PART 1

Theory, Design and Principles Common to all Cable Types

CHAPTER 2
Basic Electrical Theory Applicable to Cable Design

In all engineering undertakings, economical, technical and practical aspects are taken into consideration to establish the optimum solution or design. For the transmission, distribution and utilisation of electrical power, the choice normally lies between the use of overhead lines and underground cables.

For economic reasons, overhead lines are used extensively for the transmission and distribution of electricity in rural areas where environmental or practical considerations do not dictate otherwise. However, in urban areas it is more usual to install insulated cables which, in the main, are buried underground. The utilisation of electricity in factories, domestic premises and other locations is also mainly by cables as they present the most practical means of conveying electrical power to equipment, tools and appliances of all types. Cable designs vary enormously to meet the diverse requirements but there are certain components which are common to all.

All types of electric cable consist essentially of a low resistance conductor to carry the current except in special cases, such as heating cables, and insulation to isolate the conductors from each other and from their surroundings. In several types, such as single-core wiring cables, the two components form the finished cable, but generally as the voltage increases the construction becomes much more complex.

Other main components may include screening to obtain a radial electrostatic field, a metal sheath to keep out moisture or to contain a pressurising medium, armouring for mechanical protection, corrosion protection for the metallic components and a variety of additions extending, for example, to internal and external pipes to remove the heat generated in the cable.

This chapter contains some of the electrical theory applicable to all cable types. Further details of individual cable designs and components are given in later chapters.

VOLTAGE DESIGNATION

In the early days of electric power utilisation, direct current was widely used, but little now remains except for special applications and for a few interconnections in transmission networks. Alternating current has many advantages and 3-phase alternating current is used almost exclusively throughout the world.

So that suitable insulation and cable construction can be specified for the required 3-phase a.c. service performance, the design voltages for cables are expressed in the form U_0/U (formerly E_0/E). U_0 is the power frequency voltage between conductor and earth and U is the power frequency voltage between phase conductors for which the cable is designed, U_0 and U both being r.m.s. values.

Power cables in British Standards are thus designated 600/1000 V, 1900/3300 V, 3800/6600 V, 6350/11000 V, 8700/15000 V, 12700/22000 V and 19000/33000 V. For transmission voltages above this it is normal to quote only the value of U and thus the higher standard voltages in the UK are 66, 132, 275 and 400 kV. The maximum voltage can be 10% greater than the above values for voltages up to and including 275 kV and 5% greater for 400 kV.

Although the local distribution voltage in the UK is 240/415 V, the cables are designed for 600/1000 V, largely because during manufacture and installation this grade of cable requires an insulation designed on mechanical rather than electrical parameters.

Standardisation of system voltages has not been achieved worldwide although there is some move towards this. IEC has published voltage designations which are approaching universal acceptance.

D.C. system voltages, by which is meant d.c. voltages with not more than 3% ripple, are designated by the positive and negative value of the voltage above and below earth potential. The symbol U_0 is used for the rated d.c. voltage between conductor and the earthed core screen.

Many references will be found to cables described as low voltage (LV), medium voltage (MV), high voltage (HV) and even EHV or UHV. Apart from low voltage, which is defined internationally, these terms do not have generally accepted precise meanings and can be misleading. In some countries MV has in the past applied to 600/1000 V cables (these now fall clearly within the LV designation), whereas others have taken it to mean 6/10 kV or 8.7/15 kV and misunderstanding could arise. For precision it is best to use the actual voltage rating of the cable.

CONDUCTOR RESISTANCE

D.C. resistance

Factors affecting d.c. conductor resistance in terms of material resistivity and purity are discussed in chapter 3 and those relating to conductor design in chapter 4. The latter are associated with the fact that the prime path of the current is a helical one following the individual wires in the conductor. Hence if an attempt is made to calculate the resistance of a length of stranded conductor a factor must be applied to cater for the linear length of wire in the conductor to allow for extra length caused by the stranding effect. In a multicore cable an additional factor must be applied to allow for the additional length due to the lay of the cores.

The d.c. resistance is also dependent on temperature as given by

$$R_t = R_{20}[1 + \alpha_{20}(t - 20)] \tag{2.1}$$

where R_t = conductor resistance at t°C (Ω)
R_{20} = conductor resistance at 20°C (Ω)
α_{20} = temperature coefficient of resistance of the conductor material at 20°C
t = conductor temperature (°C)

A.C. resistance

If a conductor is carrying high alternating currents, the distribution of current is not evenly disposed throughout the cross-section of the conductor. This is due to two independent effects known as the 'skin effect' and the 'proximity effect'.

If the conductor is considered to be composed of a large number of concentric circular elements, those at the centre of the conductor will be enveloped by a greater magnetic flux than those on the outside. Consequently the self-induced back e.m.f. will be greater towards the centre of the conductor, thus causing the current density to be less at the centre than at the conductor surface. This extra concentration at the surface is the skin effect and it results in an increase in the effective resistance of the conductor. The magnitude of the skin effect is influenced by the frequency, the size of the conductor, the amount of current flowing and the diameter of the conductor.

The proximity effect also increases the effective resistance and is associated with the magnetic fields of two conductors which are close together. If each carries a current in the same direction, the halves of the conductors in close proximity are cut by more magnetic flux than the remote halves. Consequently, the current distribution is not even throughout the cross-section, a greater proportion being carried by the remote halves. If the currents are in opposite directions the halves in closer proximity carry the greater density of current. In both cases the overall effect results in an increase in the effective resistance of the conductor. The proximity effect decreases with increase in spacing between cables.

Mathematical treatment of these effects is complicated because of the large number of possible variations but Arnold[1] has produced a comprehensive report (see also chapter 8).

Skin and proximity effects may be ignored with small conductors carrying low currents. They become increasingly significant with larger conductors and it is often desirable for technical and economic reasons to design the conductors to minimise them. The Milliken conductor, which reduces skin and proximity effects, is described in chapter 4.

A.C. resistances are important for calculation of current carrying capacity. Values for standard designs of distribution and transmission cables are included in the tables in appendices 12–16.

INDUCTANCE

The inductance L per core of a 3-core cable or of three single-core cables comprises two parts, the self-inductance of the conductor and the mutual inductance with other cores. It is given by

$$L = K + 0.2\log_e \frac{2S}{d} \qquad \text{(mH/km)} \qquad (2.2)$$

where K = a constant relating to the conductor formation (table 2.1)
S = axial spacing between conductors within the cable (mm), or
= axial spacing between conductors of a trefoil group of single-core cables (mm), or
= 1.26 × phase spacing for a flat formation of three single-core cables (mm)
d = conductor diameter or for shaped designs the diameter of an equivalent circular conductor (mm)

For 2-core, 3-core and 4-core cables, the inductance obtained from the formula should be multiplied by 1.02 if the conductors are circular or sector-shaped, and by 0.97 for 3-core oval conductors.

Table 2.1 Typical values for constant K for different stranded conductors (at 50 Hz)

Number of wires in conductor	K
3	0.0778
7	0.0642
19	0.0554
37	0.0528
61 and over	0.0514
1 (solid)	0.0500
Hollow-core conductor, 12 mm duct	0.0383

REACTANCE

The inductive reactance per phase of a cable, or of the single-core cables comprising the circuit, may be obtained from the formula

$$X = 2\pi f L \times 10^{-3} \qquad (\Omega/\text{km}) \qquad (2.3)$$

where f = frequency (Hz)
L = inductance (mH/km)

IMPEDANCE

The phase impedance Z of a cable, or of the single-core cables comprising the circuit, is given by

$$Z = (R^2 + X^2)^{1/2} \qquad (\Omega/\text{km}) \qquad (2.4)$$

where R = a.c. resistance at operating temperature (Ω/km)
X = reactance (Ω/km)

INSULATION RESISTANCE

Insulation resistance is the resistance to the passage of direct current through the dielectric between two electrodes. In the case of an electric cable it is the value of the resistance between the conductor and the earthed core screen, metallic sheath, armour or adjacent conductors.

Consider a unit length of single-core cable with conductor radius r and radius over insulation R (fig. 2.1). The surface area of a ring of insulation of radial thickness δx at radius x is $2\pi x$ times the unit length. The insulation resistance δR of this ring is given by

$$\delta R = \frac{\rho \delta x}{2\pi x} \qquad (\Omega) \qquad (2.5)$$

where ρ is the specific resistivity (Ω m).

Thus the insulation resistance D_R of radial thickness $R - r$ for 1 m cable length is given by

$$D_R = \frac{\rho}{2\pi} \int_r^R \frac{\mathrm{d}x}{x} \qquad (\Omega) \qquad (2.6)$$

which evolves to

$$D_R = \frac{\rho}{2\pi} \log_e \frac{R}{r} \qquad (\Omega)$$

or for cable length l

$$\frac{\rho}{2\pi l} \log_e \frac{R}{r} \qquad (\Omega) \qquad (2.7)$$

Correction for temperature may be made according to

$$\rho_t = \rho_{20} \exp(-\alpha t)$$

where ρ_{20} = specific resistivity at 20°C
α = temperature coefficient of resistivity per degree Celsius at 20°C
t = temperature (°C)

Specific resistivity is also dependent on electric stress and hence the above derivation is a simplification. However, the effect is much less than that of temperature and in most cases it can be neglected. It can be of importance in the design of high voltage d.c.

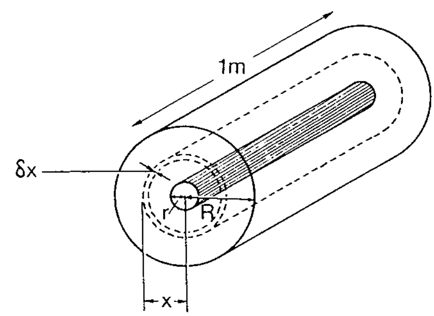

Fig. 2.1 Calculation of insulation resistance of an insulated conductor

paper cables and this is dealt with in chapter 38. In making measurements of insulation resistance it is necessary to maintain the d.c. test voltage for sufficient time to ensure that any transient currents associated with charging of the cable are of negligible value.

In a.c. cables there will be additional currents charging the insulation due to the capacitance of the insulation and for high voltage d.c. paper cables an extra factor is introduced to take account of the variation of resistivity with applied voltage (see chapter 38).

CAPACITANCE

Single-core cables or circular screened cores

Medium voltage and high voltage cable may be single-core cable with an earthed metallic layer around the core, or 3-core cable with an earthed metallic screen around each core. In both cases, the electrostatic field is contained within the earthed screen and is substantially radial.

Consider a single-core cable with a smooth conductor of radius r (m) and an internal screen radius of R (m) (fig. 2.2). Assume that the conductor carries a charge of q (coulomb/m), then the electric flux emanates from the conductor radially, giving a flux density at radius x (m) from the centre of the conductor of

$$D_x = \frac{q}{2\pi x} \qquad \text{(coulomb/m}^2\text{)}$$

The electric field intensity at radius x is

$$E_x = \frac{D_x}{\epsilon_0 \epsilon_r} = \frac{q}{2\pi x \epsilon_0 \epsilon_r} \tag{2.8}$$

where ϵ_0 = permittivity of free space, $10^{-9}/36\pi$
ϵ_r = relative permittivity of the insulation

The work done in moving a unit positive charge the distance dx in an electric field of intensity E is given by

$$\mathrm{d}W = -E_x\,\mathrm{d}x$$

i.e. the change in potential along dx is

$$\mathrm{d}V = -E_x\,\mathrm{d}x$$

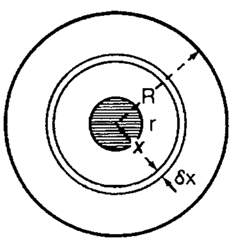

Fig. 2.2 Cross-section of cable core for derivation of capacitance

Therefore the work done in moving a unit charge from the conductor surface to the outer surface of the insulation is governed by

$$V = \int_R^r - E_x \, \mathrm{d}x$$

$$= - \frac{q}{2\pi\epsilon_0\epsilon_r} \int_R^r \frac{\mathrm{d}x}{x}$$

$$= \frac{q}{2\pi\epsilon_0\epsilon_r} \log_e\left(\frac{R}{r}\right) \qquad \text{(V)} \qquad (2.9)$$

The capacitance of the cable per metre length is given by

$$C = \frac{q}{V}$$

$$= \frac{2\pi\epsilon_0\epsilon_r}{\log_e(R/r)} \qquad \text{(F/m)}$$

$$= \frac{2\pi\epsilon_r \times 10^{-9}}{36\pi \log_e(R/r)} \qquad \text{(F/m)}$$

or

$$C = \frac{\epsilon_r}{18 \log_e(D/d)} \qquad (\mu\text{F/km}) \qquad (2.10)$$

where D = diameter over the insulation (m)
d = diameter over the conductor (m)
ϵ_r = relative permittivity

The relative permittivity is a characteristic of the insulation material and is dependent on temperature and frequency. For power frequencies and normal operating temperatures the effect is small and can be ignored for most engineering calculations.

The capacitance calculated using equation (2.10) is referred to as either the nominal capacitance per core or the nominal star capacitance. This equation is also used to calculate the capacitance of low voltage single-core cables without any metallic outer layer. This is justified on the basis that it is impossible to know what the additional capacitance is in a particular installation between the outer surface of the insulated core and any surrounding earth reference. In any case, such an additional capacitance in series with C would reduce the total star capacitance.

Three-core belted type cables

The equation for calculating the capacitance of a belted type cable is not readily formulated (see later for field theory for paper insulated cables), but an approximation of the capacitance between one conductor and the other conductors connected to the metallic sheath, screen or armour can be obtained from equation (2.10) if D is taken as

D = diameter of one conductor plus the thickness of insulation between conductors plus the thickness of insulation between any conductor and the metal sheath, screen or armour

The various other capacitances of a belted type cable may be obtained, to a close approximation, by calculating C by equation (2.10) and using the following factors:

$C_1 = 0.83 \times C$ = capacitance of one conductor to all other conductors and outer metallic layer

$C_2 = 0.50 \times C$ = capacitance of one conductor to one other conductor, with remaining conductors and outer metallic layer floating

$C_3 = 1.50 \times C$ = capacitance of all conductors (bunched) to outer metallic layer

DIELECTRIC POWER FACTOR (DIELECTRIC LOSS ANGLE)

It is of great importance that the power factor of the dielectric of cables for voltages of 33 kV and above is of a very low value. The power factor of a dielectric is the ratio

$$\frac{\text{loss in dielectric} \quad \text{(watt)}}{\text{volts} \times \text{amps}}$$

Referring to fig. 2.3, when a voltage is applied to a cable with a 'perfect' dielectric, a charging current I_C flows which is in leading quadrature with the voltage. In such a 'perfect' dielectric there would be no component of this current in phase with U. However, perfection in dielectrics has not been achieved and there is a small current I_R which is in phase with U. (See later section on dielectric losses.) This current causes losses $I_R U$ in the dielectric which generate heat. The losses in the dielectric are proportional to the cosine of the angle between the resultant current I_t and applied voltage U.

Now

$$I_t = (I_R^2 + I_C^2)^{1/2}$$

$$I_R U = I_t U \cos\phi$$

and

$$\cos\phi = \frac{I_R}{(I_R^2 + I_C^2)^{1/2}} \tag{2.11}$$

As ϕ is close to 90°, $\cos\phi$ equates approximately to $\tan(90 - \phi)$, i.e. equates (approximately) to $\tan\delta$, and the dielectric power factor of a cable is frequently referred to as $\tan\delta$, where δ is known as the dielectric loss angle (DLA).

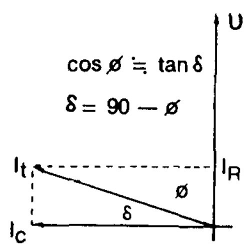

Fig. 2.3 Vector diagram to represent dielectric loss angle

The dielectric loss in watts per kilometre per phase is given by

$$D = 2\pi f C U_0^2 \tan\delta\, 10^{-6} \qquad \text{(watt/km per phase)} \qquad (2.12)$$

It will be seen from this equation that, for a specified design of cable in which values of f, C and U_0 are fixed, the dielectric loss angle must be kept to an absolute minimum to achieve low dielectric losses.

In addition to establishing the dielectric loss angle of the cable to determine the dielectric losses for cable rating purposes, valuable information can be obtained by testing the power factor of the cable in discrete voltage steps within the voltage range $0.5U_0$–$2U_0$. Such a test gives information on the ionisation which takes place in the insulation because ionisation increases with increase in applied voltage (see later under 'Mechanism of insulation breakdown in paper insulated cables').

In the case of paper insulated cables the DLA is a function of the density of the paper and the contamination in the fluid and paper. The fluid can readily be cleaned and the contaminants arise mostly from the paper as ionisable salts. To obtain the lowest DLA in transmission cables at high temperature, deionised water is used in paper manufacture.

ELECTRICAL STRESS DISTRIBUTION AND CALCULATION

The flux distribution in a.c. belted cable insulation is complex and is shown diagrammatically in fig. 2.4. The stress is a maximum at the conductor surface and varies throughout the insulation, decreasing with distance from the conductor surface, but not in a clearly defined manner because of the differing permittivities of the components and the distribution of the flux at various times during the voltage phase rotation. The screened cable used for alternating voltages has a clearly defined stress pattern, while that of cables used on d.c. transmission has a changing pattern depending on temperature due to cable loading.

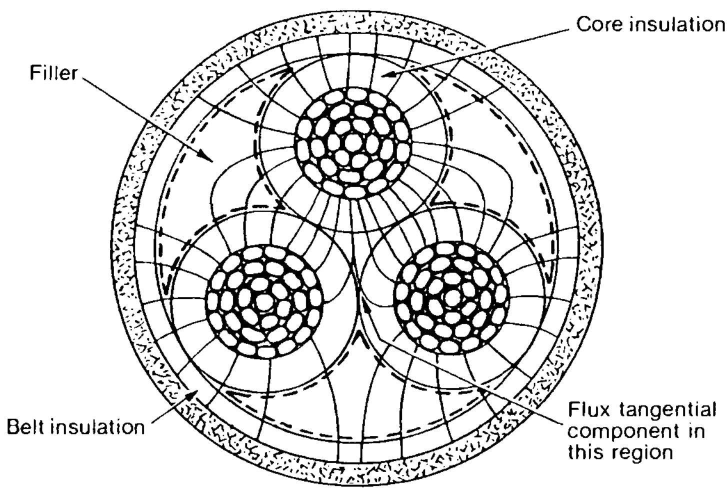

Fig. 2.4 Paper insulated belted cable with top conductor at peak potential

A.C. stress distribution in single-core and screened multicore cables

The stranding effect of unscreened conductors gives a slight unevenness of stress distribution around the periphery of the conductor because of the small radius of the individual wires. Neglecting this effect, a screened core consists of a cylindrical capacitor with the conductor as the inner electrode and the core screen as the outer electrode. Assuming a uniform permittivity, the radial stress distribution curve of a circular core is derived as below. It will be seen to be maximum at the conductor surface, reducing in a hyperbolic curve (fig. 2.5). As the permittivity of the dielectric is substantially constant throughout the operating temperature range of the cable, the stress distribution remains constant at all operating conditions.

Using the notation given previously, i.e.

r = radius of conductor (m)
R = internal radius of sheath (m)
ϵ_0 = permittivity of free space
ϵ_r = relative permittivity of the dielectric
V = potential of conductor relative to the sheath (V)
q = charge (coulomb/m of axial length)

from equation (2.9)

$$V = \frac{q}{2\pi\epsilon_0\epsilon_r}\log_e\left(\frac{R}{r}\right) \qquad \text{(V)}$$

Therefore

$$\frac{q}{2\pi\epsilon_0\epsilon_r} = \frac{V}{\log_e(R/r)}$$

Stress may be calculated from equation (2.8) which showed the electric field intensity E_x at radius x to be

$$E_x = \frac{q}{2\pi x\epsilon_0\epsilon_r}$$

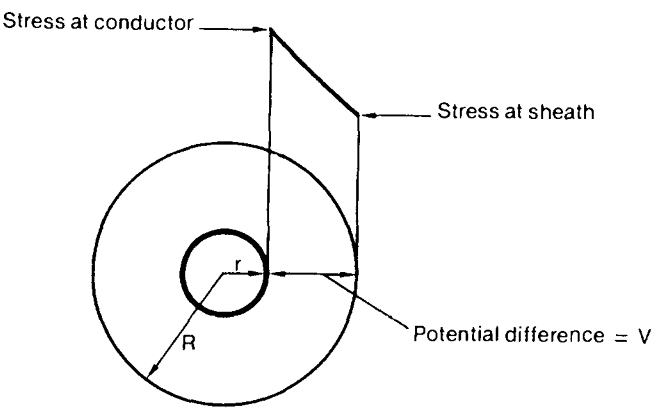

Fig. 2.5 Electrostatic stress in single-core cable

By substitution, the stress at radius x is

$$E_x = \frac{V}{x \log_e(R/r)} \qquad \text{(MV/m)} \tag{2.13}$$

It will be noted that the range is

$$\text{maximum} = \frac{V}{r \log_e(R/r)} \qquad \text{at conductor surface}$$

$$\text{minimum} = \frac{V}{R \log_e(R/r)} \qquad \text{at sheath inner surface}$$

Several features arising from this are as follows.

Stress at conductor surface

In the above derivation of the stress distribution it was assumed that the conductor surface was smooth. However, the effects of the radius of the wires in a stranded, uncompacted conductor may increase the stress substantially. In high and medium voltage cables, therefore, it is usual to apply a semiconducting screen to a stranded conductor to obtain a smooth surface. This screen would be a carbon paper tape on paper cables or an extruded semiconducting polymer on polymeric cables. When using the equation (2.13), the value of r would be the radius over this conductor screen.

Conductor diameter

The equation (2.13) derived for the stress within the cable dielectric showed the stress to be a maximum at the conductor surface. The equation may be developed further to obtain the ratio of the diameter over the conductor to that over the insulation and hence the conductor diameter which gives the minimum stress at the conductor surface for a specified voltage and diameter over the insulation:

$$E_r = \frac{V}{r \log_e(R/r)}$$

For minimum stress at the conductor for constant values of V and R

$$\frac{\mathrm{d}E_r}{\mathrm{d}r} = 0$$

i.e.

$$\frac{\mathrm{d}}{\mathrm{d}_r}\left[\frac{V}{r \log_e(R/r)}\right] = 0$$

$$\frac{\mathrm{d}}{\mathrm{d}_r}\left[\frac{V}{r \log_e R - r \log_e r}\right] = 0$$

$$\frac{-V(\log_e R - \log_e r - 1)}{(r \log_e R - r \log_e r)^2} = 0$$

Therefore

$$\log_e R - \log_e r - 1 = 0$$

$$\log_e(R/r) = 1$$

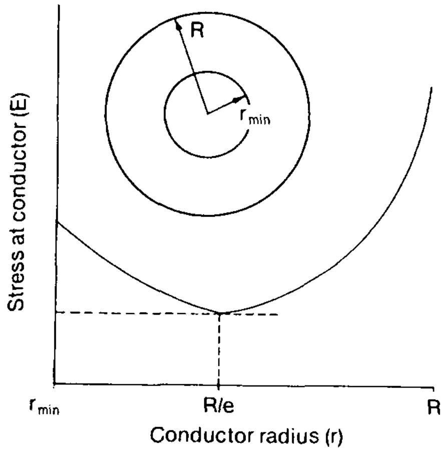

Fig. 2.6 Variation of stress with conductor radius

and

$$R/r = \mathrm{e} \tag{2.14}$$

The stress at the conductor is at a minimum when the ratio R/r equals e. By substituting this in the stress equation it will be seen that the value of the stress is V/r. This is illustrated in fig. 2.6.

The conductor cross-sectional area is determined by the current which has to be carried. When designing cables, particularly for the higher transmission voltages, it is possible that the radius of the conductor size needed to give the current carrying capacity called for will be smaller than that to give optimum ratio of diameter over conductor to diameter over insulation. This necessitates the application of thicker insulation to maintain an equal maximum stress. Frequently the smaller conductors within a specific voltage range have a greater insulation thickness than the larger sizes. An alternative design procedure is to increase the conductor diameter to attain the optimum ratio. For example, in the case of fluid-filled cables, the diameter of the central fluid duct may be increased.

Grading of insulation

In high voltage impregnated paper insulated cables it is an advantage to have material of high electric strength near the conductor to reduce the total insulation thickness. This is normally achieved by having thinner high quality, higher density papers in this region. The use of graded insulation also gives improved bending properties (chapter 19).

D.C. stress distribution

The stress distribution within a d.c. cable is determined, *inter alia*, by insulation resistivity, which, as indicated previously, is influenced by the temperature of the insulation and also the stress. The stress pattern within a d.c. cable thus alters with the load. This is discussed in chapter 38.

FIELD CONTROL IN PAPER INSULATED CABLES

In the early days of electrical power transmission the belted type cable was used extensively but, with the increase in system voltage to 33 kV in the early 1920s, the shortcomings of the belted construction became apparent and the screened type (sometimes called H or Hochstadter type) cable was introduced and has been used successfully for this voltage to the present day. As transmission voltages increased, 'pressure-assisted' type cables using the screened construction were designed and are employed at voltages of 33 kV and above.

Belted type cables

The construction of the 3-core belted type cable is shown in fig. 2.7 (left). The insulation between conductors is twice the radial thickness of the insulation around each conductor and the insulation between any conductor and the earthed sheath is the radial thickness of the insulation around a conductor plus the thickness of the belt. As the phase to phase voltage is $\sqrt{3}$ times the phase to earth voltage, the total thickness of insulation between conductors and that between conductors and sheath are designed in approximately the same ratio.

For voltages up to 22 kV the belted construction has been used as the electrical stresses are acceptably low. For cables used at higher voltages it is necessary to raise the operating stresses for economical and practical reasons and this brings to light defects in the belted cable design which are described in the later section, 'Mechanism of insulation breakdown in paper insulated cables'. Nowadays screened cables are generally used at 15 kV and above.

Screened or H type cable

To eliminate the weaknesses of the belted type cable a design of cable in which each core is individually surrounded by an earthed metallic layer was introduced and is shown in fig. 2.7 (right). This design of cable, first patented by Hochstadter in 1914,

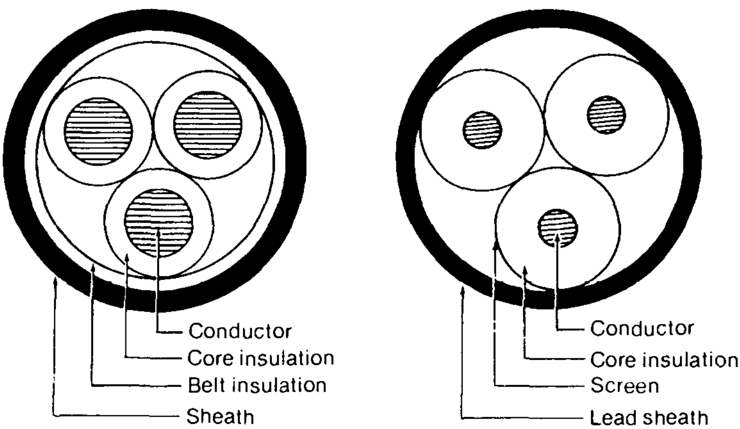

Fig. 2.7 3-core belted type cable (*left*) and screened cable (*right*)

ensures that the stress is substantially radial and hence normal to the paper surface and is also contained within the machine lapped insulation, which is electrically strong. The possibility of separation of the cores due to thermal excursions and mechanical handling, while not eliminated, does not present a hazard as all electrical flux is contained within the earthed screens.

FIELD CONTROL IN POLYMERIC INSULATED CABLES

During the development of medium voltage XLPE cables, it was soon realised that belted designs above 1.9/3.3 kV rating exhibited similar weaknesses to those of belted paper cables above 12.7/22 kV rating. That is, the electrical stress in the fillers around the cores produced partial discharge activity which impinged on the surface of the XLPE insulation, steadily eroding the dielectric and resulting in premature cable failure.

For most normal applications, therefore, polymeric cables rated at 3.8/6.6 kV and above have screened cores. Furthermore, these cables nearly always have circular cores so the cable section is similar to that in Fig. 2.7 (right).

The main functional element of the core screen is a semiconducting layer in intimate contact with the insulation. This can comprise a semiconducting varnish in combination with a semiconducting tape but, nowadays, is invariably an extruded semiconducting layer. The combination of conductor screen, insulation and core screen are produced in one production process to ensure a composite extrusion without voids at the insulation surfaces.

As a result, the electric field in these cables is kept within a homogeneous dielectric and has a radial pattern. In order to provide a continuous earth reference for the semiconducting core screen and to supply the charging currents for all parts of the cable length, a layer of metallic tape or wires is applied over the core screen.

SOURCES OF ELECTRICAL LOSSES

An electric power cable consists of three basic components, namely the conductor(s), the dielectric and the outer metallic layer(s). When the cable is energised and carrying load, heat, which must be dissipated to the surrounding medium, is generated by each of these components. The effects on current carrying capacity are discussed in chapter 8.

Conductor losses

The conductor losses are ohmic losses and are equal to

$$nI^2 R_\theta \qquad \text{(watt)}$$

where I = current carried by the conductor (A)
R_θ = ohmic a.c. resistance of the conductor at θ°C (Ω)
n = number of cores

When high a.c. currents are transmitted, the distribution of current is not evenly disposed throughout the cross-section of the conductor. This is due to the skin effect and the proximity effect as discussed earlier in relation to a.c. resistance.

Dielectric losses

The dielectric losses of an a.c. cable are proportional to the capacitance, the frequency, the phase voltage and the power factor. They are given by

$$D = n\omega C U_0^2 \tan\delta\, 10^{-6} \qquad \text{(watt/km)} \qquad \text{(see equation (2.12))}$$

where $\omega = 2\pi$ multiplied by frequency
C = capacitance to neutral (μF/km)
U_0 = phase to neutral voltage (V)
$\tan\delta$ = dielectric power factor

The loss component of the power factor (i.e. the current in phase with the applied voltage) is made up of

(a) leakage current flowing through the dielectric which is independent of frequency and consequently occurs with both a.c. and d.c. voltage applications;
(b) dielectric hysteresis, by far the largest effect, which is caused by the interaction of the alternating field with the molecules of the constituents of the insulation and is only present with a.c. voltage application;
(c) ionisation, i.e. partial discharge in the dielectric.

The power factor of the cable insulation is dependent on frequency, temperature and applied voltage. It is of a very low order and consequently for cables of up to 50 kV operating voltage the dielectric losses are small in comparison with conductor losses. However, for cables for operation above this level the losses rise rapidly with voltage and this must be taken into consideration when calculating the current carrying capacity of the cables.

Sheath losses

When single-core cables carry alternating current the magnetic field associated with the current induces e.m.f.s in the sheath of the cable and also in the sheaths of surrounding cables. Two types of sheath losses are possible resulting from such e.m.f.s: sheath eddy current loss and sheath circuit loss.

Sheath eddy current loss
Eddy currents are induced by the current or currents in the conductors of the cables in close proximity to the sheath. Consider a three-phase circuit with cables R, Y and B. The flux of cables Y and B cuts the sheath of cable R. More lines of flux cut the sections of the sheath of R closer to Y and B than that section remote from Y and B. Thus a resultant e.m.f. is induced which causes current (eddy current) to flow along one side of the sheath and return along the other.

The integral of such currents over the sheath cross-section is zero. These eddy currents are independent of the type of sheath bonding which is applied and decrease with the distance between the cables.

The sheath eddy current losses are given by

$$S_e = I^2\left[\frac{3\omega^2}{R_s}\left(\frac{d_m}{2S}\right)^2 \times 10^{-8}\right] \qquad \text{(watt/km per phase)} \qquad (2.15)$$

where S_e = sheath eddy current losses
I = current (A)
$\omega = 2\pi$ multiplied by frequency
d_m = mean diameter of the sheath (m)
S = distance between cable centres (m)
R_s = sheath resistance (Ω/km)

For single-core lead sheathed cables these losses are normally small compared with conductor losses, but are considerably higher with aluminium sheathed cables when they are in close proximity.

Sheath circuit loss

When the sheath of a single-core cable is bonded to earth or to other sheaths at more than one point, a current flows in the sheath due to the e.m.f. induced by the a.c. conductor current by 'transformer' action. This is because the sheath and return path, to which each end of the sheath is bonded, form a closed loop which is cut by the flux associated with the current in the conductor. The magnitude of the flux which cuts the sheath is dependent on the size of the loop which, in turn, is dependent on the spacing between the cables or between the sheath and the mean return path of the current through the earth or other medium.

The voltage induced in the sheath is given by

$$E_s = IX_m$$

where I = conductor current (A)
$X_m = 2\pi f M \times 10^{-3}(\Omega/\text{km})$

The mutual inductance M between conductor and sheath is given by

$$M = 0.2\log_e\left(\frac{2S}{d_m}\right) \qquad (\text{mH/km})$$

The impedance of the sheath Z_s (Ω/km) is given by

$$Z_s = (R_s{}^2 + X_m{}^2)^{1/2}$$

where R_s is the sheath resistance (Ω/km). Therefore the sheath current I_s is equal to

$$I_s = \frac{E_s}{(R_s{}^2 + X_m{}^2)^{1/2}} = \frac{IX_m}{(R_s{}^2 + X_m{}^2)^{1/2}} \qquad (\text{A})$$

The sheath current losses per phase are given by

$$I_s{}^2 R_s = \frac{I^2 X_m{}^2 R_s}{R_s{}^2 + X_m{}^2} \qquad (\text{watt/km}) \qquad (2.16)$$

Therefore total sheath losses, i.e. sheath circuit losses plus sheath eddy current losses, are given by

$$I^2 R_s\left\{\frac{X_m{}^2}{R_s{}^2 + X_m{}^2} + \left[\frac{3\omega^2}{R_s{}^2}\left(\frac{d_m}{2S}\right)^2 \times 10^{-8}\right]\right\} \qquad (2.17)$$

The heat generated by losses in the conductor, the dielectric, the sheath and armour has to pass to the surrounding medium, which may be the ground, air, water or some other material. As the current carrying capacity of an electric cable is normally dictated by the maximum temperature of the conductor, the components of the cable, in addition to meeting the electrical requirements, must also have as low a thermal resistivity as possible to ensure that the heat can be dissipated efficiently. The subjects of heat dissipation and operating temperatures of cable components are discussed in chapter 8.

MECHANISM OF INSULATION BREAKDOWN IN PAPER INSULATED CABLES

In addition to the obvious and by far the most usual reasons for failure, such as mechanical damage to the insulation or ingress of moisture, there are three basic reasons for failure:

(a) breakdown due to ionisation;
(b) thermal breakdown;
(c) breakdown under transient voltage conditions.

Breakdown due to ionisation

The 'perfect' belted solid type cable would be so manufactured that the impregnant would completely fill the interstices between the wires of the conductor, the fibres of the paper, the gaps between papers and the filler material. In short, the whole volume contained within the lead or aluminium sheath would be completely void free. During installation, however, the 'perfect' belted cable undergoes mechanical manipulation, and movement of the cores relative to each other takes place. Also, when the cable is loaded electrically the conductors, insulation, free impregnant and lead sheath expand, but the lead sheath does not expand with temperature to the same extent as the interior components of the cable. The sheath is thus extended physically by the pressure exerted by the inner components. On cooling, the lead sheath does not return to its original dimensions and consequently the interior of the sheath is no longer completely occupied, there being voids formed within the cable.

Installation, repeated load cycling and migration of compound of inclined routes can therefore all cause voids within the cable. Such voids are particularly hazardous when they occur within the highly stressed zones of the insulation. As transmission voltages increased, the insulation of the belted cables was increased to meet the higher stresses involved. On the introduction of 33 kV belted cables in the early 1920s, however, it was found that merely increasing the insulation thickness did not give satisfactory performance as there was a high failure rate. On studying the problem, certain weaknesses were found in the belted construction of cables for this voltage. Because of the design of the cable, part of the flux due to the 3-phase voltage, at a certain instant of time during the voltage phase rotation, passes radially through electrically strong core insulation; at other parts of the insulation there is a radial and a tangential component of the flux, and at still other parts the flux passes through the sound core insulation and into the inferior insulation (fig. 2.4).

The tangential strength, i.e. the strength along the surface of the papers, of lapped dielectric is only about one-fifteenth of the radial strength and also the filler insulation is much weaker than the normal core insulation; consequently these weaknesses were highlighted by the higher stresses involved in 33 kV cables.

A more serious weakness in the belted construction occurs, however, when the cores which were originally in close contact with each other move or are forced apart, either by mechanical manipulation or by cable loading. When this happens, the flux passes through sound core insulation, through the space between the two cores and then through the insulation of the second core. The space between the cores which is likely to be devoid of compound is therefore highly stressed, and any gas which may be present will ionise. The adjacent core insulation is thereby weakened by ionic bombardment and failure can occur.

The screened cable was introduced to eliminate the weakness of the belted type cable caused by the weak filler insulation, the spaces between cores and the tangential flux. The screen round the individual cores confines the stress to sound core insulation and also ensures that the flux is substantially radial.

With the introduction of the screened or H type cable, many of the weaknesses of the belted construction were eliminated and 33 kV solid H type cables have given extremely good service performance for many years. On increasing the transmission voltage above 33 kV, however, the one weakness remaining, though not manifestly harmful at 33 kV, had to be eliminated. This final weakness was the gaseous ionisation in voids formed within the insulation by compound migration resulting from cable loading and steep inclines.

The breakdown of paper insulation due to ionisation occurs through the formation of carbonaceous 'fronds' on the insulation papers (fig. 2.8). This is generally known as

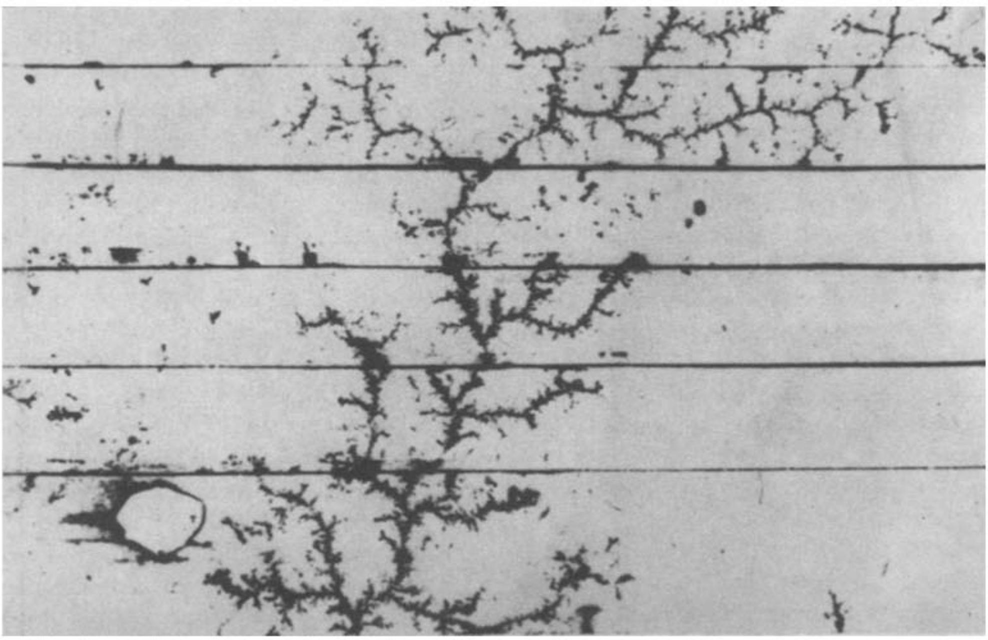

Fig. 2.8 Treeing, i.e. carbon tracking, on paper insulating tapes

'treeing'. The carbonaceous paths start at an almost imperceptible carbon core, generally at the conductor surface, and gradually spread outwards through the insulation, increasing in width and complexity as progression takes place.

Figure 2.9 depicts the development of tree paths. The steps which lead to breakdown comprise the following.

(a) Ionisation takes place within a gaseous void in the gap between the paper next to the conductor and the conductor.
(b) Owing to the ionic bombardment of the second paper, the impregnant is partly pushed out and partly condensed into cable wax with the formation of more gas. Eventually, if the ionic bombardment is sufficiently severe, a carbonaceous path will penetrate between the fibres of the second paper.
(c) There is now a conducting path extending from the conductor, through the butt gap of the first paper and reaching the surface of the third paper nearest to the conductor. Neglecting the voltage drop along this path, the potential of the path front is substantially the same as that of the conductor; thus there is a point on the conductor side of the third paper which is at conductor potential, i.e. V_1 in fig. 2.9. There is a potential gradient throughout the dielectric and thus the third paper is at a potential lower than that of the conductor, i.e. V_2 in fig. 2.9. Therefore there exists a tangential stress $V_1 - V_2$ across the surface of the third paper.
(d) Ionisation due to this tangential stress sweeps away some of the compound and condenses some of the remainder, forming wax.

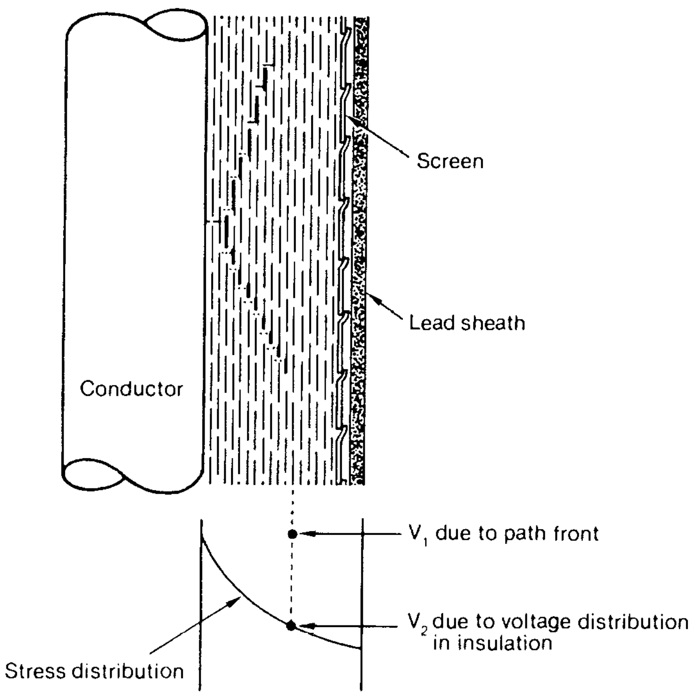

Fig. 2.9 Mechanism of breakdown of paper insulation by treeing

(e) Eventually carbonisation of the compound takes place. 'Fronds' of carbon spread out until the gap in the third paper is reached and the path proceeds, through the gap where there is no fibrous barrier, to the fourth paper.
(f) The treeing mechanism thus progresses, increasing in severity as the distance from the conductor increases owing to the greater tangential stress which exists.
(g) The carbon fronds at each paper continue in length along the surface of the paper until the voltage drop due to the current within the main track and the frond lowers the tangential stress to a value below ionising level.

Several methods of controlling ionisation may be used. One method is to prevent the formation of voids throughout the life of the cable by impregnating the cable with a low viscosity fluid and maintaining a positive fluid pressure within the cable over the complete operating temperature range of the cable. This is attained by fitting pressurised reservoir tanks at strategic positions throughout the cable route. At periods when the cable is loaded, the components within the aluminium or reinforced lead sheath expand and the displaced fluid passes along the cable via the ducts into the pressure tanks which accept the fluid and retain it until the cable cools. On cooling, the pressure tanks force the fluid back into the cable, thus retaining void-free insulation. Such a cable is called a self-contained fluid-filled cable.

Other methods of controlling ionisation are (a) to fill the voids with pressurised gas and (b) to apply sufficient pressure externally to the cable to close up the voids. The high pressure gas-filled cable controls ionisation by having the conductors and gap spaces between the pre-impregnated paper tapes filled with an inert gas under high pressure. Ionisation does not occur in the gaps because of the high pressure involved. During cable heating, the gas expands more in the gaps close to the conductor than in those at the outside of the insulation owing to the temperature differential, and the gas moves towards the aluminium or reinforced lead sheath. On cooling, the gas is forced by the differential pressure back from the outside of the insulation towards the conductor. The pressure within the cable is kept at all times at a value sufficient to prevent ionisation.

Ionisation within voids is prevented in the pipe type compression cable by the application of external pressure to the cable. In this case, the mass-impregnated single-core cables are shaped so that the sheath can be deformed under pressure. The 3-core or three single-core cables are all contained within a steel pipe and the intervening space is filled with a gas under high pressure. When the cable expands on load, the gas absorbs the expansion and on cooling the gas pressurises the cable and prevents void formation.

The pipe type high pressure fluid-filled cable is constructed with three unsheathed cores within a steel pipe. The intervening space within the pipe is filled with a low viscosity fluid under pressure which prevents the formation of voids.

Thermal breakdown in paper insulation

The dielectric loss angle for fluid/paper insulation has a minimum value in the region of 50–60°C. Thus, at around the operating temperature, a rise in temperature increases the dielectric loss, so giving a larger heat generation. The rise in temperature also increases the temperature gradient to the surroundings and raises the rate of heat dissipation. If the rate of rise of heat generation is greater than the rate of rise of heat dissipation, the cable temperature will continue to increase, with the result that the dielectric will overheat and fail electrically.

Figure 2.10 illustrates the dielectric loss angle versus temperature characteristics of two types of impregnated paper. Paper A is typical of paper in use some years ago, while paper B represents paper of the type now used for very high voltage cables. Paper B exhibits comparatively little variation of DLA with temperature over the important temperature range, whereas the DLA of paper A increases considerably above 60°C.

Figure 2.11 indicates the effect of using these papers on the thermal stability of 400 kV 2000 mm^2 self-contained fluid-filled cable buried at standard depth in ground of normal thermal resistivity. The straight line shows the relationship between the cable sheath temperature and the amount of heat which can be dissipated through the ground. The other curves show the relationship between the total losses generated with the cable and the sheath temperature. These losses comprise two main components: the I^2R loss in the conductor and the dielectric loss. The I^2R loss is approximately linearly dependent on the cable temperature, because of the increase in conductor resistance with temperature. The dielectric loss is proportional to the DLA in accordance with

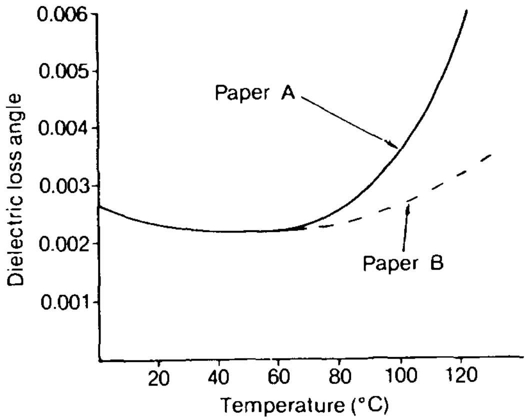

Fig. 2.10 Dielectric loss angle versus temperature characteristics of two types of impregnated paper for high voltage cables

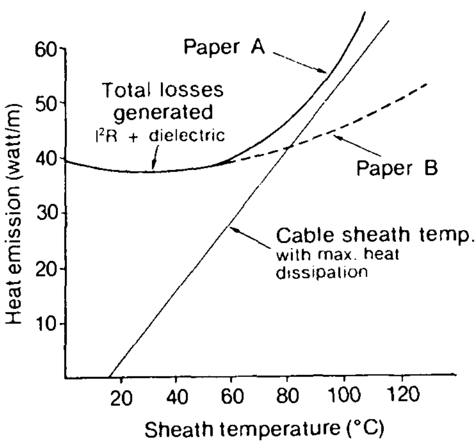

Fig. 2.11 Thermal stability of a buried 2000 mm^2, 400 kV cable with a current of 1400 A

equation (2.12). If the current is taken to be 1400 A, applied at ambient temperature, the cable with the insulation comprising paper B would at first rise rapidly in temperature because the total losses generated would greatly exceed the amount of heat which could be dissipated from the sheath. The general cable temperature would continue to rise until the heat generation and losses were in equilibrium, i.e. at the intersection of the two lines. The temperature of the cable would then remain steady (at a temperature of 80°C on the graph).

If the cable had insulation corresponding to paper A, the initial temperature rise would follow a similar pattern. However, when the temperature exceeded 60°C, the rate of rise of the dielectric losses would exceed the increase in the ability of the sheath to dissipate the losses and the cable temperature would rise. The losses generated would continue to exceed the losses dissipated, with the result that the progressive temperature rise would continue until thermal breakdown of the cable occurred. In this particular example the current loading condition is somewhat exaggerated but the principle illustrates the importance of selecting paper having suitable characteristics. It has also been assumed that the sheath bonding and spacing between cables is such that sheath losses can be ignored.

Breakdown under transient conditions

Cables are designed to withstand transient conditions appropriate to their operating voltage, and this is an important aspect in the case of pressure assisted transmission cables (chapter 29). However, should the cable insulation be subjected to transient voltages such as lightning or switching surges, which are higher than the impulse voltage for which the cable is designed, a failure may occur. Such a breakdown takes the form of a puncture of the insulation and is usually very localised in nature.

BREAKDOWN OF PLASTIC INSULATION

This subject is covered in chapters 3 and 24.

ELECTROMAGNETIC FIELDS

Insulated distribution and transmission cables have an advantage over overhead lines; the external electrostatic field is zero because of the shielding effect of the conducting insulation screen within the cable. The magnetic field external to a three-core distribution cable carrying balanced load currents rapidly reduces to zero because the vector sum of the spatial and time resolved components of the field is zero. A useful degree of ferromagnetic shielding is achieved for three-core cables by the application of steel wire armour which helps to contain the flux. The shielding effect can be significantly increased by eliminating the air gaps with steel tape armour (suitable for small diameter cables) or by the installation of the cable within a steel pipe (as employed with high pressure fluid-filled and high pressure gas-filled cables).

The magnetic field external to single-core cables laid in flat formation does not sum to zero close to the cables because of the geometric asymmetry. The distribution of flux density can be calculated analytically by the application of the Biot–Savart law[2] to each individual current carrying conductor and metallic sheath and by making a vectorially and temporally resolved summation (equations (2.18) and (2.19)). The simple analytical method can be used in those applications which have one value of permeability and which do not use eddy current shielding. For more complex application, such as those employing ferrous materials, specialised computer programs are required which usually employ a finite element algorithm with the ability to model a non-linear *B–H* hysteresis curve. It is usual in calculations to use the peak value of current. The waveform of the resultant flux density is complex, comprising both sinusoidal and bias components and with a polarised vector rotating about an axis and pulsating in magnitude. In consequence it is usual to quote either the r.m.s. value or the mean value of flux density, the preferred unit being μT (1 μT = 10 mG).

$$\bar{B} = \bar{B}_1 + \bar{B}_2 + \cdots + \bar{B}_n \tag{2.18}$$

$$\bar{B}_r = \frac{\mu_0 \mu_r I_1 \sin(\omega t + \phi_1)}{2\pi r_1} \tag{2.19}$$

where $\bar{B}_r$ = resultant flux density at r due to $I_1, I_2, \ldots, I_n$, f(t, x, y) (T)
$\bar{B}_1$ = flux density at r due to I_1, f(t, x, y) (T)
I_1 = conductor sheath current (A_{peak})
r_1 = distance from centre-line of conductor 1, f(x, y) (m)
x, y = co-ordinates of horizontal and vertical distance (m)
μ_0 = magnetic permeability of free space (T/A)
μ_r = relative magnetic permeability
ω = angular frequency of supply (radians/s)
ϕ_1 = phase displacement of I_1 (radians)

For comparative purposes it has become practice to calculate the magnetic flux density above a buried cable circuit at a height of 1 m above ground level. At this height the ratio of distance to cable centre-line spacing is comparatively large such that the maximum magnitude of the flux density is low and, compared with an overhead line,

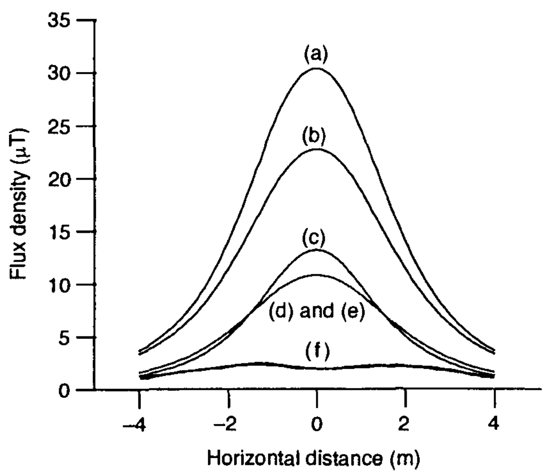

Fig. 2.12 Horizontal flux density distribution 1 m above ground level for 400 kV underground double cable circuits carrying 1000 A. (The legend is given in table 2.2.)

Table 2.2 Effect of installation configuration on magnetic flux density and cable rating (see also fig. 2.12)

Configuration (Double circuit)	Cable spacing (mm)	Circuit spacing (mm)	Depth (mm)	Flux density at 1000 A (μT) Max.	Flux density at 1000 A (μT) Fig.	Rating per circuit (A)
Flat – XB[a]	300	1500	900	30	2.12a	2432
Flat – XB[b]	300	1500	900	23	2.12b	2432
Flat – XB	200	800	900	13	2.12c	1934
Flat – XB	300	1500	1800	11	2.12d	1886
Trefoil – XB	300	1500	900	11	2.12e	2248
Flat – SB	300	1500	900	2	2.12f	1370

[a] Reference case
[b] With steel plates
XB Cross bonded sheath
SB Solidly bonded sheath

rapidly reduces in magnitude on both sides of the cable circuit, i.e. within the width of a roadway (fig. 2.12). Should it be required, significant further reduction in flux density can be achieved, however this is in varying degrees detrimental to the cable thermal rating and to the cost of the circuit.[3] Examples of flux density distributions are shown in fig. 2.12 for the 400 kV double circuit configuration given in table 2.2. The simplest methods are to lay the cables closer together and at greater depth, the most effective compromise being to lay the cables in an open trefoil formation.

A degree of cancellation of the magnetic field is obtained by solidly bonding the metallic sheaths of single core cables thereby permitting the induced voltages to drive a current which, in ideal theoretical circumstances, would be of equal magnitude and in antiphase to the conductor current. In practice the finite resistances of the metallic sheath and earth return wires, if present, reduce the magnitude and alter the phase of the sheath current thereby achieving only partial magnetic screening and with the disadvantage of generating sheath heat loss of comparatively high magnitude. Ferrous screening can be employed by positioning steel plates above the cables, a practice also used to protect cables from vertical ground loading at road crossings. The screening effect can be increased by positioning inverted, U-shaped, steel troughs over the cables but to the detriment of trapping an unwanted layer of air above the cables. Eddy current screening can be employed by positioning non-ferrous plates of high electrical conductivity over the cables, however this is an inefficient solution of high cost.

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