UNIT 2

GENERATORS AND MOTORS BATTERIES & POWER SUPPLIES.

Description and applications of single - phase and three - phase motors. Connection and starting of three - phase induction motors by star - delta starter. Motors used for driving pumps, compressors, centrifuge, Generator and motor principles - AC generators - Three-phase generation and distribution - AC motors - Practical aircraft generating systems – Storage cells - Lead-acid batteries - Nickel-cadmium batteries - Lithium batteries - Nickel-metal hydride batteries- Battery locations - Battery venting - Battery connections - Regulators - External power - Inverters - Transformer rectifier units - Transformers - Auxiliary power unit (APU) - Emergency power - Wiring and circuit protection - Construction and materials - specifications - Shielding/screening - Circuit protection - Electrical and magnetic fields - Electromagnetic interference - EMI reduction

2.1 Generator and motor principles

The generation of an e.m.f. across the ends of a conductor when it passes through a change in magnetic fl ux. In a similar fashion, an e.m.f. will appear across the ends of a conductor if it remains stationary whilst the field moves. In either case, the action of cutting through the lines of magnetic flux results in a generated e.m.f. – see Fig. 2.1 . The amount of e.m.f., e , *induced* in the conductor will be directly proportional to:

● the density of the magnetic fl ux, B , measured in tesla (T)
● the effective length of the conductor, l , within the magnetic flux
● the speed, v , at which the lines of flux cut through the conductor measured in metres per second(m/s)
● the sine of the angle, θ , between the conductor and the lines of fl ux.

The induced e.m.f. is given by the formula:

$$e = Blv \sin \theta$$

Note that if the conductor moves at right angles to the field (as shown in Fig. 2.1) maximum e.m.f.
will be induced. Conversely, if the conductor moves along the lines of flux (instead of at right angles) the induced e.m.f. will be zero. Electricity and magnetism often work together to produce motion.

In an electric **motor** , current flowing in a conductor placed inside a magnetic field produces motion.

A **generator** , on the other hand, produces a voltage when a conductor is moved inside a magnetic field. These two effects are, as you might suspect, closely related to one another and they are vitally important in the context of aircraft electrical systems!

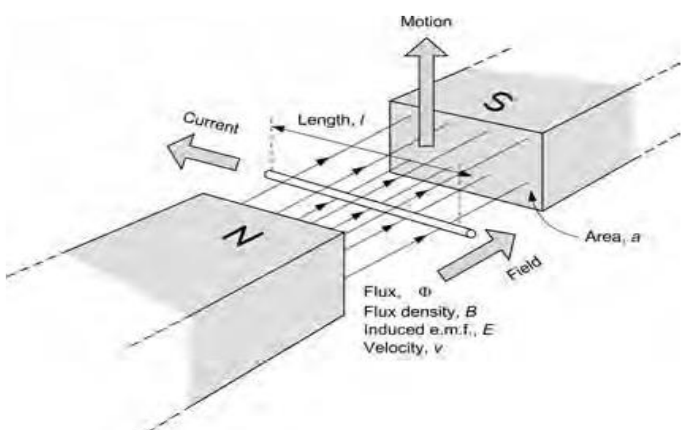

Figure 2.1 A conductor moving inside a magnetic field

2.2 A simple AC generator

Being able to generate a voltage by moving a conductor through a magnetic field is extremely useful as it provides us with an easy way of generating electricity. Unfortunately, moving a wire at a constant linear velocity through a uniform magnetic field presents us with a practical problem simply because the mechanical power that can be derived from an aircraft engine is available in rotary (rather than linear) form! The solution to this problem is that of using the rotary power available from the engine (via a suitable gearbox and transmission) to rotate a conductor shaped into the form of loop as shown in Fig. 2.2 .

The loop is made to rotate inside a permanent magnetic field with opposite poles (N and S) on either side of the loop. There now remains the problem of making contact with the loop as it rotates inside the magnetic field but this can be overcome by means of a pair of carbon **brushes** and copper **slip-rings** . The brushes are spring loaded and held against the rotating slip-rings so that, at any time, there is a path for current to flow from the loop to the load to which it is connected . The opposite sides of the loop consist of conductors that move through the field. At 0° (with the loop vertical as shown at A in Fig. 2.4) the opposite sides
of the loop will be moving in the same direction as the lines of fl ux. At that instant, the angle, θ, at which the field is cut is 0° and since the sine of 0° is 0 the generated voltage (from $E = Blv\sin\theta$) will consequently also be zero.
If the loop has rotated to a position which is 90° (position B in Fig. 2.4) the two conductors will effectively be moving at right angles to the field. At that instant, the generated e.m.f. will take a maximum value (since the sine of 90° is 1)

At 180° from the starting position the generated e.m.f. will have fallen back to zero since, once again ,the conductors are moving along the flux lines (but in the direction opposite to that at 0 °, as shown in C of Fig. 2.4).

At 270° the conductors will once again be moving in a direction which is perpendicular to the fl us lines(but in the direction opposite to that at 90°). At this point (D of Fig. 2.4); a maximum generated e.m.f will once again be produced. It is, however, important to note that the e.m.f generated at this instant will be of opposite polarity to that which was generated at 90°.The reason for this is simply that the relative direction of motion (between the conductors and flux lines) has effectively been reversed.

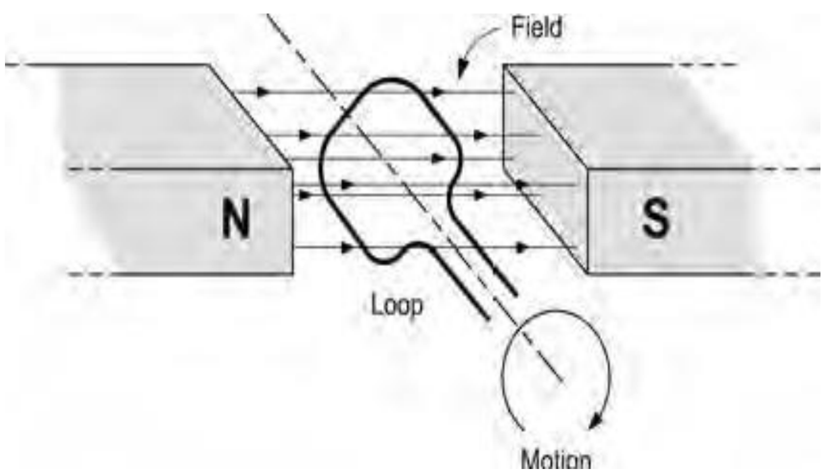

Figure 2.2 A loop rotating within a magnetic field

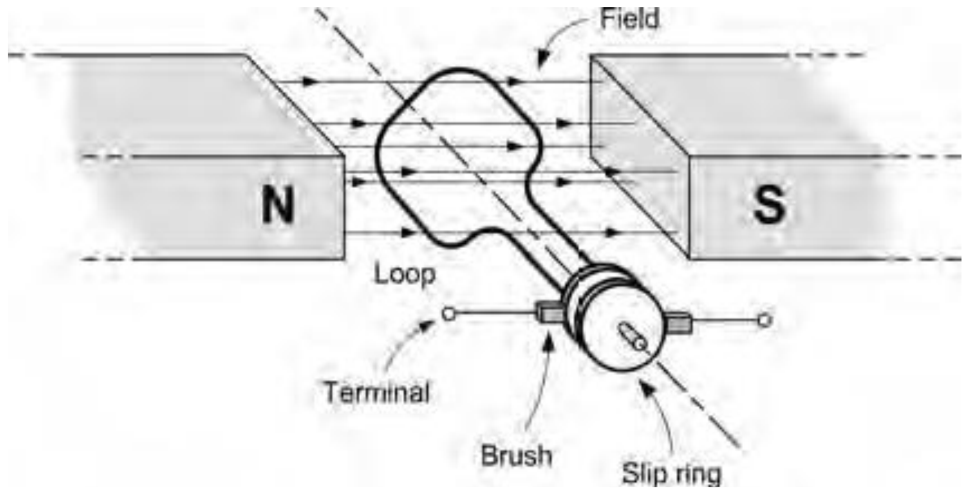

Figure 2.3 Brush arrangement

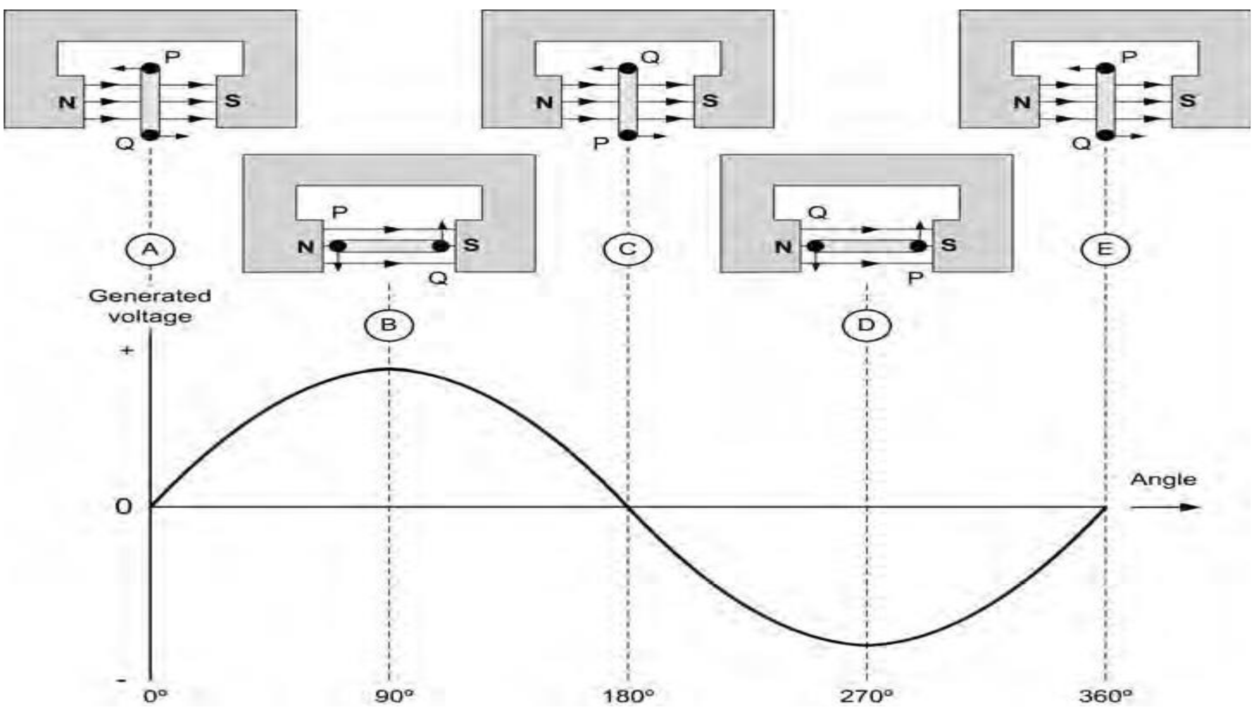

Figure 2.4 E.m.f. generated at various angles

Since $E = Blv \sin\theta$, the e.m.f. generated by the arrangement shown in Fig. 2.4 w . Note that the maximum values of e.m.f. occur at 90° and 270° and that the generated voltage is zero at 0°, 180° and 360°.In practice, the single loop shown in Fig. 2.2 would comprise a coil of wire wound on a suitable nonmagnetic former. This coil of wire effectively increases the length of the conductor within the magnetic field and the generated e.m.f. will then be directly proportional to the number of turns on the coil.

2.3 Three-phase generation and distribution

When three-phase supplies are distributed there are two basic methods of connection:

● star (as shown in Fig. 2.3.1)
● delta (as shown in Fig. 2.3.2)

A complete star-connected three-phase distribution system is shown in Fig. 2.4. This shows a three-phase AC generator connected a three-phase load. Ideally, the load will be **balanced** in which case all three load resistances (or impedances) will be identical

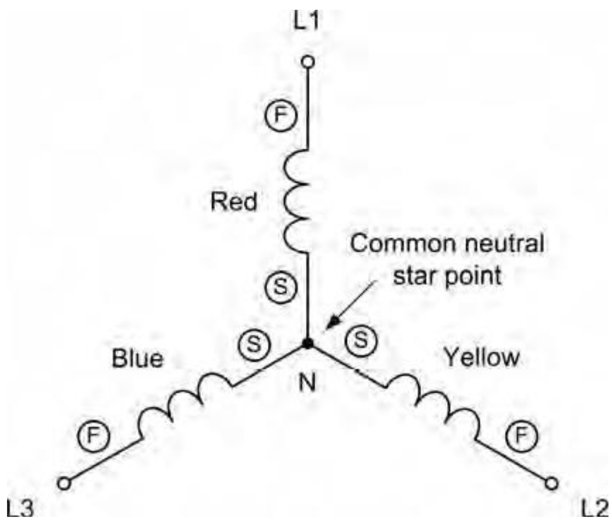

Figure 2.3.1 Star connection

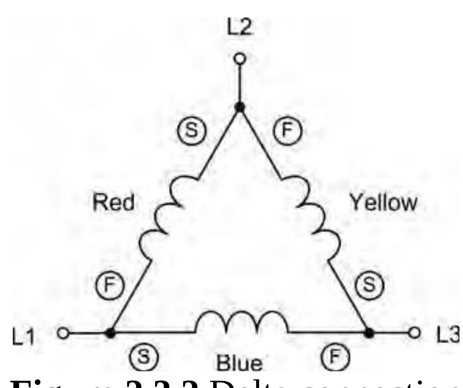

Figure 2.3.2 Delta connection

The relationship between the line and phase voltages shown in Fig. 2.4 can be determined from the **phasor diagram** shown in Fig. 2.5 . This diagram shows the relative directions of the three alternating phase voltages (V_P) and the voltages between the lines (V_L). From this diagram it is important to note that three line voltages are 120° apart and that the line voltages lead the phase voltages by 30°.In order to obtain the relationship between the line voltage, V_L , and the phase voltage, V_P , we need to resolve any one of the triangles, from which we find that:

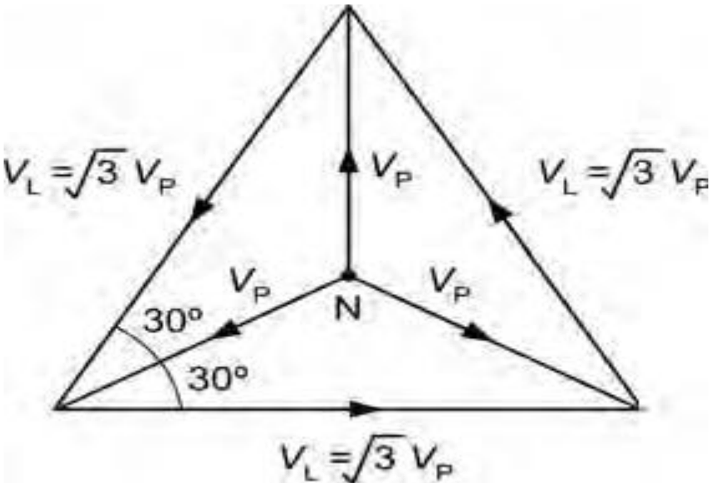

Figure 2.5 Phasor diagram for the three phase star-connected system

$$V_L = 2(V_P \times \cos 30°)$$

Now

$$\cos 30° = \frac{\sqrt{3}}{2}$$

and hence:

$$V_L = 2\left(V_P \times \frac{\sqrt{3}}{2}\right)$$

from which:

$$V_L = \sqrt{3}\ V_P$$

Note also that the phase current is the same as the line current, hence:

$$I_P = I_L$$

An alternative, delta-connected three-phase distribution system is shown in Fig. 2.6 . Once again this shows a three-phase AC generator connected a three-phase load. Here again, the load will ideally be balanced in which case all three load resistances (or impedances) will be identical. In this arrangement the three line currents are 120°apart and that the line currents lag the phase currents by 30°. Using a similar phasor diagram to that which we used earlier, we can show that:

$$I_L = \sqrt{3}\, I_P$$

It should also be obvious that:

$$V_P = V_L$$

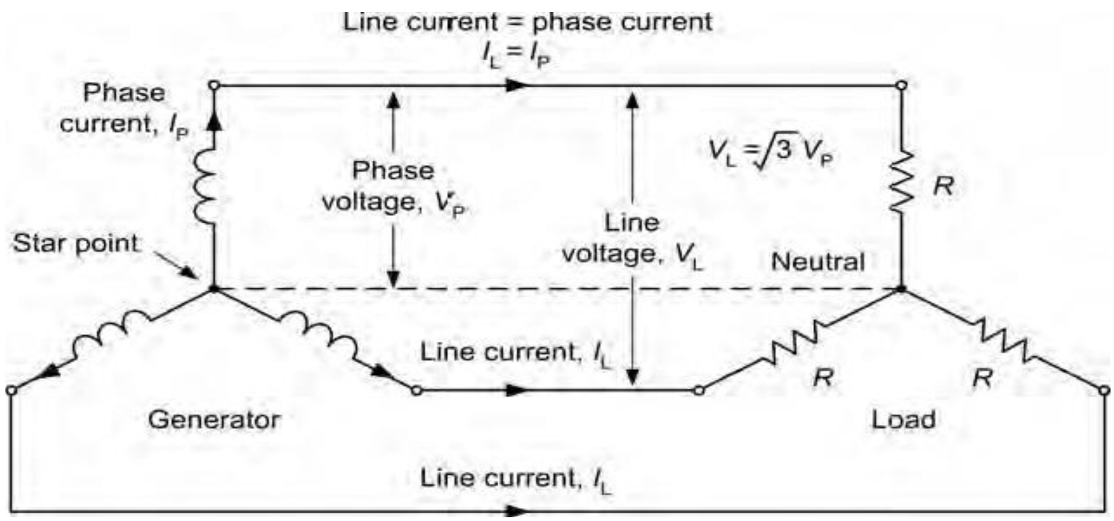

Figure 2.6 A complete star-connected three-phase distribution system

2.3.1 Power in a three-phase system

In an unbalanced three-phase system the total power will be the sum of the individual phase powers.Hence:

$$P = P_1 + P_2 + P_3$$

or

$$P = V_1 I_1 \cos \varphi_1 + V_2 I_2 \cos \varphi_2 + V_3 I_3 \cos \varphi_3$$

However, in the balanced condition the power is simply:

$$P = 3\, V_P I_P \cos \varphi$$

where V_P and I_P are the phase voltage and phase current respectively and φ is the phase angle.
Using the relationships that we derived earlier, we can show that, for both the star and delta-connected systems the total power is given by:

$$P = 3 V_L I_L \cos\varphi$$

2.4 AC motors

AC motors offer significant advantages over their DC counterparts. AC motors can, in most cases duplicate the operation of DC motors and they are significantly more reliable. The main reason for this is that the commutator arrangements (i.e. brushes and slip-rings) fitted to DC motors are inherently troublesome. Because the speed of an AC motor is determined by the frequency of the AC supply that is applied it, AC motors are well suited to constants peed applications.

AC motors are generally classified into two types:
- synchronous motors
- induction motors.

The synchronous motor is effectively an AC generator (i.e. an alternator) operated as a motor. In this machine, AC is applied to the stator and DC is applied to the rotor. The induction motor is different in that no source of AC or DC power is connected to the rotor. Of these two types of AC motor, the induction motor is by far the most commonly used

2. 4.1 Producing a rotating magnetic field

Fig. 2.33 which shows a three-phase stator to which three-phase AC is applied. The windings are connected in delta configuration, as shown in Fig. 2.34 . It is important to note that the two windings for each phase (diametrically opposite to one another) are wound in the *same* direction

At any instant the magnetic field generated by one particular phase depends on the current through that phase. If the current is zero, the magnetic field is zero. If the current is a maximum, the magnetic field is a maximum. Since the currents in the three windings are 120° out of phase, the magnetic fields generated will also be 120° out of phase

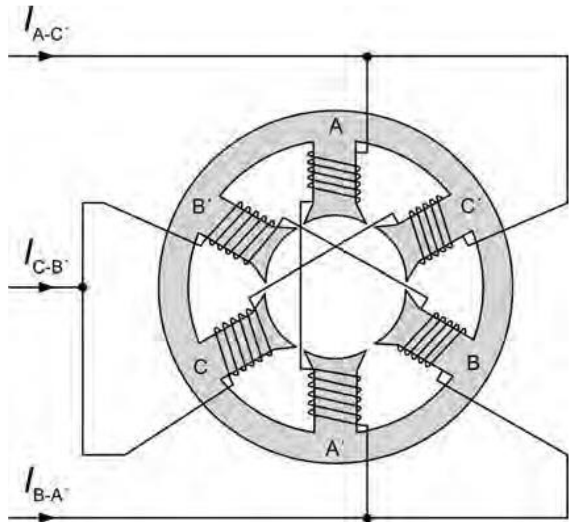

Figure 2.33 Arrangement of the field windings of a three-phase AC motor

The three magnetic fields that exist at any instant will combine to produce one field that acts on the rotor. The magnetic fields inside the motor will combine to produce a moving magnetic field and, at the end of one complete cycle of the applied current, the magnetic field will have shifted through 360° (or one complete revolution).

Figure 2.35 shows the three current waveforms applied to the field system. These waveforms are 120°out of phase with each other. The waveforms can represent either the three alternating magnetic fields generated by the three phases, or the currents in the phases. We can consider the direction of the magnetic field at regular intervals over a cycle of the applied current (i.e. every 60°). To make life simple we take the times at which one of the three current waveforms passes through zero (i.e. the point at which there will be no current and therefore no field produced by one pair of field windings). For the purpose of this exercise we will use the current applied to A and C ’ as our reference waveform (i.e. this will be the waveform that starts at 0° on our graph).

At 0°, waveform C–B _ is positive and waveform B–A_ is negative. This means that the current flows in opposite directions through phases B and C, and so establishes the magnetic polarity of phases B and C.
The polarity is shown in Fig. 2.35 . Note that B _ is a north pole and B is a south pole, and that C is a north pole and C _ is a south pole

Since at 0° there is no current fl owing through phase A, its magnetic field is zero. The magnetic fields leaving poles B _ and C will move towards the nearest south poles C _ and B. Since the magnetic fields of B and C are equal in amplitude, the resultant magnetic field will lie between the two fields, and will have the direction shown

At the next point, 60° later, the current waveforms to phases A and B are equal and opposite, and waveform C is zero. The resultant magnetic field has rotated through 60°. At point 120°, waveform B is zero and the resultant magnetic field has rotated through another 60°. From successive points (corresponding to one cycle of AC), you will note that the resultant magnetic field rotates through one revolution for every cycle of applied current. Hence, by applying a three-phase alternating current to the three
windings we have been able to produce a rotating magnetic field.

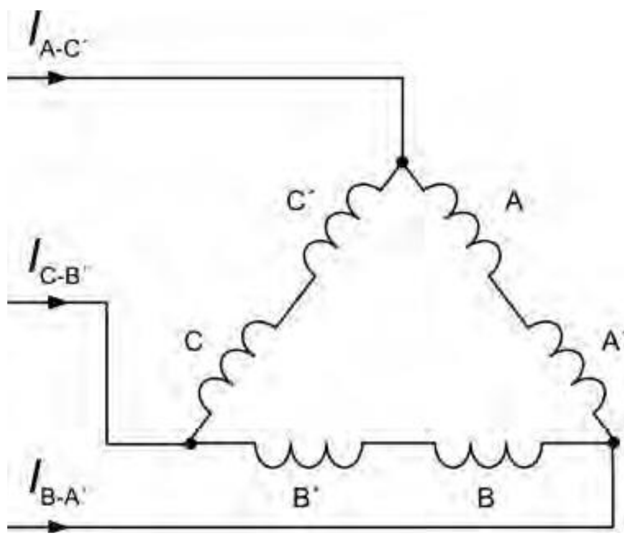

Figure 2.34 AC motor as a delta-connected load

2.5 Practical aircraft generating systems

Generators are a primary source of power in an aircraft and can either produce direct or alternating current(DC or AC) as required. They are driven by a belt drive (in smaller aircraft), or engine/APU accessory gearbox in larger aircraft. Generators will have sufficient output to supply all specified loads and charge the battery(s). Most avionic equipment requires a regulated and stable power supply depending on its function, e.g. in the case of lighting, it would be inconvenient if the intensity of lighting varied with engine speed. Generator output is affected by internal heat and this has to be dissipated.

Cooling methods can include natural radiation from the casing, however this is inadequate for high-output devices where ram-air is directed from a scoop and directed into the generator’s brush-gear and commutator. In some installations,

e.g. helicopters, a fan is installed to provide cooling when the aircraft is hovering. We know from basic theory that a generator's output will vary depending on the input shaft speed. A means of regulating the generator's output to the bus is required as is a means of
overload protection .

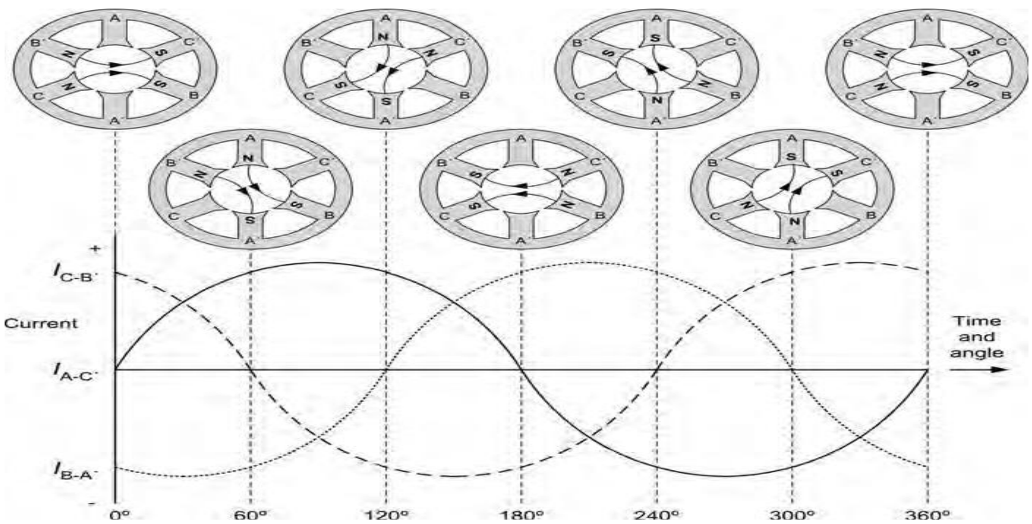

Figure 2.35 AC waveforms and magnetic field direction

2. 3.1 DC generators

DC generators are less common on modern aircraft due to their low power-to-weight ratio, poor performance at low r.p.m. and high servicing costs. The latter is due to the need for inspection and servicing of brushes and commutators since they have irregular surfaces/contact area and conduct the entire load current.

Carbon brushes are porous and will absorb substances including moisture; this provides an amount of inherent lubrication. At altitude, the atmosphere is dryer and this leads to higher brush wear. Without any lubrication, arcing occurs and static charges build up; brush erosion is accelerated. Additives can be incorporated into the brushes that deposit a lubricating film on the commutator; this needs time to build up a sufficient protection; brushes need to be run in for several hours before the protective layer forms (this is often mistaken for contamination). The alternative is an in-built lubrication that is consumed as part of the natural brush wear, i.e. no film is deposited

2. 3.2 Alternators

Automotive style alternators comprise a rotor, stator and rectifier pack. The rotor contains the field coil arranged in six sections around the shaft. Each section forms a pole piece that is supplied via slip-rings and brushes. The alternator has no residual magnetism, its field has to be excited by a DC supply (e.g. the battery). When energised, the rotor's pole pieces produce north and south poles. As these poles are rotated they induce currents in the stator windings; these are wound at 120° and this produces three phase AC.

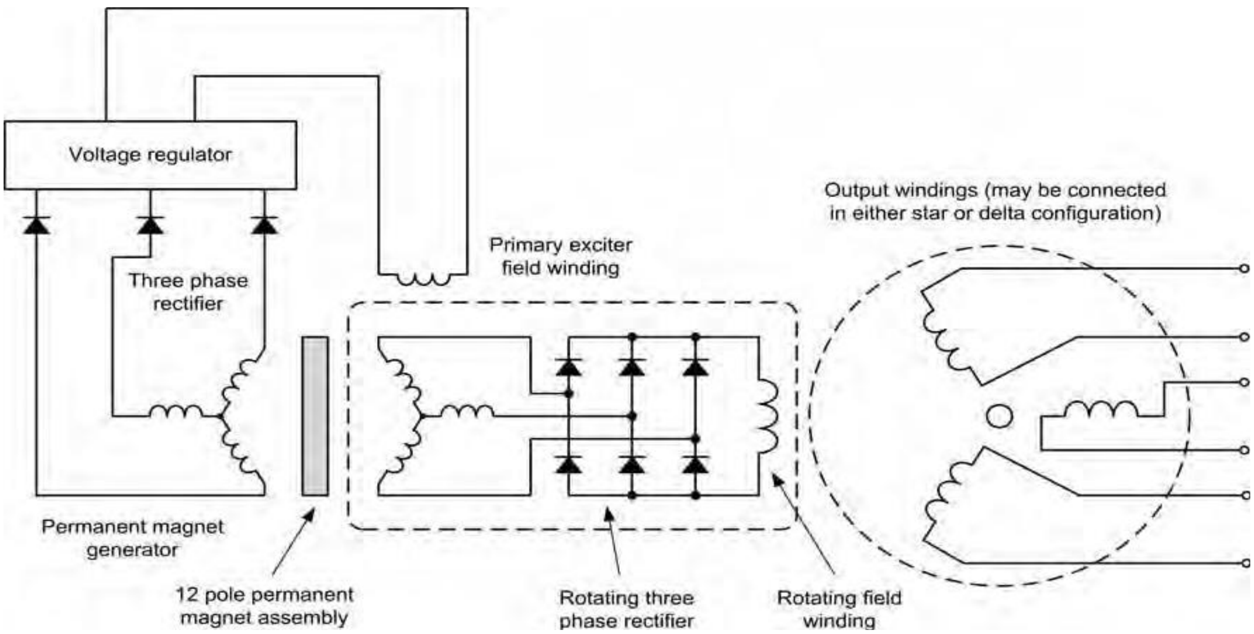

Figure 2.46 A practical brushless AC generator arrangement

The AC output is fed to a diode rectifier pack comprising six high-current diodes, see Fig. 2.46 which produces a DC output. This has to be regulated before connecting to the various aircraft systems. Voltage regulators used with alternators on general aviation aircraft can be electromechanical or electronic. There are two types of electromechanical regulators: sensing coil with contacts and carbon-pile. Modern solid-state electronic regulators are more reliable as they use no mechanical parts. The alternators previously described rely on sliprings and brushes, albeit with reduced current loading .Slip-rings and brushes require maintenance in the workshop thereby incurring an associated cost burden.

The **brushless generator** is a more complex device but has significantly increased reliability coupled with reduced maintenance requirements. A schematic diagram for the brushless generator is shown in Fig. 2.46 ;the device can be divided into three main sections

- permanent magnet generator
- rotating field

- three-phase output.

The AC generator uses a brushless arrangement based on a rotating rectifier and **permanent magnet generator** (**PMG**). The output of the PMG rectifier is fed to the voltage regulator which provides current for the primary exciter field winding. The primary exciter field induces current into a three-phase rotor winding. The output of this winding is fed to the shaft-mounted rectifier diodes which produce a pulsating DC output which is fed to the rotating field winding. It is important to note that the excitation system is an integral part of the rotor and that there is no direct electrical connection between the stator and rotor. The output of the main three-phase generator is supplied via **current transformers** (one for each phase) that monitor the load current in each line. An additional current transformer can also be present in the neutral line to detect an **out-of-balance** condition (when the load is unbalanced an appreciable current will flow in the generator's neutral connection). The generator output is fed to the various aircraft systems and a solid-state regulator. This rectifies the output and sends a regulated direct current to the stator exciter field of the PMG. The regulator maintains the output of the generator at 115 V AC and is normally contained within a **generator control unit** (**GCU**)

Although the regulator controls the output voltage of the generator, its frequency will vary depending on the speed of shaft rotation. Variable frequency power supplies(sometimes called **frequency wild**) are acceptable for resistive loads, e.g. de-icing, but they are not suitable for many induction motor loads that need to run at constant speed, e.g. fuel pumps and gyroscopic instruments. Furthermore, certain loads are designed for optimum efficiency at the specified frequency of400 Hz, e.g. cooling fans. Some larger multi-engine aircraft operate the generators in parallel; it is essential that each generator is operating at the same frequency. Constant frequency can be achieved in one of two ways: controlling the shaft speed by electromechanical methods using a **constant speed drive** (**CSD**) or by controlling the generator output frequency electronically(**variable speed constant frequency** : **VSCF**

2. 3.3 Constant speed drive/integrated drive generator

The CSD is an electromechanical device installed on each engine. The input shaft is connected to the engine gearbox; the output shaft is connected to the generator .The CSD is based on a variable ratio drive employing a series of hydraulic pumps and differential gears. CSDs can be disconnected from the engine via a clutch, either manually or automatically. Note that it is only possible to reconnect the clutch on the ground. Modern commercial aircraft employ a combined CSD and brushless AC generator, in one item – the integrated drive generator (IDG). Typical characteristics are a variable input speed of 4500/9000 r.p.m. and a constant output speed of 12,000 _ 150 r.p.m. The IDG on a large commercial aircraft is oil-cooled and produces a 115/200 V 400 Hz three-phase, 90 m kVA output.

2. 3.4 Variable speed constant frequency (VSCF)

Both the constant speed drive and integrated drive generator are complex and very expensive electromechanical devices. Advances in semiconductor technology has facilitated the development of solid-state products that can convert variable frequencies into 115/200 V AC, 400 Hz three-phase power supplies. Variable speed constant frequency (VSCF) systems comprise a generator and power converter.

A brushless AC generator is mounted onto the engine accessory gearbox as before; its output voltage and frequency varies in accordance with engine speed. The gearbox increases the generator speed by a ratio of 1:3, producing a variable output frequency between 1300 and 2500 r.p.m. The three-phase output of VSCF is full-wave rectified to produce a 270 V DC output. This direct current output is smoothed by large capacitors, filtered and fed into an inverter that produces a square wave output. The inverter converts the DC level into a three phase, pulse-width-modulated waveform. This is then converted in the sinusoidal output voltage. These outputs are then converted into AC through electronic circuits. The final output stage is monitored by a **current transformer** and **electromagnetic interference** filter (**CT** / **EMI**). Within the **generator control unit** (**GCU**) a **generator control relay** (**GCR**) energizes the field. This circuit can be interrupted by the pilot or automatically under fault conditions.

The VSCF **generator conversion control unit** (**GCCU)** can either be integrated with the generator as a single engine mounted device (weighing typically65 kg) or it can be located in the airframe. The latter arrangement has the advantage of making the engine accessories smaller; this means a lower profile nacelle .In addition, the electronics can be located in a zone with reduced temperature and vibration.VSCF systems are more reliable compared with constant speed drive and integrated drive generators since there are fewer moving parts. The VSCF system’s moving parts consist of the generator’s rotor and an oil pump used for cooling. The VSCF can be used for both primary and secondary power supplies; outputs of 110 kVA are achievable. Enabling technology for VSCF are the power transistors and diodes capable of handling currents in excess of 500 A. These diodes and transistors form the core of the rectifier and conversion circuits of the GCCU. The VSCF contains an oil pump mounted on the generator shaft that circulates oil through the system; this oil is passed through a heat exchanger. Oil temperatures and pressures are closely monitored; warnings are given to the crew in the event of malfunctions. Oil level can be checked during ground servicing through a sight glass.

3 overview of storage cell

The main aircraft battery is a primary source of electrical power; its use can be controlled by the pilot or by automatic means. The main battery provides autonomous starting for the engine(s) or auxiliary power unit (APU) when external groundPower is not available. Typical current requirement during APU starting is 1000 A, albeit for a short period of time. Batteries also supply **essential loads** in the event of generator failure. It is an airworthiness requirement that the main battery(s) supplies essential services for a specified period of time. Other aircraft systems are supplied with their own dedicated batteries, e.g. aircraft emergency lights. Individual computers use their own battery sources to provide non-volatile memory. Battery type and maintenance
Requirements have to be understood by the aircraft engineer to ensure safe and reliable operation and availability.

The battery is constructed from a number of individual cells; generic cell features consist of two electrodes (the **anode** and **cathode)** and electrolyte contained within a casing. Cell materials vary depending on the type of battery performance required for a given cost.

The simple primary cell (Fig. 3.1) causes an electron flow from the cathode (negative) through the external load to the anode (positive). The materials used refer to the two types of battery cell in widespread use on aircraft for the primary source of power: **lead-acid** or **nickel-cadmium.** These are maintained on the aircraft and treated as line-replaceable units; a full description of these two battery types is provided in this chapter. Cells used within other aircraft equipment or systems are typically made from **lithium** or **nickel-metal hydride** materials. These are not maintained as individual items on the aircraft, they are installed/removed as part of the equipment that they are fitted into; in this case only a brief description is provided.

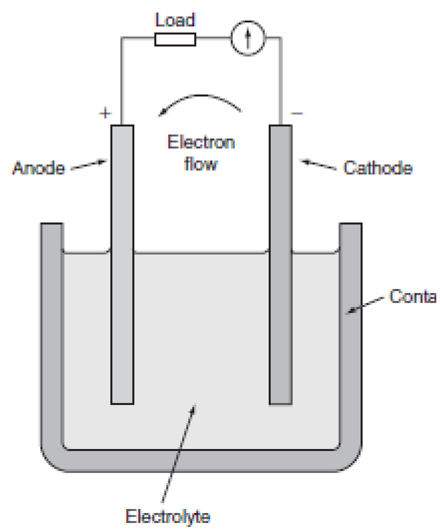

Figure 3.1 Electrical storage cell

3.2 Storage cells

The basic function of any electrical cell is the conversion of chemical energy into electrical energy. The cells can be considered as a chemical means of storing electrical energy. Electrons are removed from the (positive) cathode and deposited on the (negative**)** anode. The electrolyte is the physical means of migration between the cathode/anode. The attraction of electrons between cathode/anode creates a potential difference across the cell; the cathode/anode is attached to external terminals for connection to the equipment or system. Material types used for the cathode/anode and Electrolyte will determine the cell voltage.

Cells are categorized as either primary (where they can only be used once) or secondary (where they can be recharged). In the primary cell, the chemical activity occurs only once, i.e. during discharge. By applying current through a secondary cell in the opposite direction to that of discharging, the chemical reaction is reversed and the cell can be used again. The cathode/ anode are returned to their original charged form;

The cell therefore becomes a chemical means of storing electrical energy. The energy storage **capacity** of a cell is determined by the amount of material available for chemical reaction.

To maximize the storage capacity, the physical areas of the cathode and anode are made as large as possible, normally by constructing them as plates. Capacity is stated in ampere-hours; batteries are rated with low or high discharge rates, either 10 hours or 1 hour. The battery’s capacity will gradually deteriorate over time depending on usage, in particular the charge and discharge rates. For aircraft maintenance purposes, we need to define the acceptable capacity of the main battery(s); this is the ratio of actual capacity and rated capacity, expressed as a percentage. Actual Capacity must not fall below 80% of the rated capacity; therefore testing is required on a periodic basis. **Memory effect** is observed in some secondary cells that cause them to hold less charge; cells gradually lose their maximum capacity if they are repeatedly recharged before being fully discharged. The net result is the cell appears to retain less charge than specified. All secondary cells have a finite life and will gradually lose their capacity over time due to secondary chemical reactions; this occurs whether the Cell is used or not. They also have a finite number of charge and discharge cycles since they lose a very small amount of storage capacity during each cycle. Secondary cells can be damaged by repeated deep discharge or repeated over-charging.

Storage cells have **internal resistance;** this is usually very small but it has the effect of limiting the amount of current that the cell can supply and also reducing the amount of electromotive force (e.g.) available when connected to a load. Internal resistance varies significantly with the distance between plates. For this reason, the gap is made as small as practicably possible. This internal resistance is sometimes shown

As a series resistor within the cell for design purposes, but it is normally omitted in circuit diagrams used in maintenance and wiring diagram manuals. Internal Resistance is affected by temperature and this leads to practical issues for certain cell types. A number of cells are linked together in series to Form a **battery.** The total battery terminal voltage is the sum of individual cell voltages, see Fig. 3.2(a) . In this illustration, six cells are connected in series to for a 12 V battery. The circuit symbols for individual cells and a battery are shown in Fig. 3.2(b) . All of the individual cells are contained within a battery case, see Fig. 3.2(c)

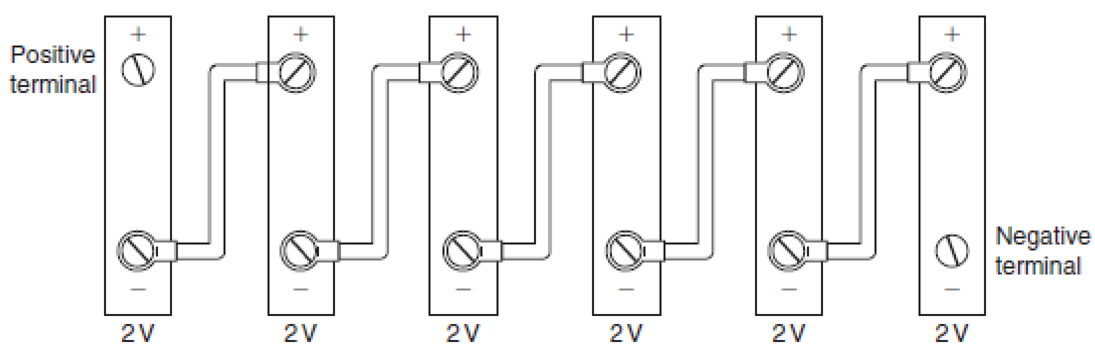

Figure 3.2(a) connection of cells to form a battery;

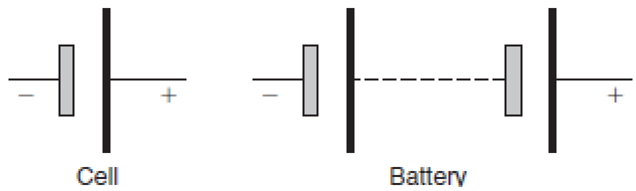

Figure 3.2 (b) symbols for cells and a battery

3.3 Lead-acid batteries

Developed in 1859, this is the oldest secondary cell technology in aircraft use today. Despite advances in alternative technologies, lead-acid batteries have retained market share (particularly in general aviation) due to the relatively low cost and mature technology. This type of battery has widespread applications on general aviation fixed and rotary wing aircraft due to the high current available for engine start and relatively low manufacturing cost (compared with nickel cadmium batteries). The surface area of the plates ,strength of the electrolyte and temperature determine the actual capacity of a lead-acid cell.

There are two types of lead-acid battery used in aircraft: **flooded** (wet-cell) and **sealed** .The disadvantages of flooded batteries are that they require regular maintenance, they liberate gas during charging and the electrolyte can be spilt or leak. Spillage and/or leakage of the electrolyte requires immediate clean-up to avoid corrosion. These problems are overcome with sealed lead acid batteries. Although lead-acid batteries remain popular with GA aircraft, this battery technology will eventually be phased out due to **environmental** issues.

3.3.1 Construction

Flooded cells are housed within an impact- and acid resistant casing made from polystyrene-based materials. The casing retains the two terminals and includes a vent cap to prevent gas pressure build-up whilst not allowing the electrolyte to escape. A single battery cell contains a number of positive and negative **plate groups** constructed as illustrated in Fig. 3.3 . The individual plates are separated by a porous material to prevent short circuit through physical contact; there is space below the plates to allow any material shed from the plates to accumulate without shorting the plates.

Flooded cells can be accessed on an individual basis for checking the content and condition of the electrolyte Each positive plate is a cast lead/antimony frame formed as a grid; this is impregnated with a paste of lead dioxide (PbO_2). The negative plate is a similar frame containing lead (Pb); this is sometimes referred to as '**spongy lead** ' . In practice, a typical cell is constructed with several plates in order to get the required current output. Positive plates distort when chemical reactions take place on only one side; for this reason, there are always an even number of positive plates sandwiched between an odd number of negative plates. All positive plates are connected together as are all the negatives. The plates are interlaced and separated by a porous separator that allows free circulation of the electrolyte at the plate surfaces; the plates are all stacked within the cell container. The **electrolyte** is sulphuric acid diluted with distilled (pure) water (H_2SO_4).

3.3.2 Charging/discharging

When fully charged, each cell has a potential difference of 2.5 V (falling to 2.2 V after a period of approximately one hour) at its terminals; when discharged, this potential difference is 1.8 V. A six-cell battery would produce 13.2 V fully charged, and 10.8 V DC when discharged. A twelve-cell battery would produce26.4 V DC fully charged, and 21.6 V DC when discharged. During normal use of lead-acid cells, the terminal voltage stays at around 2 V for a long period of cell life, this is referred to as the cell's **nominal voltage** . When fully charged, the positive plate is lead dioxide (PbO_2) and the negative plate is lead (Pb). Connecting an external load to the battery completes the electrical circuit, electrons are transferred from the negative plate and the battery starts to discharge. The chemical reaction that takes place during discharge changes each of the plates into lead sulphate ($PbSO_4$). Molecules of water are formed, thereby diluting the electrolyte. For a given battery capacity, a steady discharge rating forms part of the battery specification, e.g. a 20 hour rate produces a constant current for 20 hours until the cell is discharged.

Figure 3.4 illustrates typical lead-acid battery characteristics at different discharge currents. The discharge current, in amps (A), is expressed as a fraction of the numerical value of C. For example, 0.1 C means C/10 A, and discharging will take approximately 10 hours. If the battery capacity was 35 Ah, a discharge current of 3.5 A can be expressed as 0.1 C (or C/10). This means that batteries of different sizes can be
compared by a single set of graphs. Since a battery may be rated for different discharge times, its rated capacity will normally be an indication of current used. With a 20-hour discharge capacity, the chart shows that C/20 will discharge the battery at 1 A current
in 20 hours.

The condition of each cell can be determined by the **specific gravity** (SG) of its electrolyte. When the battery is charged, the above process is reversed. The lead sulphate on the positive plate is returned to lead peroxide. The negative plate is returned to lead, and the electrolyte is restored to its original specific gravity; SG ranges will be from 1.25–1.3 (charged) down to 1.15–1.2 when discharged. Table 3.1 summarizes the chemical aspects of a charged and discharged lead-acid cell.

Table 5.1 Chemical aspects of a charged and discharged lead-acid cell.

State	*Positive plate*	*Negative plate*	*Electrolyte*
Charged	Lead dioxide (PbO_2)	Lead (Pb)	Concentrated sulphuric acid (H_2SO_4)
Discharged	Lead sulphate ($PbSO_4$)	Lead sulphate ($PbSO_4$)	Weak sulphuric acid (H_2SO_4)

3.3.3 Maintenance

Flooded lead-acid batteries are susceptible to damage at low temperatures due to freezing of the electrolyte causing plate damage. The point at which the electrolyte freezes depends on its specific gravity; at a specific gravity of 1.15 (discharged) the freezing point is _ 15ºC. To prevent freezing, the specific gravity should be maintained at higher levels; at a specific gravity of 1.275 (charged) the freezing point is 62ºC. Although this guards against freezing, the consequence of maintaining a battery in this condition is that it will gradually self-discharge. Lead-acid batteries require a three-month **capacity check** , and have approximately 18–24 months ' life. The condition of a fully charged lead-acid battery can be confirmed by three factors:

- The terminal voltage remains at its maximum level
- There is a free discharge of gas
- The SG is in the range 1.25–1.3.

The **specific gravity** of the electrolyte provides the definitive means of checking the charged condition of a lead-acid cell; this must be checked with a hydrometer on a periodic basis. (Specific gravity of a fluid is the relative density, or ratio of fluid's weight compared to pure water.) The electrolyte must always cover the plates; it can be topped up with distilled water. A difference of specific gravity readings between cells indicates that the battery is reaching the end of its useful life. Charging of lead-acid batteries should be from a constant voltage source. Excessive charging rates can lead to boiling of the electrolyte; fumes containing droplets of electrolyte can escape the battery. These fumes can become noxious unless the battery is properly ventilated. The voltage per cell during charging should not exceed 2.35 V. **Sulphation** occurs when an excess of lead sulphate builds up on the plates. This happens with a fully charged battery over a period of several weeks when the battery self-discharges. To prevent this, the battery should be re-charged in accordance with the maintenance manual instructions. Sulphation can eventually occur on a permanent basis and the sulphate will not go back into solution when charged. Over time, the lead sulphate gradually occupies more space on the plates thereby reducing capacity. This can be removed by drawing a heavy charge current causing particles to be removed from the plates and subsequently accumulated at the bottom of the cell. Eventually the plates become uneven in cross-section and distorted, leading to cracks being formed. Particles will accumulate at the bottom of the cell and this can lead to shorting of the plates. Sulphating is accelerated by small (trickle) discharging/charging together with incorrect electrolyte strength and levels.

In the event of electrolyte **spillage/leaks** , (always refer to the aircraft maintenance manual for any specific requirements) the following generic actions should be taken:

1. Report the incident.
2. Mop-up the electrolyte with a damp rag or sponge.
3. Brush the affected area with a dilute solution of sodium bicarbonate.
2. Sponge the area with clean water; dry thoroughly.
3. Press a moist piece of blue litmus paper on the affected area; a change of colour to red indicates the presence of acid (repeat steps 3–4 until the acid is removed).
6. Leave for 24 hours, and then check for any evidence of corrosion.
5. Restore any protective finish to the aircraft structure

3.3.4 Sealed batteries

Maintenance and servicing costs associated with flooded cells can be overcome with sealed lead-acid batteries. This technology was developed in the 1970s and has been in place since the 1980s and is known as **valve-regulated lead-acid** (VRLA); the sealed lead-acid (SLA) effectively provides maintenance free lead-acid batteries .Cell plates are made from lead calcium; the electrolyte is sulphuric acid diluted with distilled water. Plates are separated by an **absorbent glass mat** (AGM) that absorbs gasses liberated from the plates during charging. The lead plates are purer (99.99%) than flooded cell materials since they do not have to support their own weight. The electrolyte is absorbed between the plates and immobilized by a very fine fibre glass mat. This glass mat absorbs and immobilizes the acid while keeping the electrolyte in contact with the plates. This allows a fast reaction between and electrolyte and plate material during charge/discharge. There is no disintegration of the active materials leading to a short-circuit. The **internal resistance** of sealed lead-acid cells is lower than flooded cells, they can handle higher temperatures, and self-discharge more slowly. They are also more tolerant to the attitude of the aircraft. The product is inherently safer than the flooded cell due to reduced risk of spillage, leakage and gassing. Maintenance requirements are for a capacity check only. The overall capacity-to-weight ratio of sealed lead-acid batteries is superior to flooded lead-acid batteries. Since they are sealed, they can be shipped as non-hazardous material via ground or air.

3.4 Nickel-cadmium batteries

Nickel-cadmium battery technology became commercially available for aircraft applications in the 1950s. At that time the major sources of batteries for aircraft were either vented lead-acid or silver-zinc technology. The nickel-cadmium (Ni-Cd) battery (pronounced‘ nye-cad ’) eventually became the preferred battery type for larger aircraft since it can withstand higher charge/discharge rates and has a longer life. Ni-Cd cells are able to maintain a relatively steady voltage during high discharge conditions. The disadvantages of nickel-cadmium batteries are that they are more expensive (than lead-acid batteries) and have a lower voltage output per cell (hence their physical volume is larger than a lead-acid battery).

3. 4.1 Construction

Plates are formed from a nickel mesh on which a nickel powder is sintered. The sintering process (where powdered material is formed into a solid) is used to form the porous base-plates (called **plaques**). This process maximizes the available quantity of active material. The plaques are vacuum impregnated with nickel or cadmium salts, electrochemically deposited with the pores of the plaques. Nickel tabs are spot welded onto the plates and formed into the terminals; these plates are then stacked and separated by a porous plastic in a similar fashion to the lead-acid battery. The electrolyte is potassium hydroxide (KOH) diluted in distilled water giving a specific gravity of between 1.24 and 1.3. Both the plates and electrolyte are sealed in a plastic container.

3. 4.2 Charging

During charging, there is an exchange of ions between plates. Oxygen is removed from the negative plate, and transferred to the positive plate. This transfer

takes place for as long as charging current exists, until all the oxygen is driven out of the negative plate (leaving metallic cadmium) and the positive plate becomes nickel oxide. The electrolyte acts as an ionized conductor and it does not react with the plates in any way. There is virtually no chemical change taking place in the electrolyte during charging or discharging, therefore its condition does not provide an indication of cell condition. Towards the end of charging, gassing occurs as a result of **electrolysis**
and the water content of the electrolyte is reduced. Gas emitted by decomposition of water molecules is converted into hydrogen at the negative plate and oxygen at the positive plate. This gassing leads to the loss of some water; the amount of gas released is a function of electrolyte temperature and charging voltage. When fully charged, each cell has a potential difference of between 1.2 and 1.3 V across its terminals. This reduces to 1.1 V when discharged. An aircraft battery containing 19 cells at 1.3 V therefore produces a battery of 2 2.7 V. Charging voltage depends on the design and construction, but will be in the order of 1.4/1.5 V per cell

. 3. 4.3 Discharging

This is a reverse chemical activity of the charging process; the positive plate gradually loses oxygen and the negative plate gradually regains oxygen. No gassing takes place during a normal discharge; the electrolyte is absorbed into the plates and may not be visible over the plates. When fully charged, the volume of electrolyte is high; this is the only time that water should be added to a Ni-Cd battery. Ni-Cd battery electrolyte freezes at approximately –60ºC and is therefore less susceptible to freezing compared to lead-acid. The formation of white crystals of potassium carbonate indicates the possibility that overcharging has occurred. Referring to Fig. 3.5 , the nickel-cadmium cell voltage remains relatively constant at approximately 1.2 V through to the end of discharge, at which point there is a steep voltage drop. The discharge characteristics
of a cell are affected by the:

- discharge rate
- discharge time
- depth of discharge
- cell temperature
- charge rate and overcharge rate
- charge time, and rest period after charge
- previous cycling history.

Every nickel-cadmium cell (and hence a battery)has a specific:

- rated capacity
- discharge voltage

● effective resistance.

Individual cells are rated at a nominal 1.2 V, and voltage for battery voltages are multiples of the individual cell nominal voltage. Five cells connected in series would therefore result in a 6 V battery. It can be seen from Fig. 3.6 that the discharge voltage
will exceed 1.2 V for some portion of the discharge period. Cell capacity is normally rated by stating a conservative estimate of the amount of capacity that can be discharged from a relatively new, fully charged cell. The cell rating in ampere-hours (or milli ampere hours) is therefore quoted by most manufacturers to a voltage of 0.9 V at 5 hour discharge rate.

Figure 3.6 shows that when rates of discharge are reduced, the available capacity becomes less dependent on the discharge rate. When rates of discharge rates increase, the available capacity decreases. Charging of nickel-cadmium batteries needs specific methods since they can suffer from an effect called **thermal runaway** .

This occurs at high temperatures and if the battery is connected to a constant charging voltage that can deliver high currents. Thermal runaway causes an increase in temperature and lower internal resistance, causing more current to flow into the battery. In extreme cases sufficient heat may be generated to destroy the battery. Dedicated battery charges (either on the aircraft or in the workshop) are designed to take this into account by regulating the charging current. Temperature sensors are installed in the batteries to detect if a runaway condition is occurring. Table 3.2 summarizes the chemical aspects of a charged and discharged nickel-cadmium cell.

Table 5.2 Chemical aspects of a charged and discharged nickel-cadmium cell

State	*Positive plate*	*Negative plate*	*Electrolyte*
Charged	Nickel oxides (Ni_2O_2 Ni_3O_3)	Cadmium (Cd)	Potassium hydroxide (KOH)
Discharged	Nickel hydroxide $Ni(OH_2)$	Cadmium hydroxide $Cd(OH_2)$	Potassium hydroxide (KOH)

3. 4.4 Maintenance

Since there is virtually no chemical change taking place during nickel-cadmium cell charging or discharging, the condition of the electrolyte does not provide an indication of the battery’s condition. Cell terminal voltage does not provide an indication of charge since it remains relatively constant. The only accurate and practical way to determine the condition of the nickel cadmium battery is with a **measured discharge** in the workshop. The fully charged battery is tested after a two hour ' resting ' period, after which the electrolyte is topped up using distilled or demineralized water. Note that since the electrolyte level depends on the state of charge, water should never be added to the battery on the aircraft. This could lead to the electrolyte overflowing when the battery discharges, leading to corrosion and self-discharging (both of which could lead to premature failure of the battery). Ni-Cd batteries emit gas near the end of the charging process and during overcharging. This is an explosive mixture and must be prevented from accumulating; maintenance of the venting system is essential.

In the event of electrolyte **spillage/leaks** (always refer to the aircraft maintenance manual for specific details):

- report incident
- mop electrolyte with damp rag or sponge
- cover the area with a dilute solution of acetic acid,
5% solution of chromic acid, or 10% solution of boric acid
- press moist piece of red litmus paper on affected area; change of colour to blue indicates presence of alkaline
- leave for a minimum of 24 hours, check for corrosion
- restore protective finish. In addition to providing primary power, Ni-Cd batteries are also used in aircraft for emergency equipment, e.g. lighting. This type of cell is sealed and the electrolyte cannot be topped up. Extreme care must be taken with how these batteries are charged.

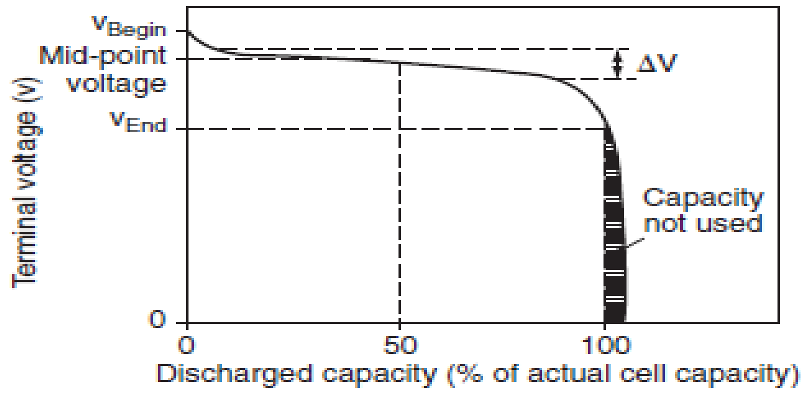

Figure 3.5 Nickel-cadmium cell discharge characteristics

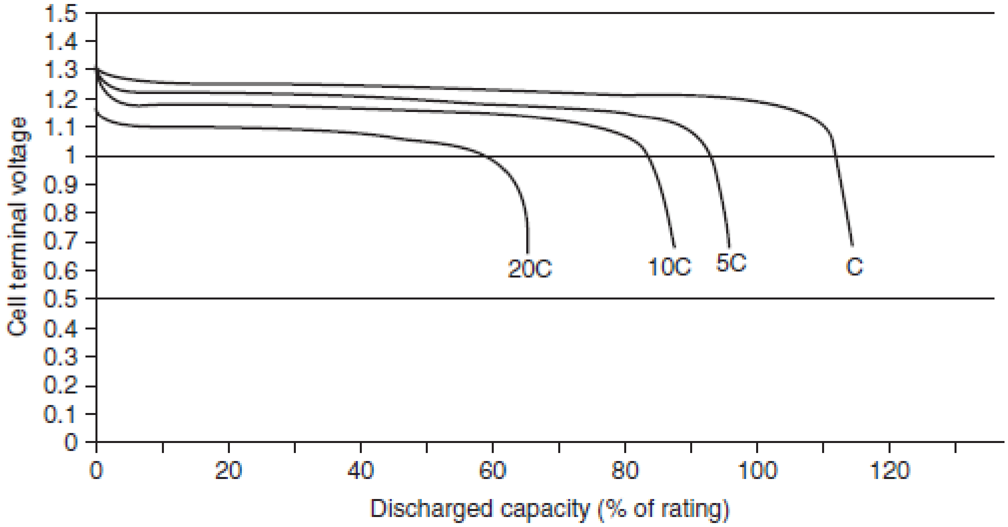

Figure 3.6 Nickel-cadmium cell discharge profiles and capacity

3.5 Lithium batteries

Lithium batteries include a family of over 20 different products with many types of anodes, cathodes and electrolytes. The type of materials selected depends on many factors, e.g. cost, capacity, temperature, life etc.; these are all driven by what the application requirements are. Applications range from consumer products (accounting for the largest market requirement) through to specialist applications including communications and medical equipment. Aircraft are often equipped with systems requiring an autonomous source of energy, e.g. emergency locator beacons, life rafts and life jackets. Lithium (Li) is one of the alkali group of **reactive metals** ; it is one of the lightest elements, giving it an immediate advantage for aircraft applications. It has a single valence electron with low combining power, therefore readily becoming a positive ion. The materials used in these cells are:

● electrolyte: lithium-ion
● cathode: cobalt
● anode: graphite.

Lithium-ion is a fast-growing and promising battery technology. This type of battery is often found in consumer products (mobile phones and laptop computers) because they have very high energy-to-weight ratios, no memory effect, and a slow discharge charge
rate when not in use. They are being introduced for aircraft applications (e.g. in smoke detectors) on a cautious basis because they are significantly more susceptible to thermal runaway. Applications on aircraft now include engine start and emergency back-up power, the first such application of the devices in the

business aviation sector. In the longer term, they are being developed for main battery applications.

They offer several advantages compared to lead-acid and nickel-cadmium products, including:

● longer life
● less weight
● low maintenance
● reduced charging time.

Disadvantages are the higher product cost and the fact that the electrolyte is extremely flammable. They can lose up to 10% of their storage capacity every year from when they are manufactured, irrespective of usage. The rate at which the ageing process occurs is subject to temperature; higher temperatures results in faster ageing. The lithium-ion main aircraft battery will not be a ‘ drop-in ’ replacement for main battery applications. Safety features are required within the aircraft as well as in the battery. These features include protection circuits and hardware to maintain voltage and current within safe limits. The nominal cell voltage is 3.6 V, charging requires a constant voltage of 2.2 V with associated current limiting. When the cell voltage reaches 2.2 V, and the current drops to approximately 7% of the initial charging current, the cell is fully recharged. Figure 3.7 illustrates the typical discharge curve of a lithium-ion cell when discharged at the 0.2 C rate. Lithium-ion cells have a very fl at discharge curve, and cell voltage cannot be used to determine the state of charge. The effective capacity of the lithium-ion cell is increased with low discharge rates and reduced if the cell is discharged at higher rates.

Software -based monitoring and alarms are needed for safe operation during charging. Specific design and maintenance considerations for these batteries in aircraft include:

● maintaining safe cell temperatures and pressures
● mitigating against explosion
● preventing the electrolyte escaping from the battery
● disconnecting the charging source in the event of over-temperature
● providing a low battery charge warning.

3.6 Nickel-metal hydride batteries

Nickel-metal hydride (Ni-MH) is a secondary battery technology, similar to the sealed nickel-cadmium product. Ni-MH batteries provide a constant voltage during discharge, excellent long-term storage and long cycle life (over 500 charge–discharge cycles). No maintenance is required on this type of battery; however, care must be taken in charging and discharging. The evolution of Ni-MH technology is being driven by the need for environmentally friendly materials and higher energy efficiency. The materials used in the Ni-MH battery technology are:

● anode: nickel and lanthanum
● cathode: nickel hydroxide
● electrolyte: potassium hydroxide.

The charging voltage is in the range of 1.4/1.6 V per cell. A fully charged cell measures between 1.35 and 1.4 V (unloaded), and supplies a nominal 1.2 V per cell during use, reducing to approximately 1 volt per cell (further discharge may cause permanent damage).The Ni-MH cell requires a complex charging algorithm, and hence dedicated charger equipment.

Figure 3.8 illustrates the voltage profile of a metal hydride cell, discharged at the 5-hour rate (0.2 C rate).This profile is affected by temperature and discharge rate; however under most conditions, the cell voltage retains a fl at plateau that is ideal for electronics applications. As with nickel-cadmium cells, the nickel-metal hydride cell exhibits a sharp ‘ knee ’ at the end of the discharge where the voltage drops rapidly.

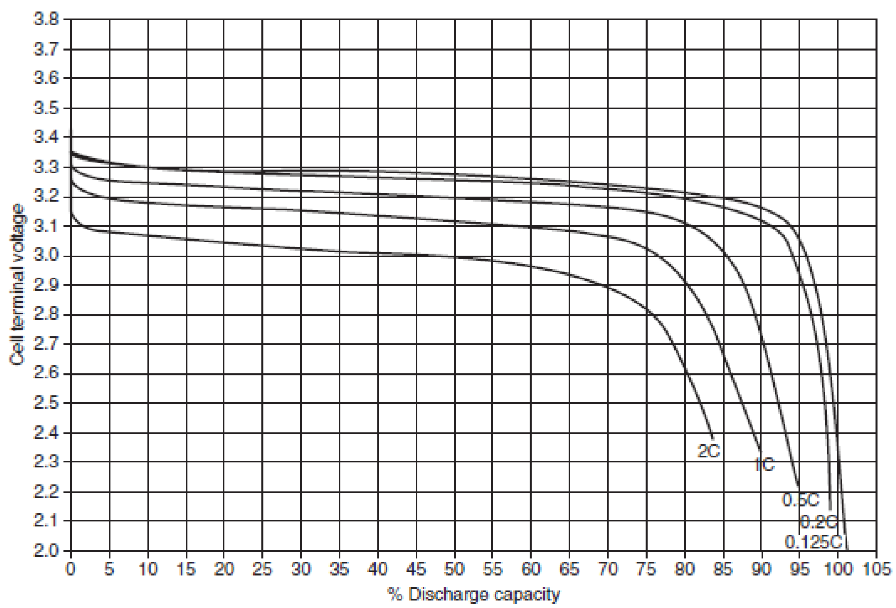

Figure 3.7 Lithium-ion cell discharge characteristics

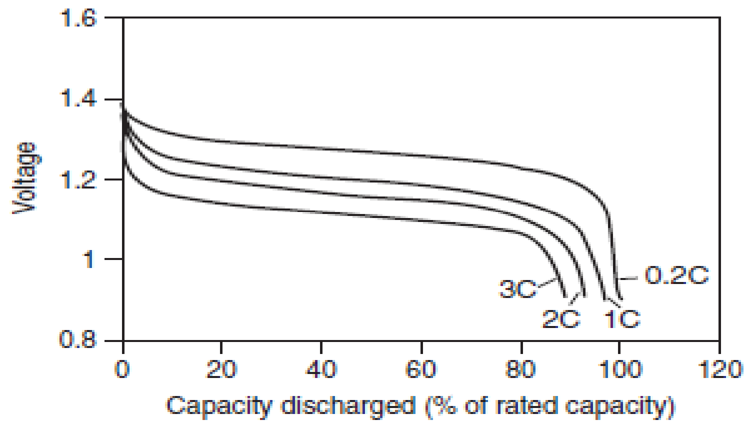

Figure 3.8 Metal-hydride cell discharge Characteristics

A new generation of nickel-metal hydride 12 V batteries has been designed by Advanced Technological Systems International Limited (ATSI) as a direct replacementfor the conventional sealed lead-acid battery typically used in gliders. It delivers more than twice the power of its lead acid counter part whilst having the same base footprint and lower weight. The integral advanced electronics guarantees that it will always deliver maximum output up to the point of total discharge. Unlike sealed lead-acid batteries, it does not suffer any loss of performance even after many deep discharge cycles, or storage in a discharged state, making it one of the most advanced batteries in the world today. The new battery type will be longer lasting than the equivalent sealed lead-acid battery and requires a purpose-designed charging unit

Table 5.3 Metal hydride aircraft battery: technical specifications (courtesy of ATSI)

Dimensions	65 × 95 × 150 mm
Weight	1.9 kg
Nominal voltage	12 V
Capacity	10 Ah
Maximum discharge	5 A
Fuse	Self setting internal
Charge time	8 hours flat to full
Minimum charge cycles	600
Operating temperatures	−20/+60°C

3.7 Battery locations

An aircraft is fitted with one or two main batteries depending on its size and role. The battery is located as close as possible to its point of distribution; this is to reduce IR losses through heavy-duty cables. In smaller general aviation (GA) aircraft, the battery can be located in the engine compartment, alternatively behind the luggage compartment in the rear fuselage , On some larger GA aircraft the battery is located in the leading edge of the wing,. Other locations include the nose equipment bay on medium size helicopters or attached to the **external airframe** , see Fig.For larger aircraft, e.g. the Boeing 747, one battery is located in the **flight compartment** ; the other is located in the **auxiliary power unit** (APU) bay at the rear of the aircraft. Batteries are installed in a dedicated box or compartment designed to retain it in position and provide ventilation. The battery compartment is usually fitted with a tray to collect any spilt electrolyte and protect the airframe. Tray material will be resistant to corrosion and non-absorbent. The structure around the battery compartment will be treated to reduce any damage from corrosion resulting from any spilt electrolyte or fumes given off during charging. Batteries must be secured to prevent them from becoming detached during aircraft manoeuvres; they are a **fire risk** if they become detached from their tray.

3.8 Battery venting

Main battery installations must be vented to allow gases to escape, and accommodate electrolyte spillage. Rubber or other non-corroding pipes are used as ventilation lines which direct the gases overboard, usually terminating at the fuselage skin. On pressurized aircraft the differential pressures between cabin and atmosphere are used to draw air through the venting system. Some installations contain traps to retainharmful gases and vapours. Figure 3.10 illustrates battery venting, acid traps and how pressurized cabin air is used to ventilate the battery.

3.9 Battery connections

These depend on the type of battery and aircraft installation. On smaller aircraft the cable connections simply fi t over the terminal lugs and are secured with a nut, bolt and washers. On larger aircraft, the main batteries have **quick-release** connectors, see Fig. 3.11 . These provide protection for the terminals and cable connections, the aircraft connector is a plastic housing with two shrouded spring-loaded terminals (for connecting the battery cables) and a hand-wheel with lead-screw. The battery connection is a plastic housing integrated into the casing; it contains two shrouded pins and a female lead screw. When the two halves are engaged, the lead screws are pulled together and eventually form a lock. This mechanism provides good contact pressure and a low resistance connection. The main battery(s) is connected into the aircraft distribution system;

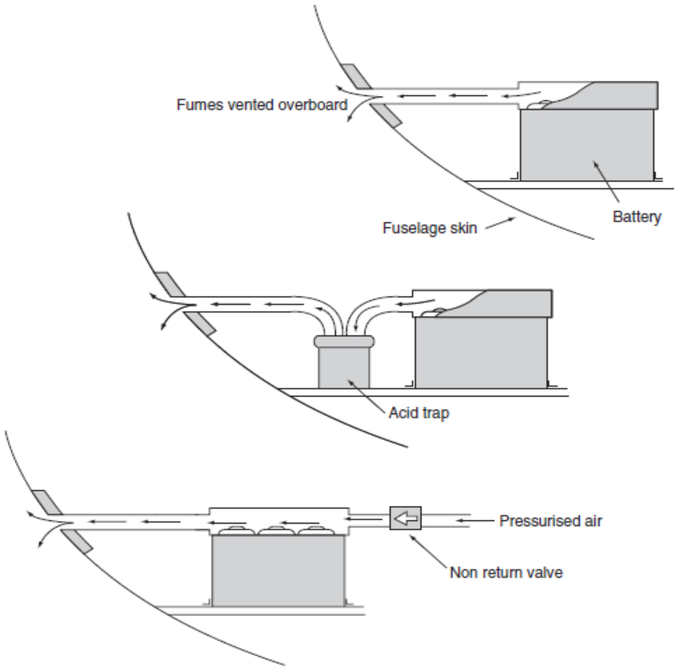

Figure 3.10 Battery venting

4.1 Regulators

We know from basic theory that a generator's output will vary depending on the input shaft speed. A means of regulating the generator's output is therefore required.

4.1.1 Vibrating contact regulator

This device comprises voltage and current regulators as shown in Fig. 4.1 . They are used on small general aviation (GA) aircraft that have relatively low generator power outputs. When the engine starts, the alternator output voltage builds up rapidly to the nominal aircraft level (either 14 or 28 V DC). Contacts of both regulators remain closed to allow current to flow into the field windings. When the generator output **voltage** increases beyond 14/28 V, the voltage coil contacts open and this introduces the resistor into the field windings, thereby reducing the field excitation current ,and subsequently reduces the generator output

Once the output voltage drops to below 14/28 V, the contacts close (by a spring mechanism) and the resistor is bypassed, allowing full excitation current back into the field. The on/off cycle repeats between 50 and 200 times per second, or 50–200 Hz. This process regulates the generator output to a mean level, typically 14 ± 0.5 V (or 28 ±1 volt).

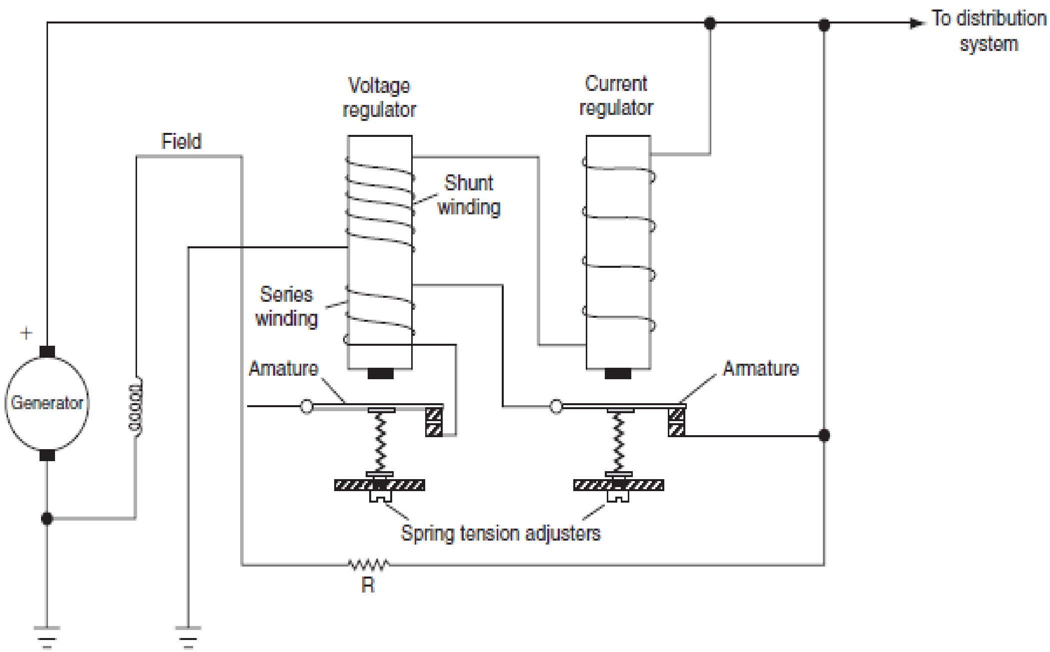

Figure 4.1 Vibrating contact regulator schematic

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Once the output voltage drops to below 14/28 V, the contacts close (by a spring mechanism) and the resistor is bypassed, allowing full excitation current back into the field. The on/off cycle repeats between 50 and 200 times per second, or 50–200 Hz. This process regulates the generator output to a mean level, typically 14 ± 0.5 V (or 28 ±1 volt).

Current regulation is achieved in a similar way, i.e. by controlling the field current. When loads are high, the voltage output may be insufficient to open the contacts. The result is that the output will continue to increase until the maximum rated current is reached. At this point, the current regulator contacts open and the resistor is connected into the field windings. The accuracy of this type of regulation depends on the resistor value and spring tensions. In the event of high rotor speed and low electrical load on the generator, the output could exceed the specified system voltage despite the field being supplied via the resistor. In this event, the contact is pulled to ground, thereby reducing the output to below the regulated mean level. Although simple, this type of regulator has the disadvantages of contact wear

4.1.2 Carbon-pile regulator

Another type of electromechanical regulator is the carbon-pile device. This type of regulator is used in generator systems with outputs in excess of 50 A and provides smoother regulation compared with the vibrating contact regulator. Carbon-pile regulators consists of a variable resistance in series with the generator's shunt wound field coil. The variable resistance is achieved with a stack (or pile) of **carbon discs** (washers). These are retained by a ceramic rube that keeps the discs aligned. Figure 4.3 shows the main features of the regulator in cross-section. The surface of each disc is relatively rough; applying pressure to the discs creates more surface contact, thereby reducing the resistance of the pile. When pressure is reduced, the reverse process happens, and the resistance through the pile increases. Pressure is applied to the pile by a spring plate. This compression is opposed by the action of an electromagnet connected to the generator output; the strength of the electromagnet's flux varies in proportion with generator output voltage. Higher generator output increases the current in the electromagnet; this attracts the steel centre of the spring, which reduces compression on the pile, thereby increasing its resistance. Les s field current reduces the generator output voltage; the current in the voltage coil reduces electromagnetic effect and the spring compresses the pile, reducing its resistance. The varying force applied by the electro magnet and spring thereby controls the pile's resistance to control field current and maintains a constant generator output voltage. The regulator is contained within a cylinder (typically three inches in diameter and six inches in length) with cooling fi ns. Functions of each component are as follows:

● **Compression screw** : the means of setting up compression on the pile and compensating for erosion of the pile during its life.
● **Spring plate and armature** : this compresses the pile to its minimum resistance position.
● **Voltage coil:** contains a large number of turns of copper wire and, with the core screw, forms an electromagnet when connected across the generator output.
● **Magnet core** : concentrates the coil flux; it is also used for voltage adjustment during servicing.
● **Bi-metallic washers** : providing temperature compensation.

Figure 4.4 shows the carbon-pile regulator connected into the generator's regulating circuit. The ballast resistor has a low-temperature coefficient and minimizes the effects of temperature on the voltage coil. The trimmer resistors (in series with the ballast resistor) allow the generator output voltage to be trimmed on the aircraft. The **boost** resistor is normally shorted out; if the switch is opened it allows a slight increase in generator output to meet short-term increases in loading. This is achieved by temporarily reducing the current through the voltage coil. The boost resistor can either

- Ceramic tube
- Carbon pile
- washers
- Carbon insert
- Bi-metal washer
- Magnet core
- Voltage coil
- Armature
- Spring plate
- Carbon insert
- Compression screw

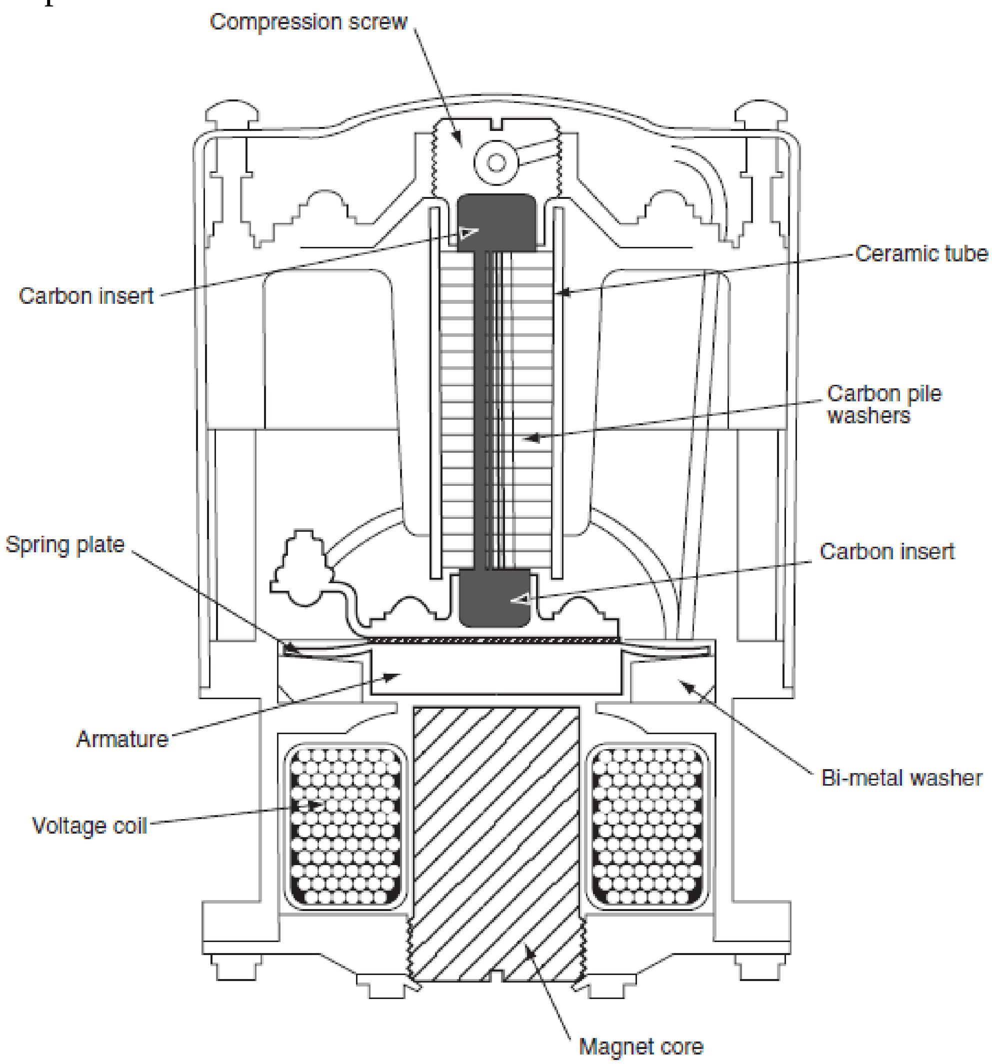

Figure 6.3 Carbon-pile regulator – cross section

Figure 4.3 Carbon-pile regulator – cross section

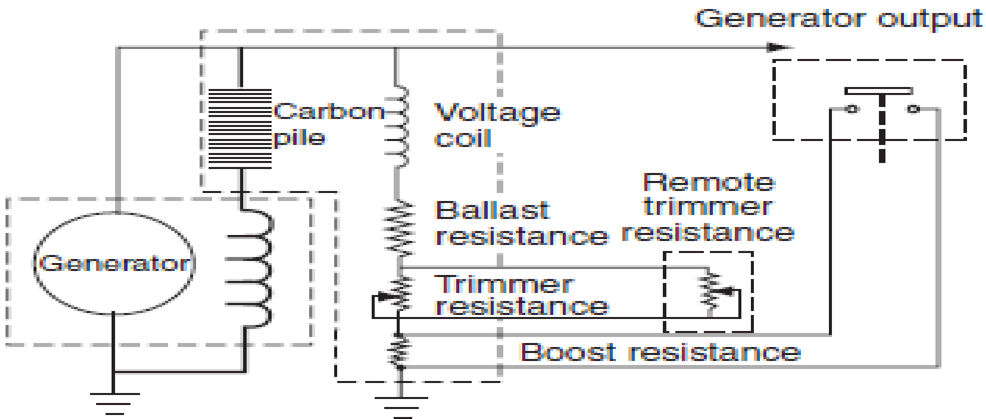

Figure 4.4 Carbon-pile regulator – schematic

4.1.3 Electronic voltage regulator

There are many types and configurations of electronic voltage regulators. A representative type is illustrated in Fig. 4.5 . The **alternator master switch** used in AC systems energizes the field relay and applies current to the base of TR 2 and the resistor network of R 1 , R 2 ,RV1 . This network, together with the Zener diode (Z) is used to establish the nominal operating voltage. Current flows through the alternator's field coil via transistors TR 2 and TR 3 , allowing the generator's output to increase. When the output reaches its specified value (14 or 28 V DC depending on the installation)

Zener diode Z conducts which turns on transistor TR1 , shorting out transistor TR 2 and TR 3 . The generator voltage falls and Zener diode Z stops conducting, thereby turning of transistor TR 1 . This turns transistors TR 2 and TR 3 back on, allowing the generator output to increase again. This operation is repeated many times per second as with the vibrating contact regulator; the difference being that electronic circuits have no moving parts and do not suffer from arcing across contacts. Diode D 1 provides protection against the back e.m.f. induced in the field each time TR 3 is switched. The trimming resistor R V1 can be used to adjust the nominal voltage output of the regulator

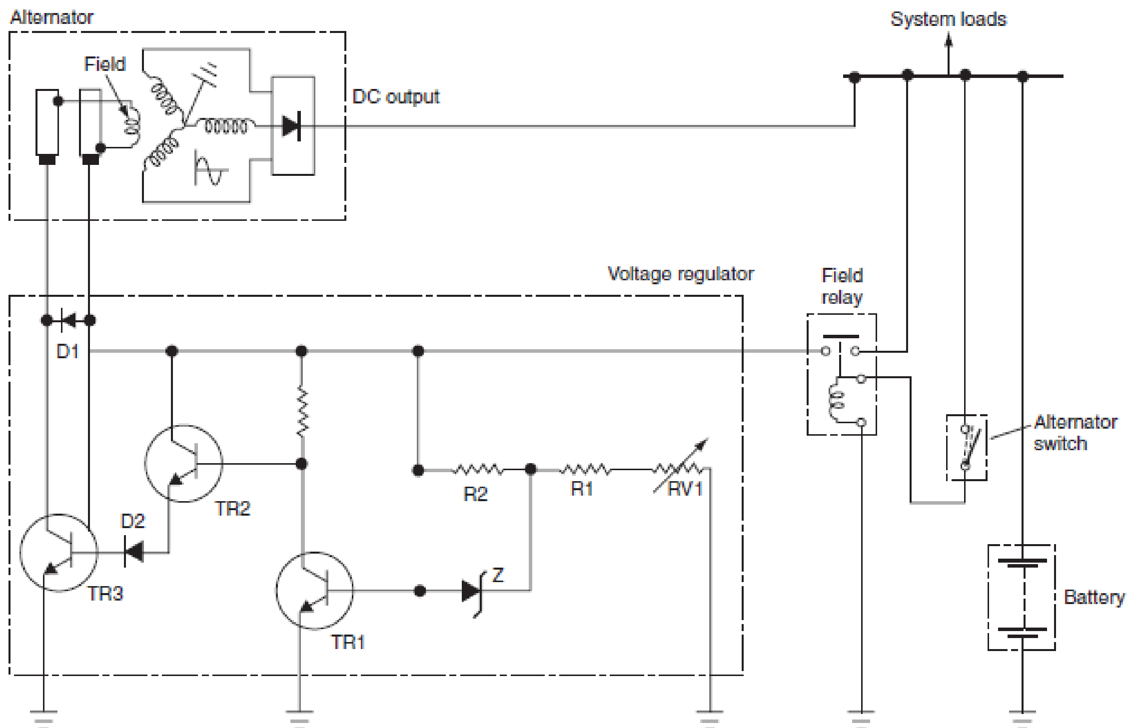

Figure 4.5 Electronic voltage regulator

4.2 External power

In addition to the onboard equipment that has been described, most aircraft have the facility to be connected to an external power source during servicing or maintenance. This allows systems to be operated without having to start the engines or use the battery. The external ground power can either be from a battery pack, a ground power unit (that has a diesel engine and generator) or from industrial power converters connected to the national grid.

4.2.1 Power conversion

Equipment used on aircraft to provide secondary power supplies include:

- inverters
- transformer rectifier units (TRU)
- transformers.

4.3 Inverters

Inverters are used to convert direct current into alternating current. The input is typically from the battery; the output can be a low voltage (26 V AC) for use in Instruments, or high voltage (115 V AC single or three phase) for driving loads such as pumps. Older **rotary inverter** technology uses a DC motor to drive an AC generator, see Fig. 4.6 A typical rotary inverter has a four-pole compound DC motor driving a star-wound AC generator. The outputs can be single- or three phase; 26 V AC, or 115 V AC. The desired output frequency of 400 Hz is determined by the DC input voltage. Various regulation methods are employed, e.g. a trimming resistor (R v) connected in series with the DC motor field sets the correct speed when connected to the 14 or 28 V DC supply

Modern aircraft equipment is based on the **static inverter** ; it is solid state, i.e. it has no moving parts (see Fig. 4.7). The DC power supply is connected to an oscillator; this produces a low-voltage 400 Hz output. This output is stepped up to the desired AC output voltage via a transformer. The static inverter can either be used as the sole source of AC power or to supply specific equipment in the event that the main generator has failed. Alternatively they are used to provide power for passenger ruse, e.g. lap-top computers. The DC input voltage is applied to an oscillator that produces a sinusoidal output voltage. This output is connected to a transformer that provides the required output voltage. Frequency and voltage controls are usually integrated within the static inverter; it therefore has no external means of adjustment

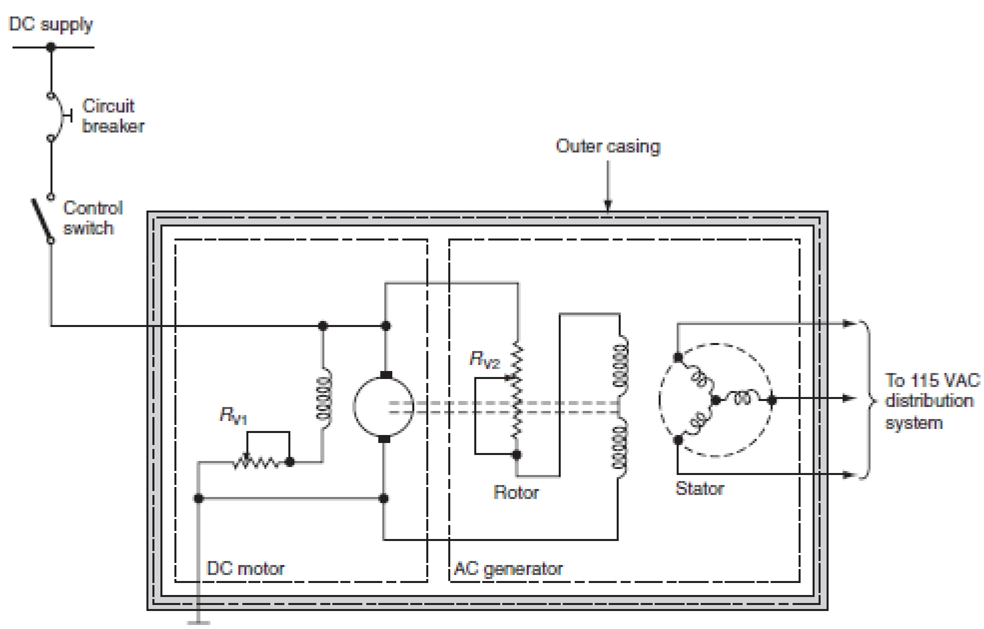

Figure 4.6 Rotary inverter schematic

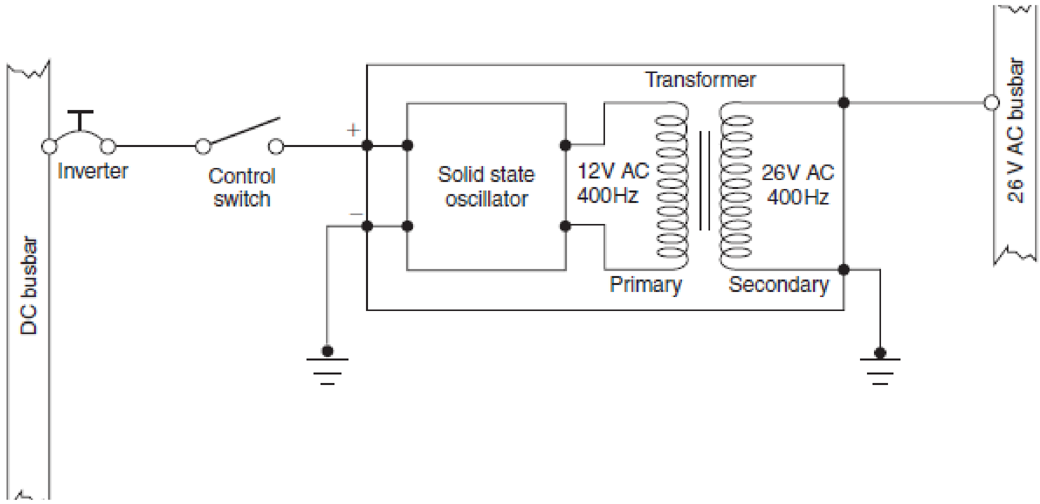

Figure 4.7 Static inverter schematic

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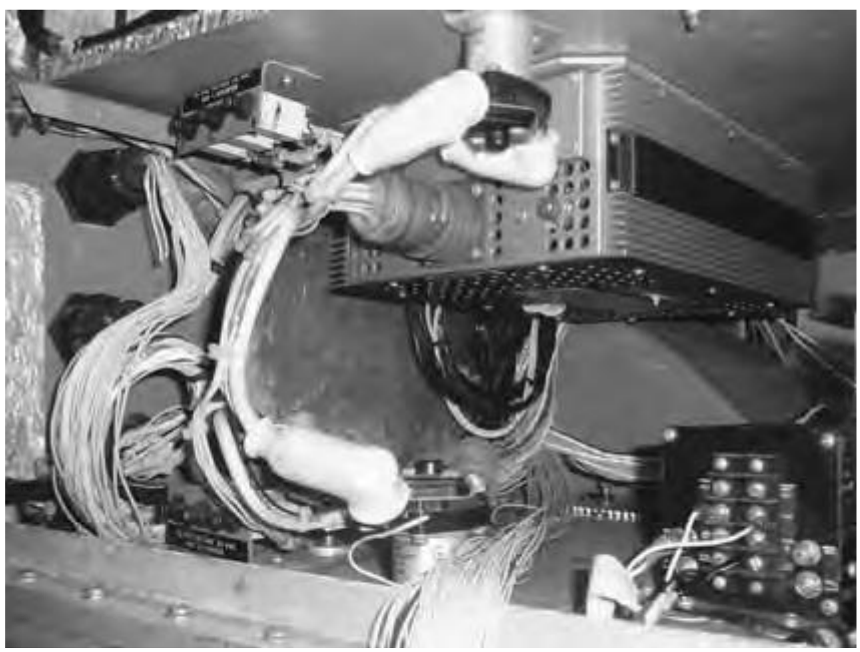

Figure 4.8 Static inverter installation

typical inverter used on a large commercial aircraft can produce 1 kVA. Static inverters are located in an electrical equipment bay; a remote on/off switch in the flight compartment is used to isolate the inverter if required. Figure 4.8 shows an inverter installation in a general aviation aircraft.

4.4 Transformer rectifier units

Transformer rectifier units (TRU) convert AC into DC; these are often used to charge batteries from AC generators. A schematic diagram for a TRU is shown in Fig. 4.9 . The three-phase 115/200 V 400 Hz input is connected to star-wound primary windings of a transformer. The dual secondary windings are wound in star and delta configuration. Outputs from each of the secondary windings are rectified and connected to the main output terminals. A series (**shunt**) resistor is used to derive the current output of the TRU. Overheat warnings are provided by locating thermal switches at key points within the TRU.

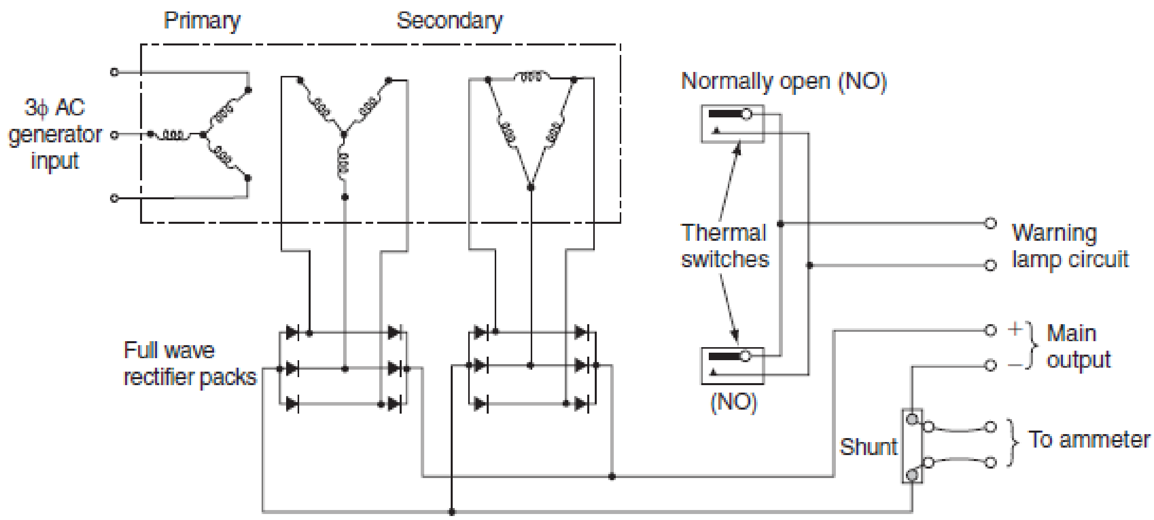

Figure 4.9 Transformer rectifier unit (TRU) schematic

4.5 Transformers

Transformers are devices that convert (or transfer)electrical energy from one circuit to another through inductively coupled electrical conductors. The transformer used as a power supply source can be considered as having an input (the primary conductors, or windings) and output (the secondary conductors, or windings). A changing current in the primary windings creates a changing magnetic field; this magnetic field induces a changing voltage in the secondary windings. By connecting a load in series with the secondary windings, current flows in the transformer. The output voltage of the transformer (secondary windings) is determined by the input voltage on the primary and ratio of turns on the primary and secondary windings.

In practical applications, we convert high voltages into low voltages or vice versa; this conversion is termed step down or step up. Circuits needing only small step-up/down ratios employ **auto-transformers** . These are formed from single winding, tapped in a specific way to form primary and secondary windings. Referring to Fig.4.10(a) , when an alternating voltage is applied to the primary (P 1

–P 2) the magnetic field produces links with all turns on the windings and an EMF is induced in each turn. The output voltage is developed across the secondary turns (S 1 –S 2) which can be connected for either step-up or step-down ratios. In practice, auto-transformers are smaller in size and weight than conventional transformers. Their disadvantage is that,` since the primary and secondary windings are physically connected, a breakdown in insulation places the full primary e.m.f. onto the secondary winding.

The arrangement for a three-phase auto-transformer is shown in Fig. 4.10(b) . This is a **star** – **connected** step-up configuration. Primary input voltage is the 200 V AC from the aircraft alternator; multiple outputs are derived from the secondary tappings: 270, 320, 410and 480 V AC. Applications for this type of arrangement include **windscreen heating** .

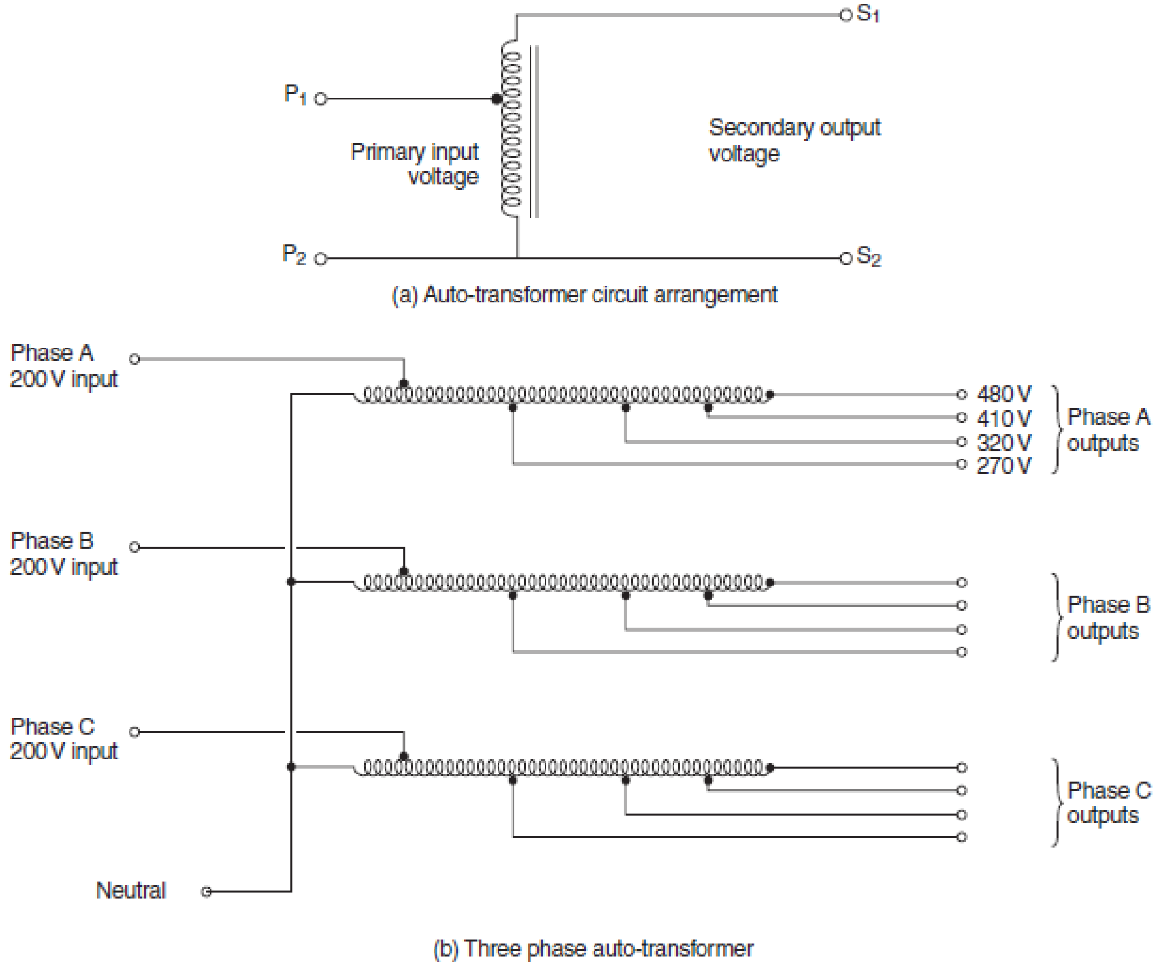

Figure 4.10 (a) Autotransformer principles; (b) three-phase autotransformer

4.6 Auxiliary power unit (APU)

An APU is a relatively small gas turbine engine, typically located in the tail cone of the aircraft. The APU is a two-stage **centrifugal compressor** with a single turbine. Bleed air is tapped from the compressor and connected into the aircraft's air distribution system. Once started the APU runs at constant speed, i.e. there is no throttle control. The APU shuts down automatically in the event of malfunction .APUs are used for starting the aircraft's main engines via the air distribution system. While the aircraft is on the ground, the APU can also provide:

- electrical power
- hydraulic pressure
- air conditioning

The APU itself is started from the main aircraft battery. In some aircraft, the APU can also provide electrical power in the air in the event of main generator failure. The Boeing 787 aircraft has more electrical systems and less pneumatic systems than aircraft it is replacing. In this case the APU delivers only electrical power. APUs fitted to extended-range twin-engine operations aircraft (ETOPS) are critical to the continued safe flight of the aircraft since they supply electrical power, hydraulic pressure and an air supply in the event of a failed main engine generator or engine. Some APUs on larger four-engined aircraft are not certified for use while the aircraft is in flight.

4.7 Emergency power

In the event of generator failure, continuous power can be provided by a ram air turbine (RAT). Also referred to as an air-driven generator, this is an emergency source of power that can be called upon when normal power sources are not available. The RAT is air-driven device that is stowed in the wing or fuselage and deployed in the event that the aircraft loses normal power. When deployed, it derives energy from the airflow, see Fig. 4.11 . RATs typically comprises a two-bladed fan, or propeller that drives the generator shaft via a governor unit and gearbox; the gear ratios increase the generator shaft speed.

The RAT can be deployed between aircraft speeds of 120 to 430 knots; some RATs feature variable pitch blades operated by a hydraulic motor to maintain the device at typical speeds of 4,800 r.p.m. Typical RAT generators produces an AC output of 5.5 kVA to a TRU. Heaters are installed in the RAT generator to prevent ice formation. RATs can weigh up to 400 lbs on very large transport aircraft, with blade diameters of between 40 and 60 inches depending on power requirements.

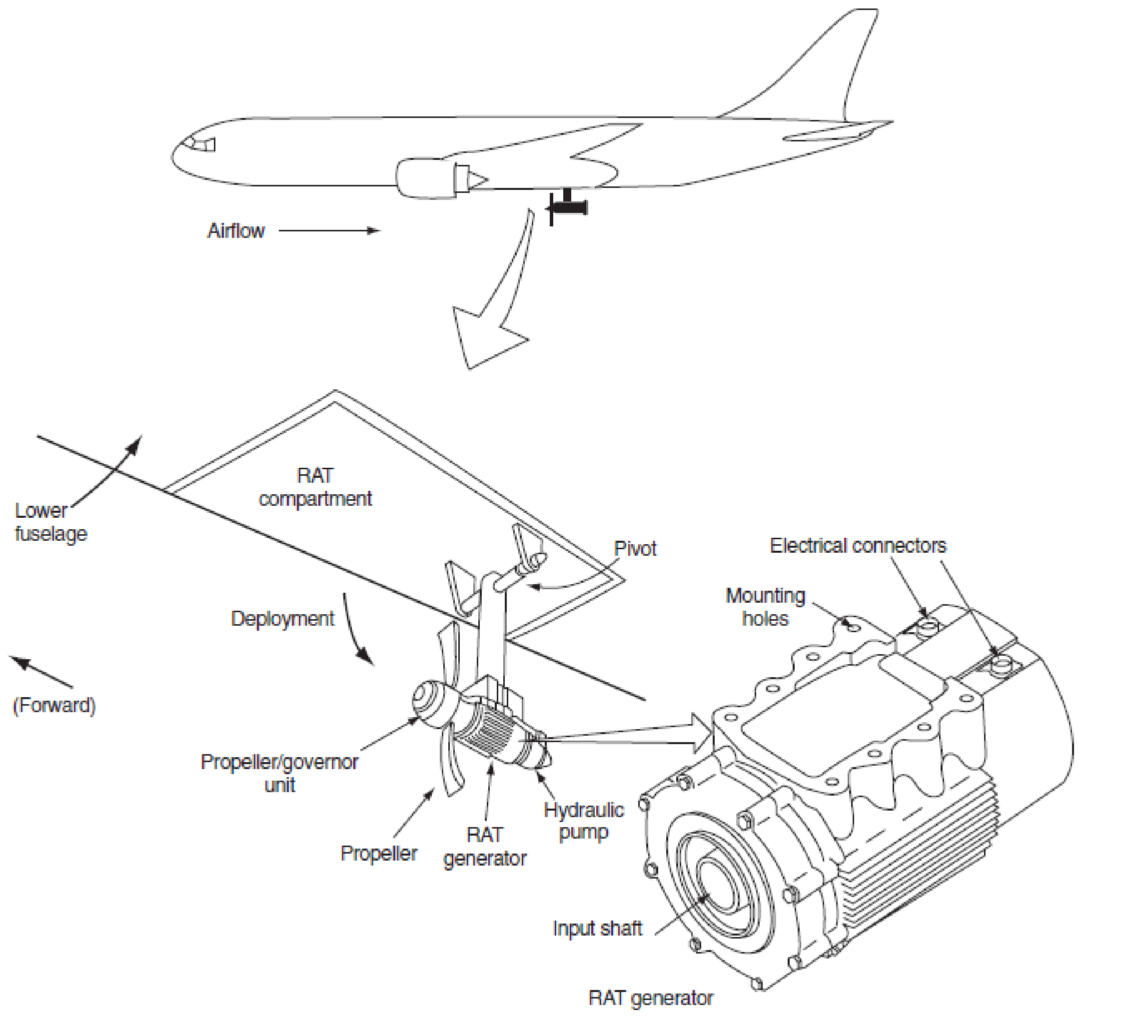

Figure 4.11 Ram air turbine

5.2 Construction and materials

Aircraft wiring needs to be physically flexible to allow it to be installed, and then to withstand the vibration of the aircraft that will cause the wires to fl ex. **Multistranding** of the conductor increases the flexibility of the wire or cable, making it easier to install and withstand vibration of the aircraft. The insulating material l has to be able to withstand the applied voltage ;the sheath material needs to be able to withstand the specified contaminants. Conductors need to be able to carry the required current without overheating or burning; they must also have low insulation resistance to minimize voltage drops. From **Ohm's law** , we know that (at a given temperature) the voltage across a resistance is proportional to the current. For a given current (*I*) and resistance (*R*), the voltage drop is quoted in terms of ***IR* losses** . For these reasons, most aircraft conductors are constructed from copper or aluminium contained within man-made insulating material(s).

Aluminium conductors are sometimes used in aircraft; however, the majority of installations are copper. The choice of conductor material is a trade-off; the first consideration is the material's resistance over a given length (given the term **resistivity** , symbol ρ ,measured in ohm-metres, abbreviated Ω m). Annealed copper at 20°C has a resistivity of 1.725×10^{8} Ω m; copper is more ductile than aluminium, and can be easily soldered. Aluminum has a resistivity value of 2.8×10^{8} Ω m, it is 60% lighter than copper but it is more expensive.

A major consideration for using aluminum is that it is **self-oxidizing** ; this reduces manufacturing costs (no plating required) but extra precautions are necessary for terminating the conductors due to the increased termination resistance. The quantity
and gauge of these strands depends on the current carrying capacity (or rating) and degree of flexibility required. Individual strands of copper need to be coated to prevent oxidation. The choice of coating for the strands depends on the operating temperature of the wire. In general terms, three types of coating are used: tin, silver or nickel, giving temperature ratings of 135°C, 200°C and 260°C respectively.

To summarize, copper conductors are used extensively
on aircraft due to the material's

- low resistivity
- high ductility
- high tensile strength
- ease of soldering

Conductors must be insulated to prevent short-circuits between adjacent circuits and the airframe. Power supplies of 12 or 28 V do not pose a threat of electricalshock, but the wires must be insulated to prevent arcing, loss of system integrity and equipment failure. The combined effects of insulation damage and fluid contamination gives rise to **wet arc tracking** . This phenomenon can occur when insulating surfaces are contaminated with any material containing free ions; the surface then behaves as an electrically conductive medium (an **electrolyte**). Leakage currents are sufficiently high to vaporize the contamination; this drives away the electrolyte and results in the formation of localized dry areas. These areas now offer a higher resistance to the current flow. In turn, high voltages will develop across these areas and result in small surface discharges. Initially, these discharges will emit flashes of light at the insulation surface, and produce localized temperatures in the order of 1000ºC. These high temperatures cause degradation of the insulation material. The ability of aircraft wiring to resist wet arc tracking is highly dependent on the wire insulation material. The conductivity level of the electrolyte will influence the **failure mode** resulting from this wet arc tracking. Higher power supply voltages are potentially lethal and the insulation provides a level of protection against this. The insulation material and its thickness depend mainly on the operating temperature and system voltage; examples of insulating and sheath materials include:

● ethylene tetrafluoroethylene (ETFE): this is afluorocarbon-based polymer (fl uoropolymer) inthe form of plastic material
● polytetra fluoroethylene (PTFE), a synthetic fluoropolymer
● fluorinated ethylene-propylene (FEP): this retains the properties of PTFE, but is easier to form
● polyvinylidene fluoride (PVF 2 or PVFD) has good abrasion and chemical resistance, and (like most fluoropolymers) is inherently flame-retardant.

5.3 Specifications

These have become more complex over the years to address the higher performance needed from wires and cables. This has been driven largely from in service experience with electrical fi res and the drive to reduce weight as more and more avionics equipment is introduced onto the aircraft. Reduced weight for a given length and diameter of wire is achieved through reducing the wall thickness of the insulation. Typical specifications used for wires and cables are contained in the US military specification **MIL-W-M22759E** .This specification covers fluoropolymer- insulated single conductor electrical wires manufactured with copperor copper alloy conductors coated with either tin, silver or nickel. The fluoropolymer insulation of these wires can either be PTFE, PVF 2 , FEP or ETFE. Wires manufactured to this specification are given a part number using the following format: M22759/x-xx-x.
● *M22759/x* -xx-x determines the specific wire type(Insulation, sheath and wire coating) from a table in the specification
● M22759/x- *xx* -x determines the wire size from a table in the specification
● M22759/x-xx- *x* determines the insulation colour from another specification (MIL-STD-681).

Examples of wires are shown in Fig. 5.1 . The single walled construction in Fig. 5.1(a) has a composite insulator and protective sheath to reduce cost and weight. The twin-walled construction, Fig. 5.1(b) ,illustrates the conductor, insulator and separate protective sheath. Outer sheaths on either type of wire can crack over long periods of time; in the single wall- type wire, moisture ingress can migrate into the wire through capillary action. This can lead to tracking inside the insulation, leading to overheating; twin walled wiring is more resistant to this effect.

5.3.1 Wire size

Wire sizes used on aircraft are defined in accordance with the **American Wire Gauge** or **Gage** (AWG). For a given AWG, the wire will have a specified diameter and hence a known conductance (the reciprocal of resistance). Cable size relates to the conductor's diameter; the overall wire or cable diameter is therefore larger due to the insulation. The largest wire size is 0000 AWG; the smallest is 40 AWG. The range of AWG wire/cable sizes is detailed in the Appendices. Selection of wire size depends on the specified current to be conducted. Larger diameter wires add weight, but offer less voltage drop for a given length and lower heating effect due to *I*2*R* losses. **Wire identification** is printed on the outer surface of the sheath at intervals between 6 and 60 inches. This includes the wire part number and manufacturers' commercial and government entity (**CAGE**)designation. The printing is either green or white (depending on the actual colour of the wire)

5.3.2 Performance requirements

Wires manufactured to MIL-W-M22759E have to demonstrate compliance with dimensions and construction, together with criteria to meet the following requirements:

- ease of removing the insulation
- ease of soldering
- dielectric testing
- flexibility
- elongation and tensile strength
- wicking
- high- and low-temperature testing
- flammability
- life cycle testing
- fluid immersion
- humidity
- smoke emission.

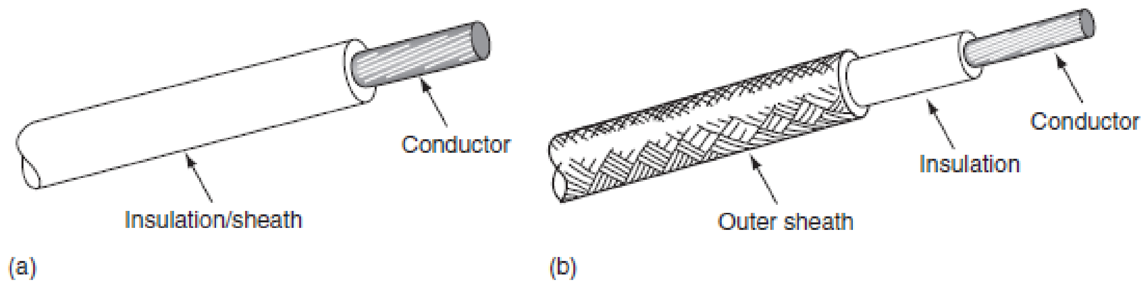

Figure 5.1 Typical aircraft wires and cables: (a) single-walled, (b) twin-walled

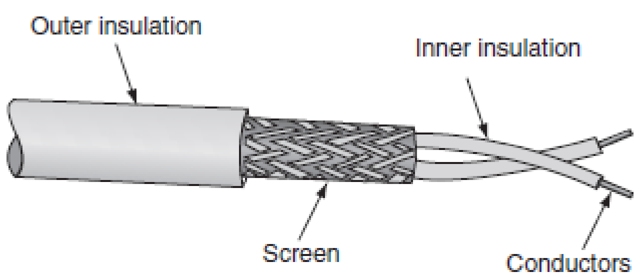

Figure 5.2 Screened cable

5.4 Shielding/screening

Shielded or screened wiring either prevents **radiation** from circuits switching high currents or protects **susceptible** circuits (see Fig. 5.2). The inner conductor
carries the system current; the screen provides a low resistance path for coupling of electromagnetic fields. These fields are coupled into the shield and are dissipated to ground. Typical applications where shielding is used includes wiring installed near generators, ignition systems or contacts that are switching high currents. Shielded wires can be formed with single, twin, triple or quadruple cores.

The classic example of screened wiring occurs with the Arinc 429 data bus which uses twisted screened pairs of cable to transmit digital data. This is being transmitted at either 12.5–1 2.5 (low speed) or 100 (high speed) k bits per second with a differential voltage of10 V between the pair of wires. Examples of screened wire and cable specifications are found in M27500-22TG1T-1 2.

5. 2.1 Crimps and splices

Individual wires and cables can be terminated or connected using crimps and splices. Care must be taken when stripping shielded cables; both the inner conductor
and outer screen must be exposed in order to make the connection. The outer shield is formed into a pigtails and terminated with a **crimp** , or ring tongue terminal, see Fig. 5.3(a) . Alternatively, individual wires can be joined with an in-line **splice** , e.g. if a system is being modified with additional wiring, see Fig. 5.3(b) . Crimps and splices are formed over the exposed conductor and insulating material. The entire crimp or splice termination is then protected mechanically with a hard plastic case

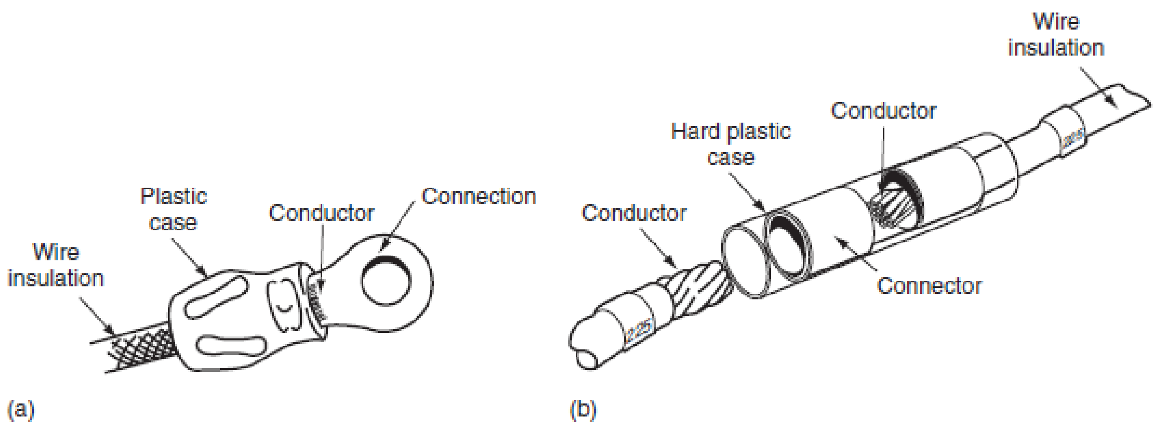

Figure 5.3 Wire termination and splicing: (a) ring tongue terminal, (b) in-line splice crimping

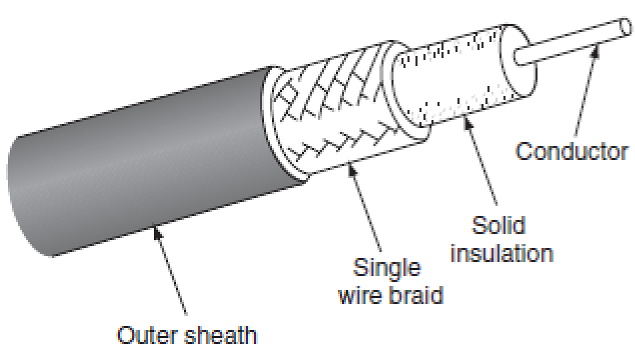

Figure 5.4 Coaxial cable overview

5. 2.2 Coaxial cables

A specialized version of the shielded wire is the coaxial cable. The inner conductor is solid or stranded; it can be plain copper or plated. The outer conductor forms a shield and is a single wire **braid** made from fine strands of copper or steel. The inner and outer conductors are separated by a solid insulation, forming a **dielectric** . The outer sheath or jacket provides protection against fluid contaminants. Coaxial cables are normally used to guide radio-frequency (RF)energy between antennas and receivers or transmitters. The inner conductor is shielded by the braiding from electric and magnetic fields; the conductor's own field is contained within the same shield. The net result is that fields from the inner and outer conductors cancel each other out. In most practical RF applications, coaxial cable radiation and susceptibility are virtually eliminated.

The typical construction of coaxial cable is shown in Fig. 5.4 ; the salient features are:

- **inner conductor:** silver plated copper
- **solid insulation:** (dielectric) foamed FEP
- **single wire braid:** (screen) tin plated copper
- **outer insulation:** (jacket) FEP.

.

5.5 Circuit protection

The current-carrying capacity of a wire or cable is determined by its length and cross sectional area; heat dissipation is determined by *I*2*R* losses. When the circuit or system is designed, the wire size is selected to safely carry this current. Wires and cable are subjected to abrasion during the normal service life of the aircraft; this can lead to the conductor being exposed. This exposure could lead to a low resistance
path between the conductor and the airframe and/or an adjacent conductor. Faulty equipment, low resistance paths or overloading from additional circuits will cause the current to increase and this might exceed the current-carrying limit of the conductor. Heat will build up in the wire leading to fumes, smoke and ultimately fire. It is vital that we protect against this whilst allowing for transients; the methods used in aircraft are selected from the following devices:

- fuse
- circuit-breaker
- limiting resistor.

5. 5.1 Fuses

Fuses are links of wire that are connected in series with the circuit. Their current-carrying capacity is predetermined and they will heat up and melt when this is exceeded, thereby interrupting and isolating the circuit. Materials used for the **fusible link** include lead, tin-bismuth alloy, copper or silver alloys .Referring to Fig. 5.6(a) , the fuse wire is contained with a glass or ceramic casing (or cartridge) to prevent any particles of hot metal escaping which could cause secondary damage. End-caps provide a connection for the fuse wire and make contact with the circuit wiring. Fuse holders consist of terminals and a panel clamp-nut.

Some fuse holders have an indication of the fuse condition, i.e. if the fuse has blown. The **indicating cap** is black with an integrated coloured light. When the fuse has blown, the cap illuminates; different colours indicate different power supply voltages. Heavy-duty fuses (typically protecting circuits with up to 50 A current) are constructed with a ceramic body and terminals, see Fig. 5.6(c) . Fuses are either clipped into position on a terminal board, see Fig. 5.7 ,or screwed into a panel, see Fig. 5.8 . Fuses are relatively low cost items, but they can only be used once.

In some applications, the fuse material and physical construction is designed to have a time delay; the so-called **slow-blow** fuse, or **current limiter** . This is made from a copper alloy that has a higher melting point than lead/tin. It has a single strip of material waisted into a narrow cross-section to provide the fusing point. Heavy-duty fuses are used at power distribution points. They have multi-strands of parallel elements and are rated up to 500 A. This type of fuse is fitted with a packing medium to contain the debris following rupture.

Materials used include quartz, magnesium oxide, kieselguhr or calcium carbonate(chalk). Fuses have a rating that determines the maximum current it can carry without melting. The fuse will also have a minimum fusing current that is affected by ageing; a process that occurs when the fuse is operated at the minimum fuse rating for prolonged periods of time. Ambient temperature affects the current rating and response time of a fuse. They must be located close to power source to minimize the length of unprotected wire; at the same time they have to be accessible for replacement. Spare fuses must be carried on the aircraft and be accessible to the flight crew. Typical requirements are to carry 50% of each rating as spares, e.g. if the aircraft is fitted with four10 A and five 15 A fuses, then two 10 A and three 15 A fuses should be carried as spares.

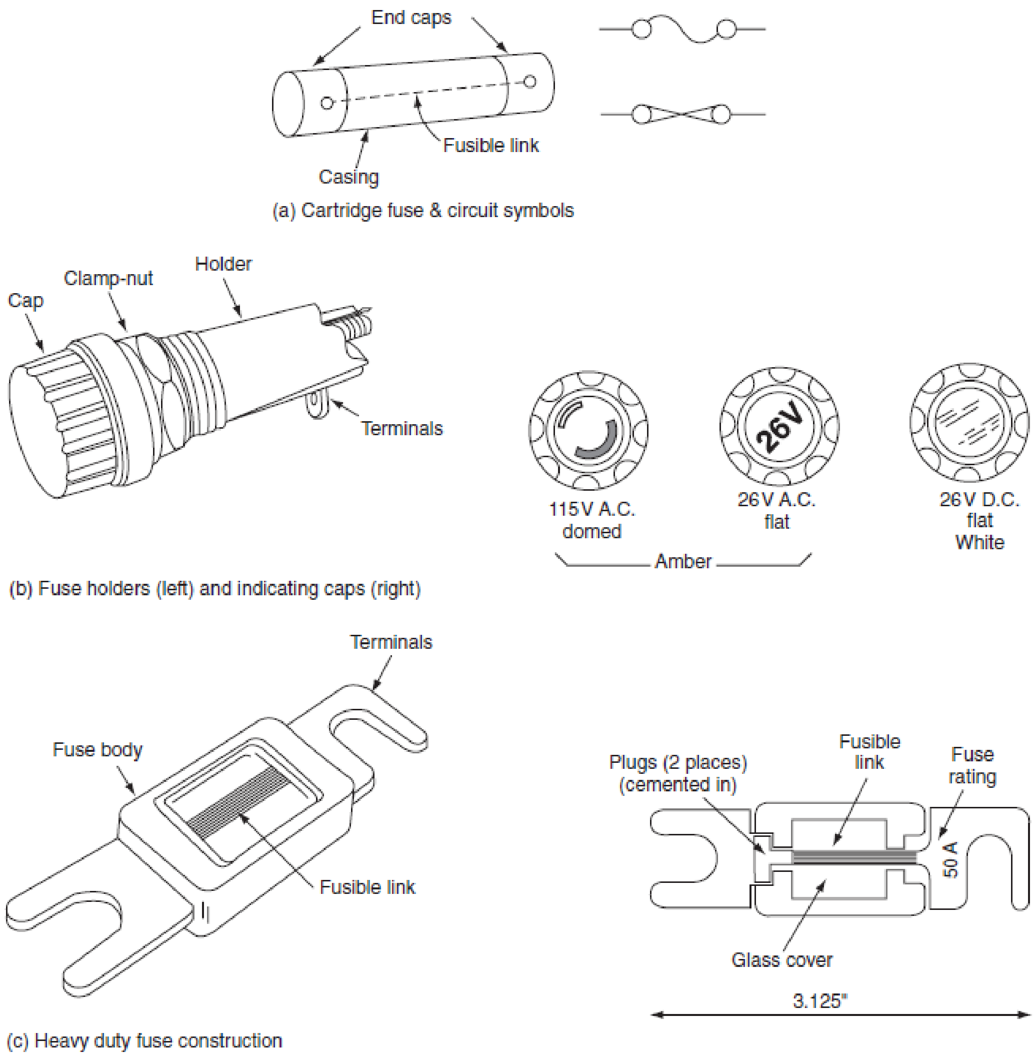

Figure 5.6 Aircraft fuses

5. 5.2 Circuit-breakers

Circuit-breakers are electromechanical devices that interrupt and isolate a circuit in the event of excessive current. Unlike fuses, circuit-breakers can be reset (assuming that the fault condition has cleared). There are two circuit-breaker principles: electromagnetic and thermal.

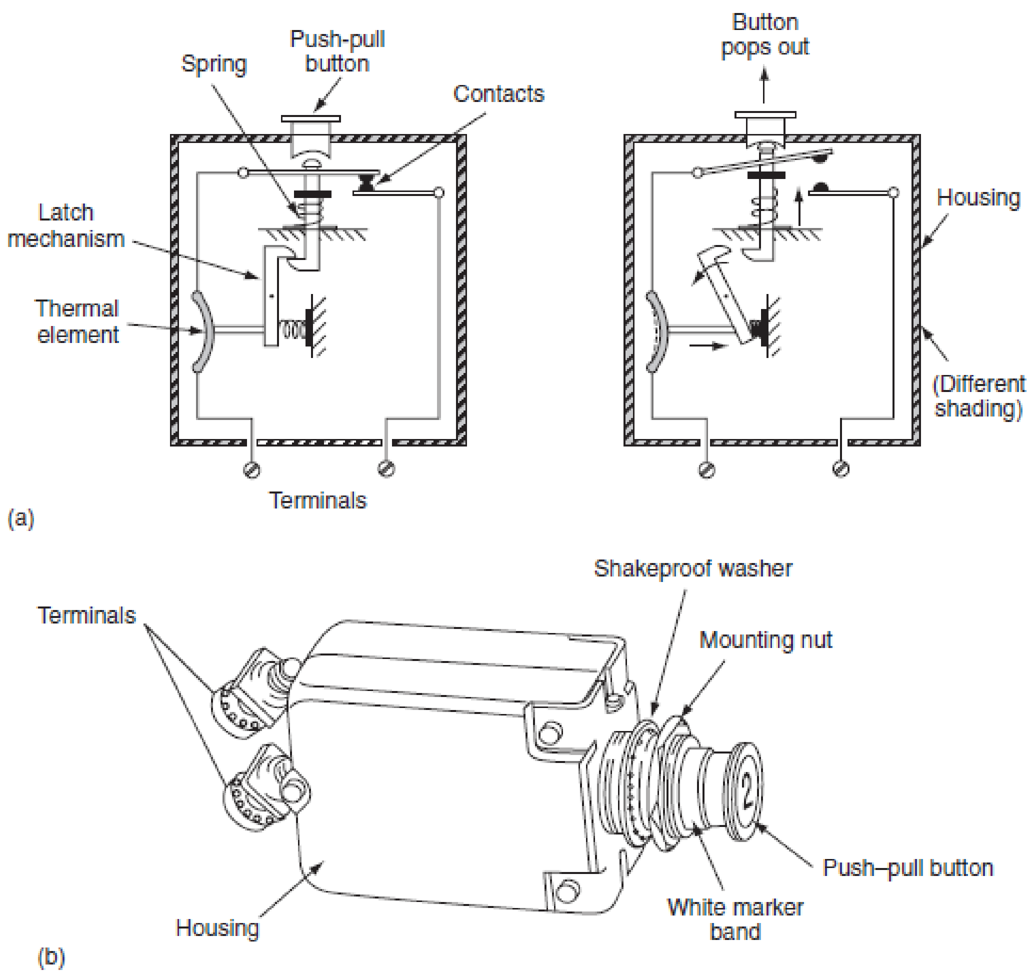

Figure 5.9 Aircraft circuit-breakers (thermal type): (a) internal schematic (closed and tripped),
(b) external features

An **electromagnetic** circuit-breaker is essentially a relay with current fl owing through a coil; the resulting magnetic field attracts an armature mechanism. The current is normally a proportion of the main load current; this increases in proportion to the main load current. The armature mechanism is linked to a pair of contacts that carry the main load current. These contacts are opened when the current through the coil exceeds a certain limit

.

Thermal -type circuit-breakers consist of a bimetallic thermal element, switch contacts and mechanical latch. The internal schematic of a thermal circuit breaker and its external features are illustrated in Fig. 5.9 . The thermal element is a **bimetallic** spring that heats up as current passes through it; this eventually distorts and trips the mechanism when the rated level is exceeded. The mechanism is linked to the main switch contacts, when the circuit-breaker '**trips '**the contacts open, thereby disconnecting power from the circuit. When the contacts open, a **button** is pushed out of the circuit-breaker. This button is used to manually reset the contacts; a **white collar** just below the button provides visual indication that the circuit-breaker is closed or tripped. Some circuit-breakers use a large collar grip to identify specific systems. They can be locked open if required, e.g. if the system is installed but not certified for operation. As with fuses, the circuit-breaker should be located as close as possible to source of power; they are often arranged on the panels in groups.

Circuit-breakers can also be used to conveniently isolate circuits, e.g. during maintenance. Certain circuit-breakers are fitted with removable collars so that they can be readily identified. The circuit-breaker current rating is engraved on the end of the button Circuit-breakers can be single- or multipole devices (poles are defined as the number of links that a switching device contains). Multi-pole devices
are used in three-phase AC circuits.
Various configurations of circuit-breaker are installed on aircraft, including:

1. automatic reset
2. automatic trip/push to reset
3. switch types
2. trip free.

The circuit symbols for each of these types is illustrated in Fig. 5.11 . **Trip-free** circuit-breaker contacts cannot be closed whilst a fault exists. This is the preferred type of circuit-breaker on aircraft, especially on new installations

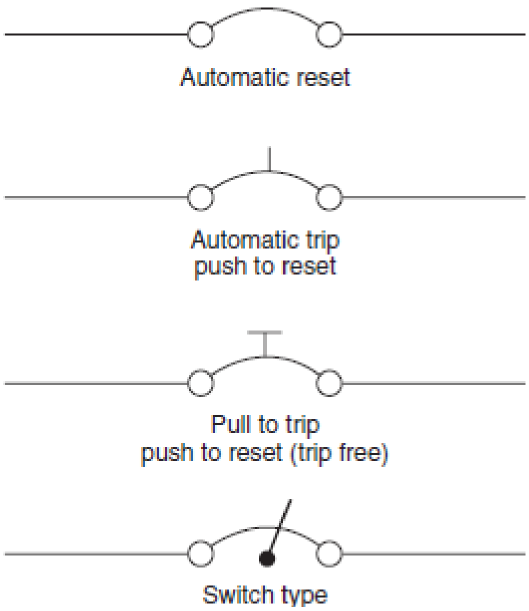

Figure 5.11 Circuit-breaker symbols/type

5. 5 .3 Limiting resistors

These are used to limit current surges, primarily in DC circuits, where the initial current surge is large. When these circuits are switched they create large current flows that can be harmful to other components and reduce the power supply voltage fora period of time (determined by the time constants of the circuit). Limiting resistors are connected in series with such circuits and then automatically shorted out once the circuit current has stabilized

.

Typical applications of limiting resistors are found in engine starting circuits and voltage regulators. Limiting resistors are also used in fire extinguishing systems. Fire extinguishers are activated by applying direct current (DC) through current-limiting resistors to the associated squib; this ruptures a disc that allows extinguishing agent to be expelled under pressure. The limiting resistors prevent inadvertent operation of the squib. In electronics, limiting resistors are used to protect devices such as diodes.

6.Electrical and magnetic fields

One of the consequences of operating electrical and electronic equipment is the possibility of disturbing, or interfering with, nearby items of electronic equipment. The term given to this type of disturbance is electromagnetic interference (EMI). Placing a portable radio receiver close to a computer and tuning through the radio's wavebands can illustrate this effect. The computer will radiate electromagnetic energy; this is received by the radio and heard as noise ' . Radio equipment is designed to receive electromagnetic energy; Electrical or electronic products will both radiate and be susceptible to the effects of EMI. This is a paradox since many principles of electrical engineering are based on electromagnetic waves coupling with conductors to produce electrical energy and vice versa (generators and motors).

Furthermore, systems are specifically designed to transmit and receive electromagnetic energy, i.e. radio equipment. The problem facing aircraft electrical and electronic systems is the unwanted noise; in the case of the computer/radio experiment, this unwanted noise is no more than a nuisance. In complex avionic systems, the consequences of EMI can be more serious.

The ability of an item of equipment to operate alongside other items of equipment without causing EMI is electromagnetic compatibility (EMC).speed and relatively low power levels. In addition to EMI, high-intensity radiated fields (HIRF) are received from the external environment, e.g. from radio and radar transmitters, power lines and lightning. The high energy created by these radiated fields disrupts electronic components and systems in the aircraft. (This effect is also referred to as high-energy radiated fields – HERF.) The electromagnetic energy induces large currents to flow, causing direct damage to electronic components together with the secondary effects of EMI.

6.1 Electromagnetic Interference

Electromagnetic interference (EMI) can be defined as the presence of unwanted voltages or currents that can adversely affect the performance of an electrical/ electronic system. The effects of EMI include:

- errors in indications
- unwanted noise on audio signals
- random patterns on electronic displays
- repetitive ' buzzing ' on intercom and cabin phone systems
- desensitizing of radio and radar receivers
- false indications in radar and navigation equipment
- Nuisance triggering of alarms.

Consider the current-carrying conductor illustrated in Fig. 6.1 . It can be seen that the field strength is

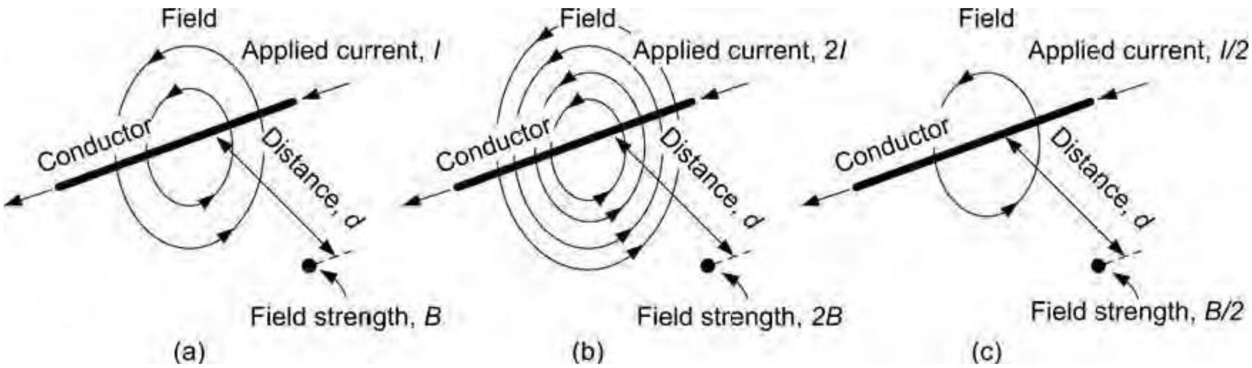

Figure 6.1 Current-carrying conductor

measure of **flux density** at any given point. From first principles, the field strength *B* is proportional to the applied current and inversely proportional to the distance from the conductor. If an alternating current is applied to the conductor, this field will build up and collapse around the conductor. If a second conductor
is now placed alongside the first conductor, the alternating field from the first conductor will induce currents in the second conductor. These induced currents will be superimposed onto any current fl owing in the second conductor. The first conductor is **radiating** EMI; the second conductor is **susceptible** to EMI. The total EMI effect depends primarily on the amount of current in the first conductor, rate of change of current (i.e. alternating, digital or switched currents) and the distance between the two conductors.

Alternating currents, or digital signals being carried by a conductor, will set up alternating magnetic fields thus causing EMI as described. In summary, the amount of electromagnetic field radiated from a conductor depends on amount of current in the conductor and the rate of change of a magnetic field from the conductor.

6.1.1 Shielding

For a given current, the distance between conductors and the provision of shielding (or screening) are the main considerations when trying to design and install wiring and equipment to minimize EMI. From Fig. 6.1 we can see that the distance between conductors has a direct effect on the amount of unwanted current induced into the second conductor. The addition of shielding on conductors limits the coupling of electromagnetic fields, see Fig. 6.2 . The electromagnetic field created by current *I*1 in the first conductor induces a current *I*2 in the second conductor

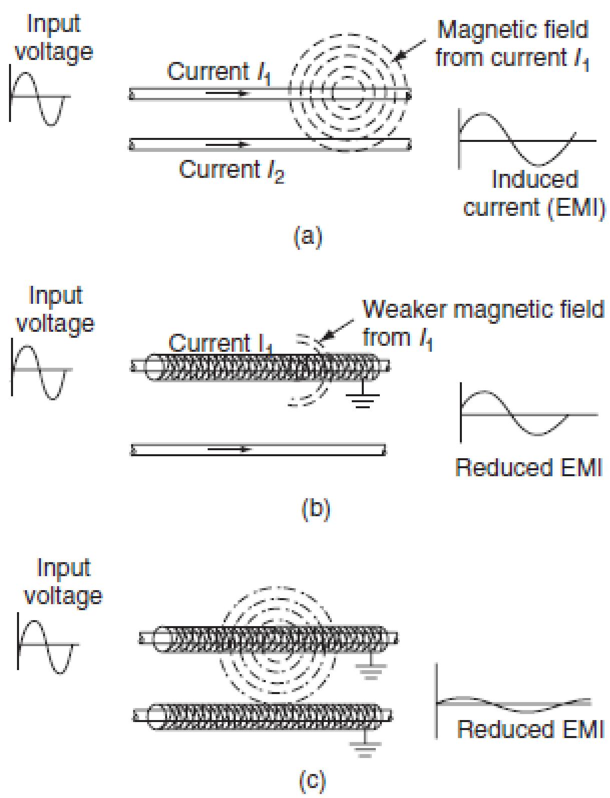

Figure 6.2 Shielding principles: (a) conductors unshielded, (b) one conductor shielded, (c) both conductors shielded

With one conductor shielded, some of the electromagnetic field created by current *I*1 induces current in the shielding; this current and taken away to a ground connection at one or both ends of the shielding. The shielding effectively absorbs some of the electromagnetic field created by *I*1 ; the remaining (weaker) field induces a reduced current *I*2 in the second conductor. If both conductors are shielded, most of the weaker field created by *I*1 is absorbed into the shielding of the second conductor; this further reduces the current *I*2 in the second conductor. Shielding can reduce the coupling of electromagnetic fields between conductors. The amount of reduction depends upon the screening material used, its thickness, and the frequency of the applied current. Typical materials used for shielding are metallic mesh, or braiding formed on the outside of the conductor’s protective sheath; this ensures that the wire or cable retains some degree of mechanical flexibility. The shielding impedes the radiation of signals from the first conductor, and also minimizes signals from being induced into the second conductor.

6.1.2 Electromagnet waves

We have been using the term electromagnet wave to develop the concept of EMI. The electromagnet wave actually comprises two components. As with light, electromagnet waves propagate outwards from a source of energy (transmitter) and comprise **electric** (*E*) and **magnetic** (*H*) fields at right angles to each other. These two components, the *E* -field and the *H* -field, are inseparable. The resulting wave travels way from the source with the *E* and *H* lines mutually at right angles to the direction of propagation, as shown in Fig. 6.3 .

Electromagnet waves are said to be **polarized** in the plane of the electric (*E*) field. Thus, if the *E* –field is vertical, the signal is said to be vertically polarized whereas, if the *E* -field is horizontal, the signal is said to be horizontally polarized. In the case of intentional propagation of electromagnet waves, i.e. radio transmitters and receivers (Fig. 6.4), the electric *E* -field lines are shown in the space between a transmitter and a receiver. The transmitter aerial (or antenna) is supplied with a high frequency alternating current. This gives rise to an alternating electric field between the ends of the aerial/antenna and an alternating magnetic field around (and at right angles to) it. The direction of the *E* –field lines is reversed on each cycle of the signal as the wave front moves outwards from the source. The receiving aerial/antenna intercepts the moving field, and voltage and current is induced as a consequence.

These voltages and currents are similar (but of smaller amplitude) to those produced by the transmitter. Note that in Fig. 6.4 (where the transmitter and receiver are close together) the radiated *E* –field is shown spreading out in a spherical pattern (this is known more correctly as the near field).

The magnetic field (not shown) will be perpendicular to the *E* -field. In practice, there will be some considerable distance between the transmitter and the receiver and so the wave that reaches the receiving aerial/antenna will have a plane wave front. In this far field region, the angular field distribution is essentially independent of the distance from the transmitting antenna.

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A simple wiring installation connects the shielding to ground, thereby ‘ soaking ’ away the unwanted currents, rather than inducing them into the second conductor. Although shielding provides some protection against EMI, it also adds cost and weight to the installation. Furthermore, the currents being carried away in the shielding radiate their own fields that can cause secondary EMI. This unwanted current is referred to as a **ground loop** ; current flows in a conductor connecting two points that are intended to be at the same potential, e.g. ground potential. (The fact that current is fl owing can only occur because they are actually at different potentials.) As with many engineering situations, solving one problem often comes at a cost together with the introduction of new problems!

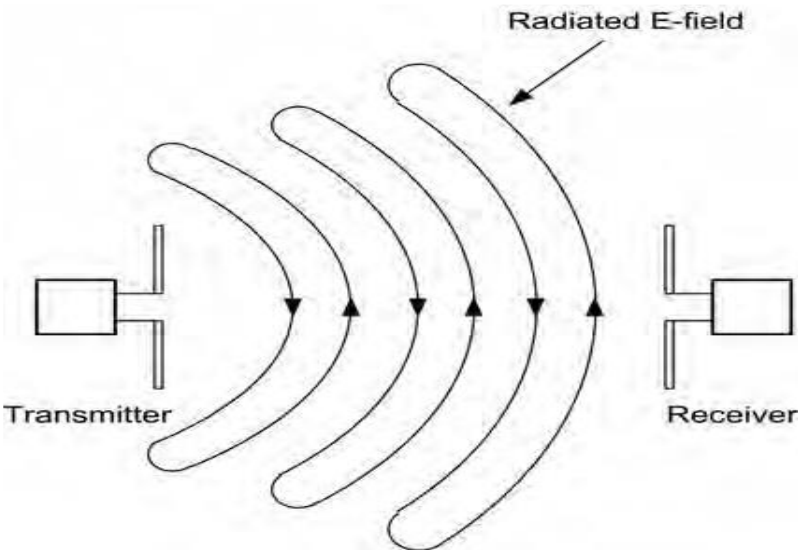

Figure 6.4 Radio transmitters and receivers

6.1.3 Twisted pair

Another technique used to minimize EMI in wiring is the **twisted pair** . This a form of wiring in which the two conductors are wound together to cancel out electromagnetic interference (EMI) from external sources, and minimize **cross-talk** between adjacent pairs of wires. Cross-talk is the consequence of EMI between one electrical circuit to another, i.e. when a signal transmitted in one circuit creates an undesired effect in another circuit. A twisted pair cable consists of two independently insulated wires twisted around one another. Twisting the cables forms repetitive loops; each twist reverses the polarity of the loop, therefore magnetic fields can only couple into each loop and not the entire cable length. When current is supplied through a loop, a magnetic field is set up; it can be seen that the flux is concentrated in the centre of the loop as illustrated in Fig. 6.5 .

The twisted pair also provides a physical means of minimizing EMI in wires carrying digital signals; each wire is positioned alternatively next to the source of interference; the net effect is to cancel out any differential between the wires. Twisting a pair of wires to form a cable is an extremely effective way of transmitting high-speed signals because:

● most of the electrical noise entering into and/or radiating from the cable can be eliminated

● cross-talk (signals ‘ leaking ’ between wires in the cable) is minimized.

In addition to the electrical energy fl owing down each wire, energy can also be coupled between wires due to electrostatic and magnetic effects. For the

electrostatic effects, the insulation between the two conductors is the dielectric of a capacitor. More surface area is created by longer cables; this leads to increased inter-wire capacitance. Higher frequency signals can lead to cross-talk between wires as a result of reduced capacitance.
Typical applications of signals transmitted down a twisted-pair of wires include Arinc 429 signals as

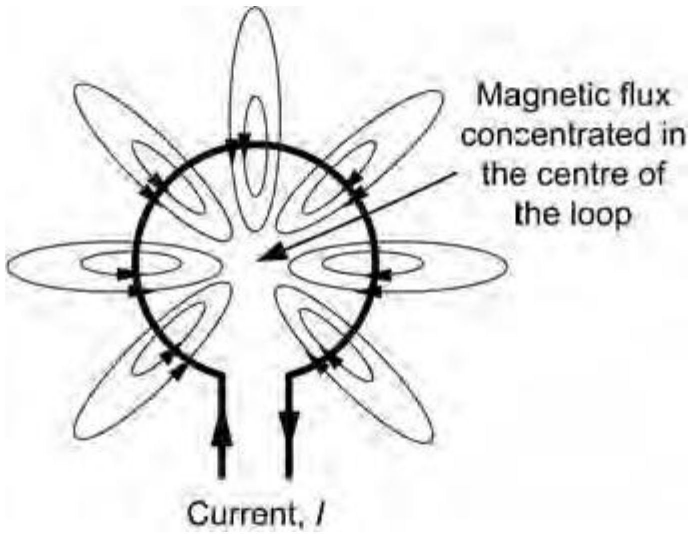

Figure 6.5 Magnetic field illustrated

Any other system wires adjacent to this pair will be affected by cross-talk. Two wires (A and B) each carry a _ 5 volt digital signal arranged as bipolar return to zero (BPRZ). The extent of the cross-talk is equal to the sum of the digital signals; if this sum is zero (or nearly zero) then the affects of cross-talk are eliminated.

Consider three wires in a cable as illustrated in Fig. 6.7 . Wires A and B are formed as a twisted pair carrying a digital signal. If the signal sent through wire A is _ 10 volts with respect to wire B (a reference voltage of zero) then wire C wire picks up crosstalk noise. If the digital signals are arranged as per the second illustration, the opposite polarity signal of _ 5 volts on wires A and B cancel each other out, the cross-talk effect wire C is eliminated.

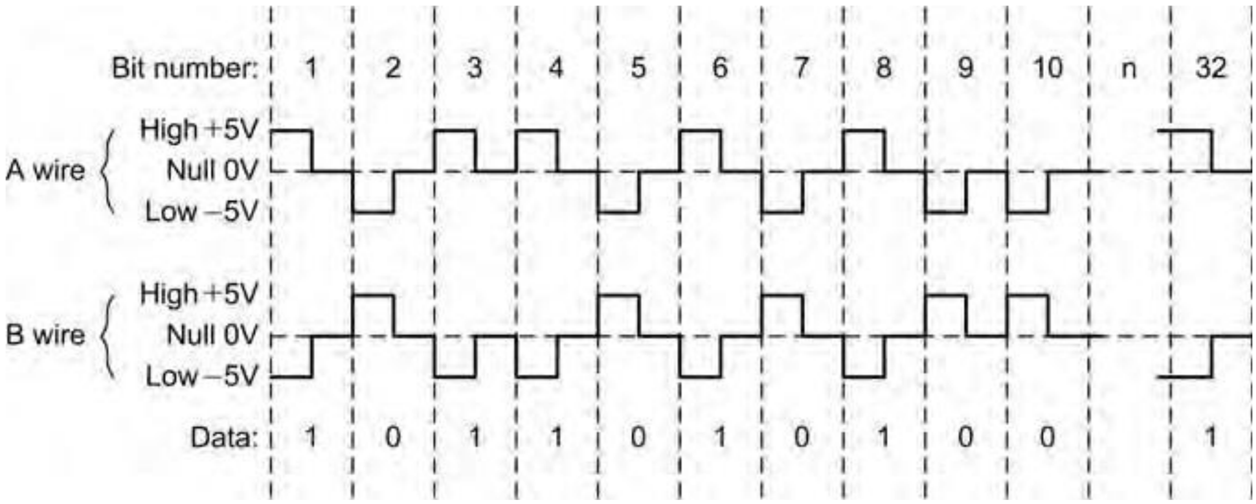

Figure 6.6 Digital signal

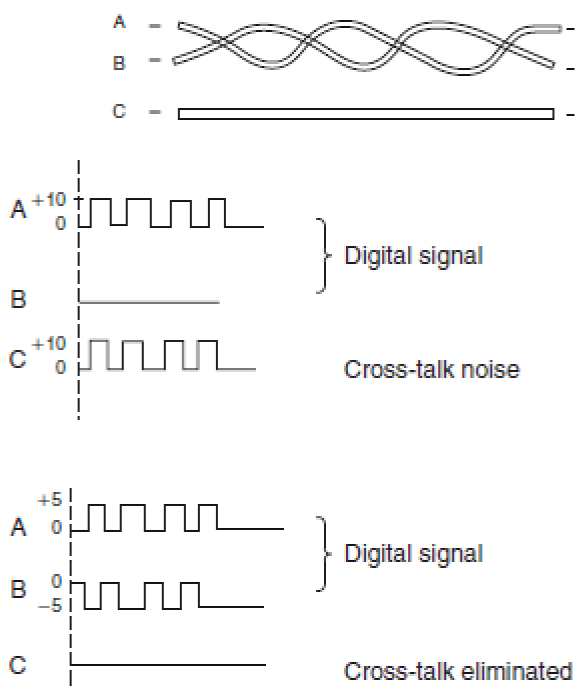

Figure 6.7 Twisted pairs and cross talk

6.1.4 Bandwidth

Bandwidth is the difference between the upper and lower cut-off frequencies of analogue amplifying circuits; the unit of **bandwidth** is hertz (Hz). The characteristics of bandwidth is illustrated in Fig. 6.8 . This is a central concept in electronics, radiofrequency (RF) systems and signal processing. It also has to be considered in the context of EMI; high frequencies should be filtered out of a circuit wherever possible, without compromising its functionality. In computers, digital bandwidth refers to the rate at which data is transmitted/received; this is measured in **bits per second (BPS)**. A digital communication network has a given bandwidth in terms of its overall channel capacity and throughput (consumption). Channel capacity (in BPS) is proportional to the analogue bandwidth in hertz (Hz); this is the maximum amount of error-free digital data that can be transmitted via a communication link with a specified bandwidth in the presence of EMI.

6.1.5 Radiated EMI

There are many sources of EMI throughout the aircraft. Those sources known to **radiate** EMI include:

- fluorescent lights
- radio and radar transmitters
- power lines
- AC powered window heat controllers
- motors/generators
- switching and light dimming circuits
- microprocessors
- pulsed high-frequency circuits
- data bus cables (but not fibre optic cables)
- static discharge and lightning.

The energy generated by these sources is radiated as an electromagnetic field. From first principles, we know that the coupling only takes place when there is a relative movement of electromagnet field and conductor; digital circuits are (by definition) switching currents on/off with fast and short pulse rise/fall times. Unless adequate precautions are taken to eliminate the interference at source and/or to reduce the equipment's radiation of EMI, the energy can then become coupled into other circuits. In electromagnetic field radiation, energy is transmitted through electrically nonconductive paths, such as air, plastic materials, or fibre glass.

6.1.6 EMI susceptibility

There are many systems on the aircraft that which may be **susceptible** to electromagnetic interference.

These include:

- radio and radar receivers
- microprocessors and other microelectronic systems
- electronic instruments
- control systems

● audio and in-flight entertainment systems (IFE).

Whether a system will have an adverse response to **electromagnetic interference** depends on the type and amount of emitted energy in conjunction with the susceptibility threshold of the receiving system. The threshold of susceptibility is the minimum interference signal level (conducted or radiated) that results in equipment performance that is indistinguishable from the normal operation. If the threshold is exceeded then the performance of the equipment will become degraded. Note that, when the susceptibility threshold level is greater than the levels of radiated emissions, electromagnetic interference problems do not exist. Systems to which this applies have **electromagnetic compatibility** (EMC). In other words, the systems will operate as intended and any EMI generated is at such a level that it does not affect normal operation.

6.2 EMI reduction

Planning for electromagnetic compatibility must be initiated in the design phase of a device or system. If this is not satisfactorily addressed, interference problems may arise. The three factors necessary to produce an EMI problem are:

● source(s) of interference (sometimes called noise)
● a means of coupling (by conduction or radiation)
● susceptible components or circuits.

To reduce the effects of EMI, or **electrical noise** , at least one of these factors must be addressed. The following lists some techniques used for EMI reduction to tackle these three factors (note that some techniques address more than one factor).

1. Suppress the interference at source

● Enclose the interference source(s) in a screened metal enclosure and then ensure that the enclosure is adequately grounded
● Use transient suppression on relays, switches and contactors
● Twist and/or shield bus wires and data bus connections
● Use screened (i.e. coaxial) cables for audio and radio-frequency signals
● Keep pulse rise times as slow and long as possible
● Check that enclosures, racks and other
supporting structures are grounded effectively.

2. Reduce noise coupling

● Separate power leads from interconnecting signal wires
● Twist and/or shield noisy wires and data bus connections
● Use screened (i.e. coaxial) cables for audio and radio-frequency signals
● Keep ground leads as short as possible

- Pay close attention to potential ground loops
- Filter noisy output leads
- Physically relocate receivers and sensitive equipment away from interference sources.

3. Increase the susceptibility thresholds

- Limit the bandwidth of circuits wherever possible
- Limit the gain and sensitivity of circuits wherever possible
- Ensure that enclosures are grounded and that internal screens are fitted
- Fit components that are inherently less susceptible to the effect of stray radiated fields.