

integration). This means there can be more than 100 000 active elements on one chip. Development in this area is moving so fast that often the science of electronics is now concerned mostly with choosing the correct combination of chips, and discreet components are only used as final switching or power output stages.

1.3.4 Amplifiers

The simplest form of amplifier involves just one resistor and one transistor, as shown in Figure 1.19. A small change of current on the input terminal will cause a similar change of current through the transistor and an amplified signal will be evident at the output terminal. Note, however, that the output will be inverted compared with the input. This very simple circuit has many applications when used more as a switch than an amplifier. For example, a very small current flowing to the input can be used to operate, say, a relay winding connected in place of the resistor.

One of the main problems with this type of transistor amplifier is that the gain of a transistor (β) can be variable and non-linear. To overcome this, some type of feedback is used to make a circuit with more appropriate characteristics. Figure 1.20 shows a more practical AC amplifier.

Resistors Rb_1 and Rb_2 set the base voltage of the transistor and, because the base–emitter voltage is constant at 0.6 V, this in turn will set the emitter voltage. The standing current through the collector and emitter resistors (Rc and Re) is hence defined and the small signal changes at the input will be reflected in an amplified form at the output, albeit inverted. A reasonable approximation of the voltage gain of this circuit can be calculated as: Rc/Re.

Capacitor C_1 is used to prevent any change in DC bias at the base terminal and C_2 is used to reduce the impedance of the emitter circuit. This ensures that Re does not affect the output.

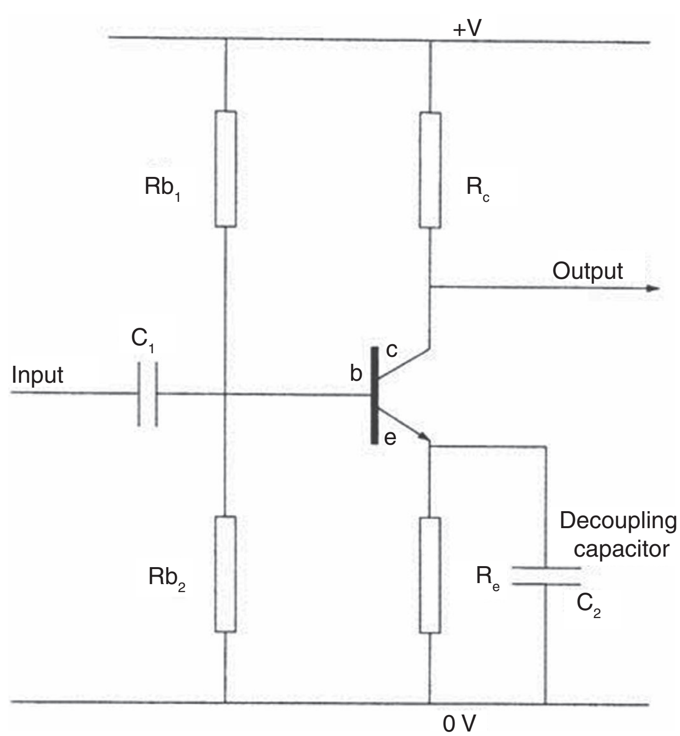

Figure 1.20 Practical AC amplifier circuit

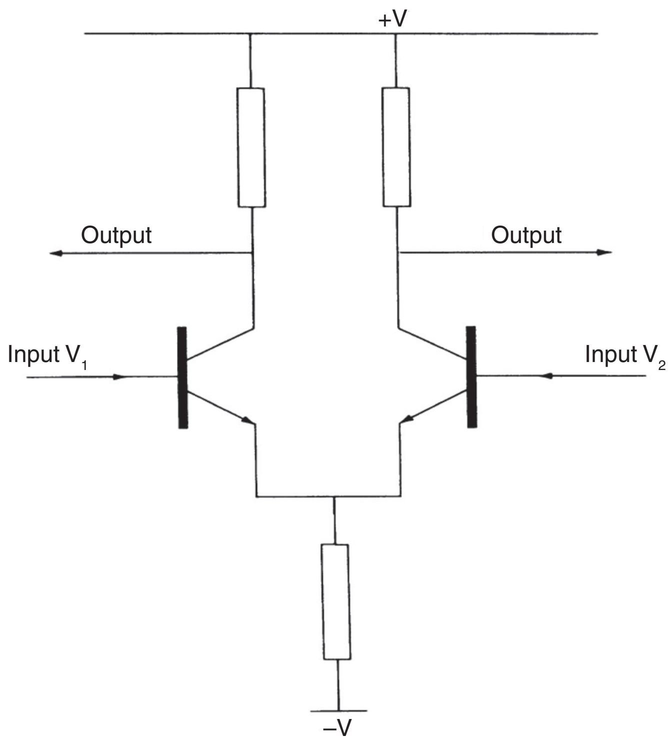

Figure 1.21 DC amplifier, long tail pair

For amplification of DC signals, a differential amplifier is often used. This amplifies the voltage difference between two input terminals. The circuit shown in Figure 1.21, known as the long tail pair, is used almost universally for DC amplifiers.

The transistors are chosen such that their characteristics are very similar. For discreet components, they are supplied attached to the same heat sink and, in integrated applications, the method of construction ensures stability. Changes in the input will affect the base–emitter voltage of each transistor in the same way, such that the current flowing through Re will remain constant. Any change in the temperature, for example, will affect both transistors in the same way and therefore the differential output voltage will remain unchanged. The important property of the differential amplifier is its ability to amplify the difference between two signals but not the signals themselves.

Integrated circuit differential amplifiers are very common, one of the most common being the 741 op-amp. This type of amplifier has a DC gain in the region of 100 000. Operational amplifiers are used in many applications and, in particular, can be used as signal amplifiers. A major role for this device is also to act as a buffer between a sensor and a load such as a display. The internal circuit of these types of device can be very complicated, but external connections and components can be kept to a minimum. It is not often that a gain of 100 000 is needed so, with simple connections of a few resistors, the characteristics of the op-amp can be changed to suit the application. Two forms of negative feedback are used to achieve an accurate and appropriate gain.

These are shown in Figure 1.22 and are often referred to as shunt feedback and proportional feedback operational amplifier circuits.

The gain with shunt (parallel) feedback is: $-R_2/R_1$

The gain with proportional feedback is: $R_2/(R_1 + R_2)$

Key fact

Integrated circuit differential amplifiers can have a DC gain in the region of 100 000.

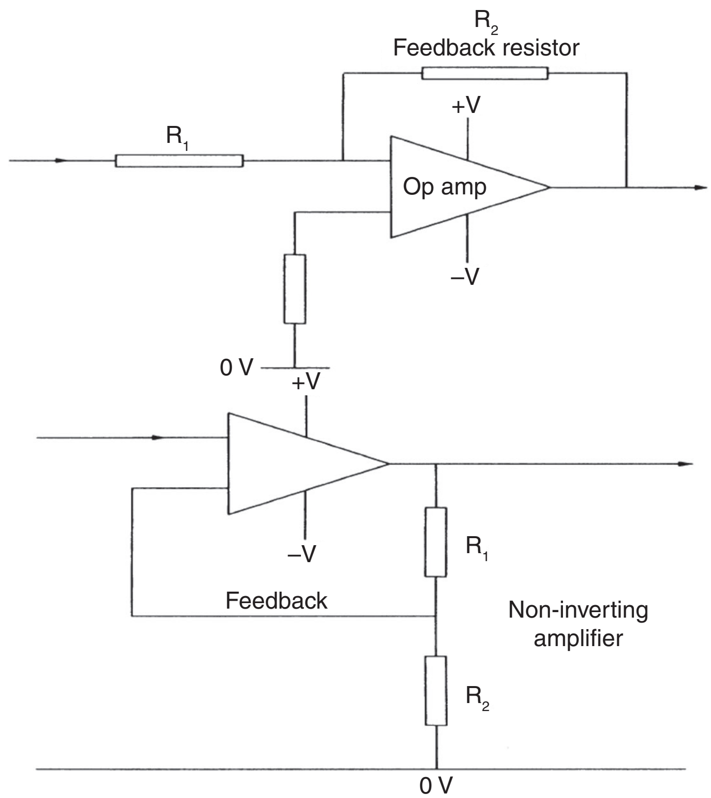

Figure 1.22 Operational amplifier feedback circuits

Key fact

Operational amplifier gain is dependent on frequency.

An important point to note with this type of amplifier is that its gain is dependent on frequency. This, of course, is only relevant when amplifying AC signals. Figure 1.23 shows the frequency response of a 741 amplifier. Op-amps are basic building blocks of many types of circuit, and some of these will be briefly mentioned later in this section.

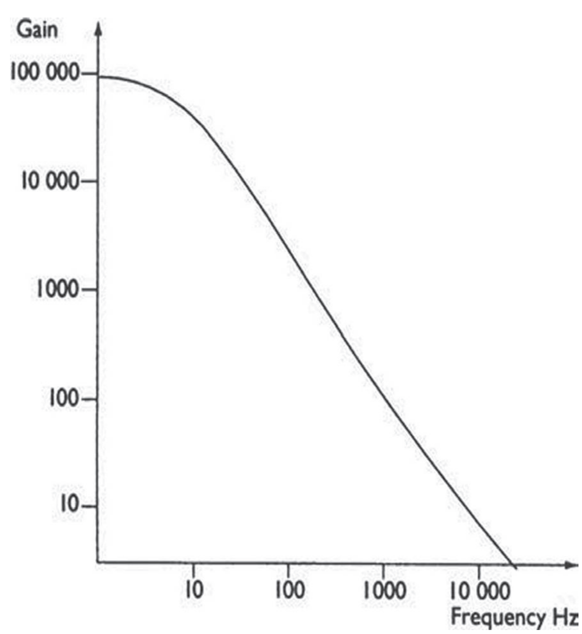

Figure 1.23 Frequency response of a 741 amplifier

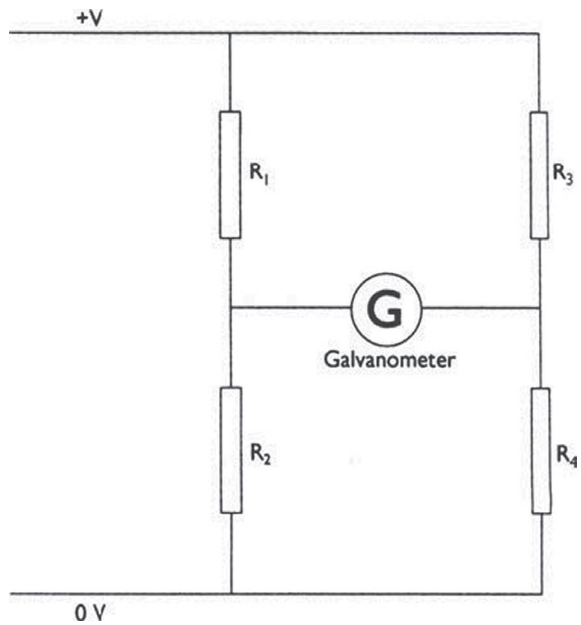

Figure 1.24 Wheatstone bridge

1.3.5 Bridge circuits

There are many types of bridge circuits but they are all based on the principle of the Wheatstone bridge, which is shown in Figure 1.24. The meter shown is a very sensitive galvanometer. A simple calculation will show that the meter will read zero when:

$$R_1/R_2 = R_3/R_4$$

To use a circuit of this type to measure an unknown resistance very accurately (R1), R3 and R4 are pre-set precision resistors and R2 is a precision resistance box. The meter reads zero when the reading on the resistance box is equal to the unknown resistor. This simple principle can also be applied to AC circuits to determine unknown inductance and capacitance.

A bridge and amplifier circuit, which may be typical of a motor vehicle application, is shown in Figure 1.25. In this circuit R_1 has been replaced by a temperature measurement thermistor. The output of the bridge is then amplified with a differential operational amplifier using shunt feedback to set the gain.

1.3.6 Schmitt trigger

The Schmitt trigger is used to change variable signals into crisp square-wave type signals for use in digital or switching circuits. For example, a sine wave

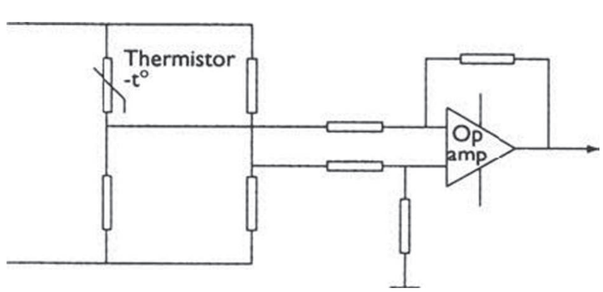

Figure 1.25 Bridge and amplifier circuit.

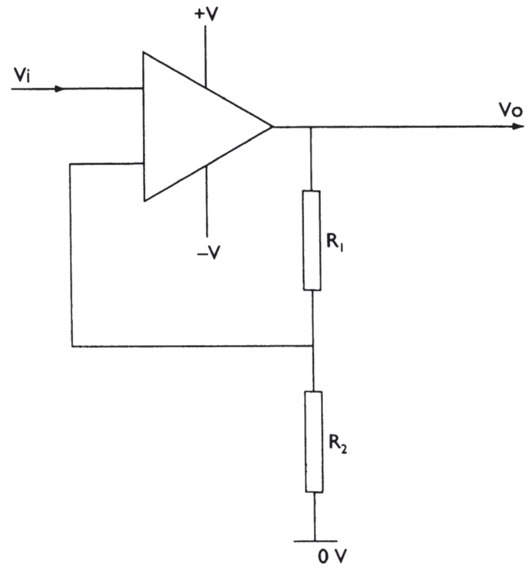

Figure 1.26 Schmitt trigger circuit utilizing an operational amplifier

Key fact

A Schmitt trigger is used to change variable signals square-wave type signals.

Definition

UTP and LTP: Upper and lower trigger points.

fed into a Schmitt trigger will emerge as a square wave with the same frequency as the input signal. Figure 1.26 shows a simple Schmitt trigger circuit utilizing an operational amplifier.

The output of this circuit will be either saturated positive or saturated negative due to the high gain of the amplifier. The trigger points are defined as the upper and lower trigger points (UTP and LTP) respectively. The output signal from an inductive type distributor or a crank position sensor on a motor vehicle will need to be passed through a Schmitt trigger. This will ensure that either further processing is easier, or switching is positive. Schmitt triggers can be purchased as integrated circuits in their own right or as part of other ready-made applications.

1.3.7 Timers

In its simplest form, a timer can consist of two components, a resistor and a capacitor. When the capacitor is connected to a supply via the resistor, it is accepted that it will become fully charged in 5CR seconds, where R is the resistor value in ohms and C is the capacitor value in farads. The time constant of this circuit is CR, often-denoted τ.

The voltage across the capacitor (Vc), can be calculated as follows:

$$V_c = V(I - e^{-t/CR})$$

where: V = supply voltage; t = time in seconds; C = capacitor value in farads; R = resistor value in ohms; e = exponential function.

These two components with suitable values can be made to give almost any time delay, within reason, and to operate or switch off a circuit using a transistor. Figure 1.27 shows an example of a timer circuit using this technique.

1.3.8 Filters

A filter that prevents large particles of contaminates reaching, for example, a fuel injector is an easy concept to grasp. In electronic circuits the basic idea is just the same except the particle size is the frequency of a signal. Electronic

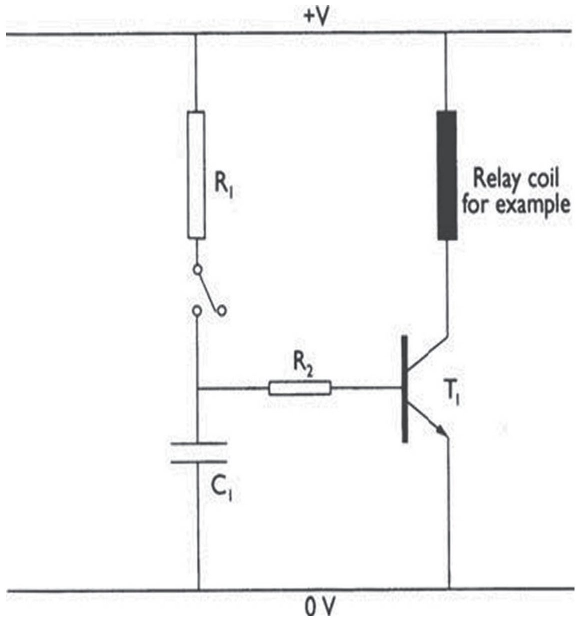

Figure 1.27 Example of a timer circuit

filters come in two main types: a low pass filter, which blocks high frequencies, and a high pass filter, which blocks low frequencies.

Many variations of these filters are possible to give particular frequency response characteristics, such as band pass or notch filters. Here, just the basic design will be considered. The filters may also be active, in that the circuit will include amplification, or passive, when the circuit does not. Figure 1.28 shows the two main passive filter circuits.

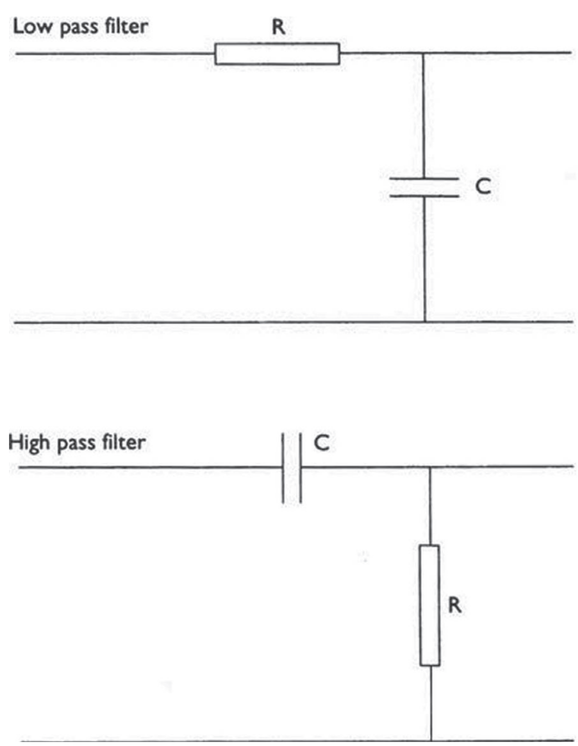

Figure 1.28 Low pass and high pass filter circuits

Definition

Reactance: The non-resistive component of impedance in an AC circuit, due to the effect of inductance or capacitance or both. It also causes the current to be out of phase with the voltage.

The principle of the filter circuits is based on the reactance of the capacitors changing with frequency. In fact, capacitive reactance, X_c decreases with an increase in frequency. The roll-off frequency of a filter can be calculated as shown:

$$f = \frac{1}{2\pi RC}$$

where: f = frequency at which the circuit response begins to roll off, R = resistor value; C = capacitor value.

It should be noted that the filters are far from perfect (some advanced designs come close though), and that the roll-off frequency is not a clear-cut 'off' but the point at which the circuit response begins to fall.

1.3.9 Darlington pair

A Darlington pair is a simple combination of two transistors that will give a high current gain, of typically several thousand. The transistors are usually mounted on a heat sink and, overall, the device will have three terminals marked as a single transistor – base, collector and emitter. The input impedance of this type of circuit is of the order of 1 MΩ, hence it will not load any previous part of a circuit connected to its input. Figure 1.29 shows two transistors connected as a Darlington pair.

Key fact

The Darlington pair configuration is used for many switching applications.

The Darlington pair configuration is used for many switching applications. A common use of a Darlington pair is for the switching of the coil primary current in the ignition circuit.

1.3.10 Stepper motor driver

A later section gives details of how a stepper motor works. In this section it is the circuit used to drive the motor that is considered. For the purpose of this

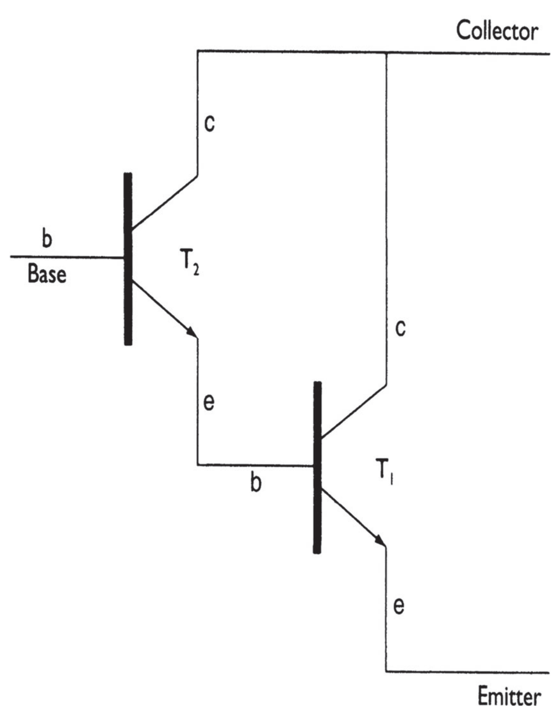

Figure 1.29 Darlington pair

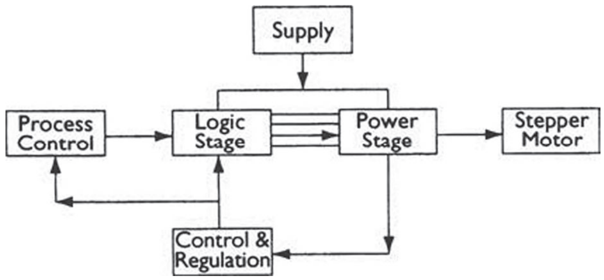

Figure 1.30 Stepper motor control system

explanation, a driver circuit for a four-phase unipolar motor is described. The function of a stepper motor driver is to convert the digital and 'wattless' (no significant power content) process control signals into signals to operate the motor coils. The process of controlling a stepper motor is best described with reference to a block diagram of the complete control system, as shown in Figure 1.30.

The process control block shown represents the signal output from the main part of an engine management ECU (electronic control unit). The signal is then converted in a simple logic circuit to suitable pulses for controlling the motor. These pulses will then drive the motor via a power stage. Figure 1.31 shows a simplified circuit of a power stage designed to control four motor windings.

1.3.11 Digital-to-analogue conversion

Conversion from digital signals to an analogue signal is a relatively simple process. When an operational amplifier is configured with shunt feedback the input and feedback resistors determine the gain.

$$\text{Gain} = -R_f/R_1$$

If the digital-to-analogue converted circuit is connected as shown in Figure 1.32 then the 'weighting' of each input line can be determined by choosing suitable resistor values. In the case of the four-bit digital signal, as shown, the most significant bit will be amplified with a gain of one. The next bit will be amplified with a gain of 1/2, the next bit 1/4 and, in this case, the least significant bit will be amplified with a gain of 1/8. This circuit is often referred to as an adder. The output signal produced is therefore a voltage proportional to the value of the digital input number.

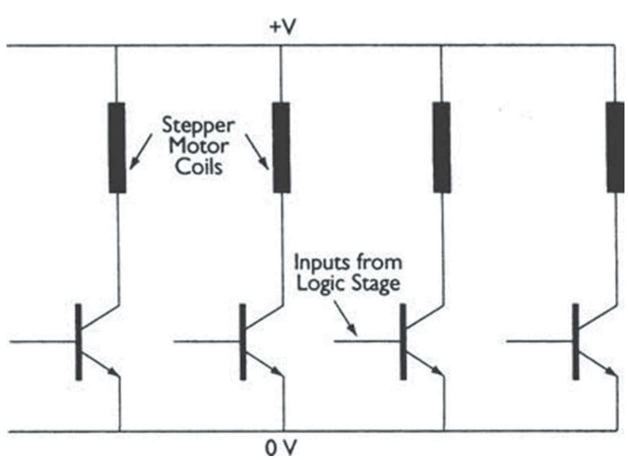

Figure 1.31 Stepper motor driver circuit (power stage)

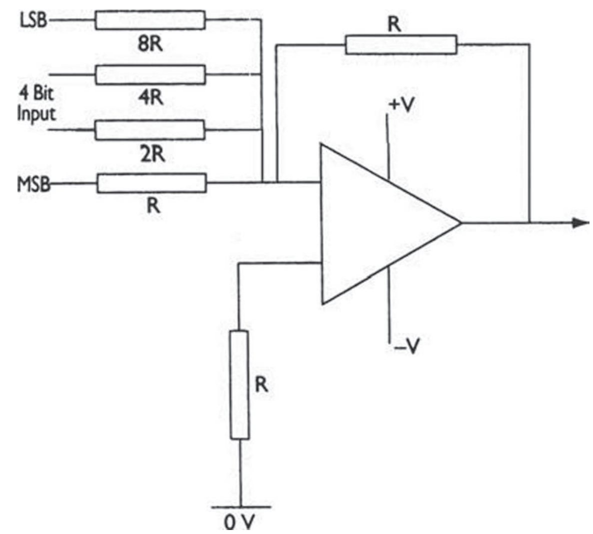

Figure 1.32 Digital-to-analogue converter

The main problem with this system is that the accuracy of the output depends on the tolerance of the resistors. Other types of digital-to-analogue converter are available, such as the R2R ladder network, but the principle of operation is similar to the above description.

1.3.12 Analogue-to-digital conversion

The purpose of this circuit is to convert an analogue signal, such as that received from a temperature thermistor, into a digital signal for use by a computer or a logic system. Most systems work by comparing the output of a digital-to-analogue converter (DAC) with the input voltage. Figure 1.33 is a ramp analogue-to-digital converter (ADC). This type is slower than some others

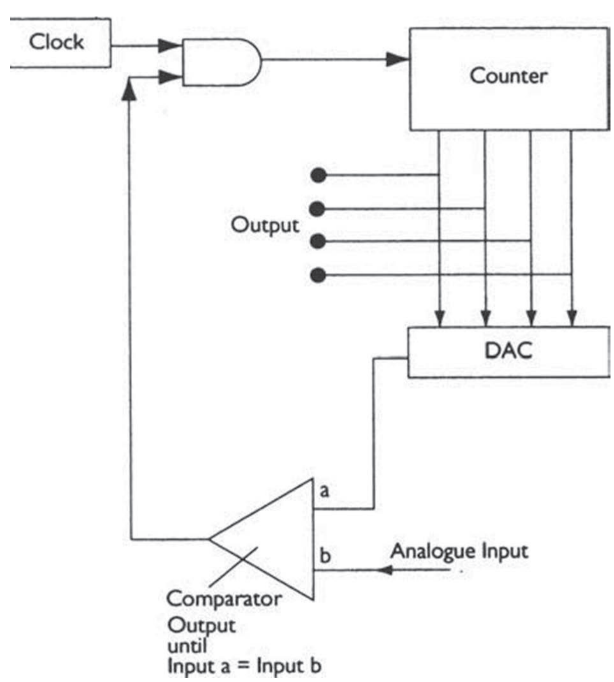

Figure 1.33 Ramp analogue-to-digital converter

but is simple in operation. The output of a binary counter is connected to the input of the DAC, the output of which will be a ramp. This voltage is compared with the input voltage and the counter is stopped when the two are equal. The count value is then a digital representation of the input voltage. The operation of the other digital components in this circuit will be explained in the next section.

ADCs are available in IC form and can work to very high speeds at typical resolutions of one part in 4096 (12-bit word). The speed of operation is critical when converting variable or oscillating input signals. As a rule, the sampling rate must be at least twice the frequency of the input signal.

Definition

DAC: Digital-to-analogue converter.
ADC: Analogue-to-digital converter.

1.4 Digital electronics

1.4.1 Introduction to digital circuits

With some practical problems, it is possible to express the outcome as a simple yes/no or true/false answer. Let us take a simple example: if the answer to either the first or the second question is 'yes', then switch on the brake warning light, if both answers are 'no' then switch it off.

1. Is the handbrake on?
2. Is the level in the brake fluid reservoir low?

In this case, we need the output of an electrical circuit to be 'on' when either one or both of the inputs to the circuit are 'on'. The inputs will be via simple switches on the handbrake and in the brake reservoir. The digital device required to carry out the above task is an OR gate, which will be described in the next section.

Once a problem can be described in logic states then a suitable digital or logic circuit can also determine the answer to the problem. Simple circuits can also be constructed to hold the logic state of their last input – these are, in effect, simple forms of 'memory'. By combining vast quantities of these basic digital building blocks, circuits can be constructed to carry out the most complex tasks in a fraction of a second. Due to integrated circuit technology, it is now possible to create hundreds of thousands if not millions of these basic circuits on one chip. This has given rise to the modern electronic control systems used for vehicle applications as well as all the countless other uses for a computer.

Key fact

If a problem can be described in logic states then a digital or logic circuit can also determine the answer to the problem.

In electronic circuits, true/false values are assigned voltage values. In one system, known as TTL (transistor-transistor-logic), true or logic '1', is represented by a voltage of 5 V and false or logic '0', by 0 V.

1.4.2 Logic gates

The symbols and truth tables for the basic logic gates are shown in Figure 1.34. A truth table is used to describe what combination of inputs will produce a particular output.

Key fact

A truth table is used to describe what combination of inputs will produce a particular output.

The AND gate will only produce an output of '1' if both inputs (or all inputs as it can have more than two) are also at logic '1'. Output is '1' when inputs A AND B are '1'.

The OR gate will produce an output when either A OR B (OR both), are '1'. Again more than two inputs can be used.

A NOT gate is a very simple device where the output will always be the opposite logic state from the input. In this case A is NOT B and, of course, this can only be a single input and single output device.