# 31

# Cables

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## Contents

## 31.1 Introduction

The essential components of a cable are a metallic conductor of low resistivity to carry the current and insulation to provide a dielectric medium for isolating conductors from one another and from their surroundings. The conductor may consist of solid metal or of wires or segments stranded together. A single-core wiring cable for installation in conduit represents this basic construction. For other applications, two or more single-core units may be assembled together with overall protective coverings to prevent moisture ingress, and provide resistance to mechanical damage and to other external influences such as corrosion and fire.

In general, the voltage range extends from automobile cables at 6–12 V to the highest transmission voltages, which now are reaching towards 760 kV. In order to specify suitable insulation and construction for the required service performance, the design voltages are quoted in the form of $U_0/U$, i.e. (voltage to earth)/(voltage between phases). Cables are not manufactured, however, for every individual voltage requirement—e.g. although the most common supply voltage in the UK is 240/415 V, the cables actually used are designated as 0.6/1 kV. This is largely related to the fact that the minimum thickness of insulation which can be economically applied meets the higher voltage.

It has been traditional practice to describe cables in categories of low-voltage (l.v.), medium-voltage (m.v.), high-voltage (h.v.), supertension (s.t.), extra-high-voltage (e.h.v.) and ultra-high-voltage (u.h.v.). However, the exact demarcations have never been very precise, because they vary between different countries, among different groups of engineers and with the passing of time. Not so long ago, the conventional supply cables operating at 240/415 V were known as m.v., but now they are l.v.; 11 kV cables have also changed from h.v. to m.v. Thus, there can be confusion especially at international meetings, and it is better to refer only to the actual voltage designation.

There is also some overlap when cables are classified into the three major groups of usage: (1) wiring and general, (2) power distribution, and (3) transmission. When heavy power cables were essentially of the paper-insulated type, there was little problem, because they tended to be made in different factories from wiring cables and the type of insulation governed the usage group. When paper insulation operated with internal or external fluid or gas pressure, as required for voltages above 33 kV, the cable came into the transmission grouping. Nowadays, the basic insulation materials and constructions used for wiring cables can, with appropriate insulation thickness, be used across the three major groupings, and it is becoming more complex to define specific cable categories. For public supply there is no problem, but for ship cables, offshore supplies and large factory distribution there can be considerable overlap between the wiring and the distribution categories. At the top end of the voltage range we now have 132 kV cables for distribution rather than transmission, and polyethylene or cross-linked polyethylene is finding acceptance across the whole spectrum from 1 to 275 kV.

In this chapter, the section on power distribution cables is aimed at public supply networks together with the larger power cables used in factories, etc., from 1 to 33 kV. Where the broad wiring cable category encroaches on this field, reference is made in the text. Cables for voltages above 33 kV are covered in the section on transmission cables.

### 31.1.1 Standards

*Table 31.1* lists most of the British (BS) and International (IEC) Standards applicable to cables and cable systems, including tests. While most national standards are in accordance with IEC requirements, the IEC Standards represent a consensus of national opinion and take many years to prepare. There is, consequently, a time lag in taking account of new developments, but British Standards have been more comprehensive in requirements and in updating revisions.

However, a fundamental change affecting the British Standards arises from the activities of the European Committee for Electrotechnical Standardisation (CENELEC), of which the membership consists of the standards organisations of the European Common Market and the EFTA countries. The aim of CENELEC is to remove technical barriers to trade among the member countries, and to this end it is engaged in the harmonisation of their national standards.

The mechanism is the preparation of Harmonisation Documents and, after these are issued, the member countries are required to bring the technical requirements of their national standards into conformity with them. There must be no extra requirements or deviations, except in special circumstances and subject to general agreement, and then only on a temporary basis.

To date, the two most important harmonisation documents for cables which have come into effect are:

HD 21 Polyvinyl chloride (PVC) insulated cables and flexible cords of rated voltage up to and including 450/750 V

HD 22 Rubber insulated cables and flexible cords of rated voltage up to and including 450/750 V

and it is intended to extend harmonisation to all types of mains cables.

Among the features arising from this structure are the following:

(1) The broad policy is to use IEC standards, if suitable and available, as a basis for harmonisation.
(2) When CENELEC begins work on a particular type of cable (or a subject having an important bearing on cable standards), a 'standstill' or 'status quo' arrangement comes into effect. Changes in relevant national standards cannot then be made until harmonisation has been agreed or permission obtained from CENELEC, to avoid prejudicing the harmonisation.
(3) While the number of cable designs and types will be kept to a minimum, it will still be possible to have a national standard for a type of cable not of interest to other member countries of CENELEC.
(4) Individual customers can still obtain cables made to their own specification, but it is hoped that this will be kept to a minimum. Because they have to be produced as 'specials' they may suffer from a delivery and/or a price penalty.
(5) Implementation for flexible cables and some wiring cables has been effected and work on the harmonisation of mains cables is at an advanced stage. PVC cables to BS 6346 will probably be the first mains cables involved, but the changes are likely to be relatively minor.

Another important facet of CENELEC activity relates to certification and associated marks. These are issued by national approval organisations (NAOs) to indicate independent assurance of manufacture to specification. A common marking scheme, utilising the 'HAR' mark, has been devised. There is a reciprocal agreement accepted by most of the CENELEC countries' national approval organisations, under which for cables to harmonised standards, each NAO will recognise the common marking as superseding its own national mark. The procedures for granting

**Table 31.1** British and IEC Standards

| | |
|---|---|
| *Cables and Flexible Cords* | |
| BS 638 | Arc welding plant (includes cables) |
| BS 4553 | PVC-insulated split concentric cables with copper conductors for electricity supply |
| BS 5055 | PVC-insulated and elastomer-insulated cables for electric signs and h.v. luminous discharge tube installations |
| BS 5308 | Instrumentation cables intended for intrinsically safe systems<br>Part 1 Polyethylene insulated cables<br>Part 2 PVC-insulated cables |
| BS 5467 | Cables with thermosetting insulation for electricity supply |
| BS 5593 | Impregnated paper insulated cables with aluminium sheath/neutral conductor and three shaped solid aluminium phase conductors (Consac) for electricity supply |
| BS 6004 | PVC-insulated cables (non-armoured) for electric power and lighting |
| BS 6007 | Rubber-insulated cables for electric power and lighting |
| BS 6116 | Elastomer-insulated flexible trailing cables for quarries and miscellaneous mines |
| BS 6141 | Insulated cables and flexible cords for use in high temperature zones |
| BS 6195 | Insulated flexible cables and cords for coil leads |
| BS 6207 | Mineral insulated copper sheathed cables with copper conductors |
| BS 6231 | PVC-insulated cables for switchgear and controlgear wiring |
| BS 6346 | PVC-insulated cables for electricity supply |
| BS 6480 | Impregnated paper-insulated lead or lead alloy sheathed electric cables for working voltages up to 33 kV |
| BS 6500 | Insulated flexible cords and cables |
| BS 6622 | Cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 6.6 kV to 33 kV |
| BS 6708 | Trailing cables for mining purposes |
| BS 6724 | Armoured cables having thermosetting insulation with low emission of smoke and corrosive gases when affected by fire |
| BS 6726 | Festoon and temporary lighting cables and cords |
| BS 6862 | Cables for vehicles<br>Part 1 Cables with copper conductors |
| BS 6883 | Elastomer-insulated cables for fixed wiring in ships |
| BS 6977 | Insulated flexible cables for lifts and for other flexible connections |
| BS 7211 | Thermosetting cables (non-armoured) for electric power and lighting with low emission of smoke and corrosive gases when affected by fire |
| B.S. Aerospace Series | |
| | G210 (PTFE) |
| | G212 (General requirements) |
| | G222 (Efglas) |
| | G230 (General requirements) |
| | G231 (Conductors for general purposes) |
| | G232 (Cables for 135°C use, wrapped insulation) |
| | G233 (Cables for interconnect use, at 135°C, extruded insulation) |
| | G235 (Cables for general or interconnect use, 150°C, wrapped insulation, silver plated conductors) |
| | G236 (Cables for general or interconnect use, 200°C, nickel plated conductors) |
| | G237 (Cables for general or interconnect use, 200°C, extruded insulation, nickel plated conductors) |
| | G238 (Cables for general or interconnect use, 260°C, wrapped insulation, nickel plated conductors) |
| | G241 (Fireproof cables for engine fire zone and airframe use) |
| | G243 (Igniter cables for engine use (4 kV, d.c.) |
| IEC 55 | Paper insulated metal sheathed cables for rated voltages up to 18/30 kV (with copper or aluminium conductors and excluding gas pressure and oil-filled cables)<br>55.1: Part 1 Tests<br>55.2: Part 2 Construction |
| IEC 92 | Electrical installations in ships<br>92-352 Choice and installation of cables for low-voltage power systems |
| IEC 245 | Rubber-insulated flexible cables and cords with circular conductors and a rated voltage not exceeding 750 V |
| IEC 502 | Extruded solid dielectric insulated power cables for rated voltages from 1 kV to 30 kV |
| IEC 541 | Comparative information on IEC and North American flexible cord types |
| IEC 702-1 | Mineral insulated cables |
| *Conductors* | |
| BS 2627 | Wrought aluminium for electrical purposes—Wire |
| BS 3988 | Wrought aluminium for electrical purposes—Solid conductors |
| BS 4109 | Copper for electrical purposes: wires for general electrical purposes and insulated cables and flexible cords |
| BS 5714 | Method of measurement of resistivity of metallic materials |
| BS 6360 | Conductors in insulated cables and cords |
| IEC 228 | Conductors of insulated cables<br>228A (Supplement). Guide to the dimensional limits of circular conductors |

*Cont'd*

**Table 31.1** (*continued*)

| | |
|---|---|
| *Insulation and Sheathing (Non-metallic)* | |
| BS 6234 | Polyethylene insulation and sheath of electric cables |
| BS 6746 | PVC insulation and sheath of electric cables |
| BS 6899 | Rubber insulation and sheath of electric cables |
| IEC 173 | Colours of the cores of flexible cables and cords |
| IEC 304 | Standard colours for insulation for low frequency cables and wires |
| IEC 391 | Marking of insulated conductors |
| IEC 446 | Identification of conductors by colours or numerals |
| *Tests on Cables and Materials* | |
| BS 903 | Physical testing of rubber (This specification is issued in parts) |
| BS 4066 | Tests on electric cables under fire conditions |
| | Part 1 Method of test on a single vertical insulated wire or cable |
| | Part 2 Method of test on a single small vertical insulated wire or cable |
| | Part 3 Method for classification of flame propagation characteristics of bunched cables |
| BS 5099 | Spark testing of electric cables |
| BS 6469 | Methods of test for insulation and sheaths of electric cables |
| IEC 55 | See above |
| | 55.1: Part 1 Tests |
| IEC 60 | High voltage test techniques: |
| | 60-1: Part 1 General definitions and test requirements |
| | 60-2: Part 2 Test procedures |
| | 60-3: Part 3 Measuring devices |
| | 60-4: Part 4 Application guide for measuring devices |
| IEC 141 | Tests on oil-filled and gas pressure cables and their accessories |
| | 141-1: Part 1 Oil-filled, paper-insulated, metal-sheathed cables and accessories for alternating voltages up to and including 400 kV |
| | 141-2: Part 2 Internal gas-pressure cables and accessories for alternating voltages up to and including 275 kV |
| | 141-3: Part 3 External gas-pressure (gas compression) cables and accessories for alternating voltages up to 275 kV |
| | 141-4: Part 4 Oil-impregnated paper-insulated high pressure, oil-filled, pipe-type cables and accessories for a.c. voltages up to 400 kv |
| IEC 229 | Tests on anti-corrosion protective coverings for metallic cable sheaths |
| IEC 230 | Impulse tests on cables and their accessories |
| IEC 270 | Partial discharge measurements |
| IEC 332 | Tests on electric cables under fire conditions |
| | 332-1: Part 1 Test on a single vertical wire or cable |
| | 332-2: Part 2 Test on a single small vertical insulated copper wire or cable |
| | 332-3: Part 3 Tests on bunched wires or cables |
| IEC 754 | Test on gases evolved during combustion of electric cables |
| IEC 811 | Common test methods for insulating and sheathing materials of electric cables |
| IEC 840 | Tests for power cables with extruded insulation for rated voltages above 30 kV up to 150 kV |
| IEC 885 | Electrical test methods for electric cables |
| *Jointing and Accessories* | |
| BS 4579 | Performance of mechanical and compression joints in electric cable and wire connectors |
| | Part 1 Compression joints in copper conductors |
| | Part 2 Compression joints in nickel, iron and plated copper conductors |
| | Part 3 Mechanical and compression joints in aluminium conductors |
| BS 5372 | Cable terminations for electrical equipment |
| BS 6081 | Specification for terminations for mineral insulated cables |
| BS 6121 | Mechanical cable glands for elastomer and plastics insulated cables |
| IEC 702 | 702-2: Part 2 Mineral insulated cables—Terminations |
| *Miscellaneous* | |
| BS 801 | Lead and lead alloy sheaths of electric cables |
| BS 1441 | Galvanised steel wire for armouring submarine cables |
| BS 1442 | Galvanised mild steel wire for armouring cables |
| BS 5345 | Code of practice for selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosive processing and manufacture) (in 8 parts) |
| BS 6387 | Performance requirements for cables required to maintain circuit integrity under fire conditions |
| IEC 38 | IEC Standard voltages |
| IEC 183 | Guide to the selection of high-voltage cables |

*Cont'd*

**Table 31.1** (*continued*)

| | |
|---|---|
| IEC 287 | Calculation of the continuous current rating of cables (100% load factor) |
| IEC 331 | Fire resisting characteristics of electric cables |
| IEC 364-5-523 | Electrical installations of buildings—Current carrying capacities of wiring systems |
| IEC 724 | Guide to the short-circuit temperature limits of electric cables with a rated voltage not exceeding 0.6/1 kV |
| IEC 853 | Calculation of the cyclic and emergency current rating of cables |
| | 853-1: Part 1 Cyclic rating factor for cables up to and including 30 kV |
| | 853-2: Part 2 Cyclic rating of cables greater than 30 kV and emergency ratings for cables of all voltages |
| IEC 949 | Calculation of thermally permissible short-circuit effects, taking into account non-adiabatic heating effects |
| IEC 986 | Guide to the short-circuit temperature limits of electric cables with a rated voltage from 3 kV to 30 kV |

a licence to a manufacturer to use the mark are identical in all the participating countries, based on initial approval, from inspection of manufacturing and testing facilities and testing of samples, and subsequent surveillance in the form of periodic testing of samples. In the UK the approval organisation is British Approvals Service for Cables (BASEC). Under the Low Voltage Directive, of which the requirements have to be incorporated in the national laws of the Common Market countries, it is required that electrical equipment for voltages up to 1000 V should be accepted in each country as meeting the safety requirements of the directive if it conforms with a harmonised standard. Moreover, it should be presumed to conform with the relevant harmonised standard if the manufacturer qualifies for the use of the common mark.

## 31.2 Cable components

### 31.2.1 Conductors

#### *31.2.1.1 Conductor materials*

Materials and the form in which they are used comprise normally: (a) copper in solid form up to 2.5 mm$^2$ for wiring cables and power cables, and 150 mm$^2$ for mineral insulated cables, and in stranded form up to 2000 mm$^2$; (b) tinned copper similarly but in a narrower range for wiring cables; (c) solid aluminium up to 300 mm$^2$ and stranded aluminium up to 2000 mm$^2$; (d) an aluminium sheath as a concentric neutral conductor; and (e) lead and aluminium sheaths and steel wire or strip as an earth conductor.

In the USA some use was made of sodium by filling it into an insulating polyethylene tube. Although technically satisfactory, handling difficulties were found to outweigh the economic advantage. Another, more novel, application, which has been proved technically but not yet brought to commercial fruition, is the use of niobium alloys with superconducting properties at very low temperatures. Further reference to this subject is made in Section 31.5.

Some typical physical and electrical properties of the metals used in cables are given in *Table 31.2*.

*Copper* Because of its excellent conductivity, reasonable price and ease of working into rod and wire, copper has always been the basic material of the cable industry. Until the 1950s it was virtually without any challenger. Except when tensile strength is important, notably for self-supporting overhead line cables, it is always used in the annealed condition, partly to obtain flexibility, but more because conductivity decreases significantly with degree of working. Impurities also affect conductivity and are kept to a maximum of 0.01%.

Tinned copper wires have been used for wiring and flexible cables, partly to improve solderability but mainly to prevent interaction between copper and the sulphur present to produce vulcanised rubber insulation. With the substitution of synthetic insulation for natural rubber the use of tinned conductors has diminished.

*Aluminium* Although having only 61% of the conductivity of copper and, hence, for equal conductance requiring a conductor area 1.6 times that of copper, the low density of aluminium results in the actual weight of a comparable

**Table 31.2** Physical properties of metals used in cables (20°C)

| *Property* | *Copper* | *Aluminium* | *Lead* |
|---|---|---|---|
| Density (kg/m$^3$) | 8890 | 2703 | 11 370 |
| Resistivity (μΩ-m) | 0.01724 | 0.02826 | 0.214 |
| Res.-temperature coefficient (per °C) | 0.0039 | 0.0040 | 0.0040 |
| Thermal expansion coefficient (per °C) | $17 \times 10^{-6}$ | $23 \times 10^{-6}$ | $29 \times 10^{-6}$ |
| Melting point (°C) | 1083 | 659 | 327 |
| Thermal conductivity (W/m-K) | 380 | 240 | 34 |
| Ultimate tensile strength | | | |
| Soft temper (MN/m$^2$) | 225 | 70–90 | — |
| $\frac{3}{4}$H to H (MN/m$^2$) | — | 125–205 | — |
| Elastic modulus (GN/m$^2$) | 260 | 140 | — |
| Hardness | | | |
| Soft (DPHN) | 50 | 20–25 | 5 |
| $\frac{3}{4}$H to H (DPHN) | — | 30–40 | — |
| Stress fatigue endurance limit (MN/m$^2$) | ±65 | ±40 | ±2.8 |

$\frac{3}{4}$H, Three-quarters hard; H, hard.

conductor being only half that required with copper; i.e. the current-carrying capacity of an aluminium conductor is 78% of that of a copper conductor of equal area, and 1 t of aluminium does the work of 2 t of copper. However, as the size is larger, the amounts of all the other materials in the cable are increased. Any economic advantage, therefore, varies with the relative metal prices and with the type of cable. When the conductor metal is a small fraction of overall volume, the use of aluminium is uneconomical.

Another difference from copper is that, whereas solid copper conductors become difficult to handle above about 16 or 25 mm$^2$, solid aluminium conductors can be handled easily up to 240 or 300 mm$^2$, which further keeps dimensions to a minimum. Aluminium in a soft temper is quite suitable for these solid conductors, but lacks strength in wire for stranded conductors. However, as aluminium does not suffer the same penalty as copper in loss of conductivity with work-hardening, it is satisfactory to use a broad $\frac{3}{4}$-hard temper for aluminium wire.

Certain impurities lower the conductivity of aluminium, but the effect is not as great as with copper. Subject to control, the basic grade of 99.5% purity produced by electrolytic refining is satisfactory and appropriately defined in cable standards.

Apart from the economic factor and its reduced weight, aluminium has no real advantage over copper for cables and it also suffers from a positive disadvantage. This relates to the protective oxide skin which is always present and which requires somewhat greater care to be taken when making soldered joints. To a large extent, compression joints have replaced soldering and have been designed to deal satisfactorily with this aspect.

*31.2.1.2 Constructions*

Metric conductor sizes, standard in the UK since 1969, are used in all countries other than the USA. *Table 31.3* shows some comparisons.

Stranded conductors are available in circular form up to 2000 mm$^2$ and, for the lower voltage ranges, in sector-shaped contour up to 630 mm$^2$ in specific cases. The minimum number of wires is defined in IEC 228. Shaped conductors are normally pre-spiralled so that the cores fit easily together without applied twist in the laying-up operation. To provide a smooth surface and reduce the dimensions, it is now the practice to compact stranded conductors by a rolling process.

In the UK, aluminium conductors for cables up to 1.8/3 kV have largely been solid and of sector shape for multicore cables. Sector corner radii are fairly sharp to produce a compact construction. In Europe larger radii have been used and this form is adopted for high-voltage applications. Four 90° sector conductors laid-up together are used for 380–960 mm$^2$ solid-sectoral circular cables to obtain increased flexibility.

The Milliken construction is frequently used for circular conductors in sizes of 960 mm$^2$ and above to reduce skin effect and improve flexibility. Four or six individual sectors are used with a layer of insulation tape over alternate sectors.

The comments above refer largely to wiring and distribution cables. Different conditions apply to conductors for transmission cables, particularly of the oil filled type. Single-conductor sizes extend to 2500 mm$^2$ and an oil duct is required in the centre. The duct may be formed by laying the conductor strands round an open metal helix or, more usually, by creating a self-supporting centre by the use of

**Table 31.3** Conductor data

| *Standard metric size* (mm$^2$) | *Equivalent Imperial size* (in.$^2$) | *Maximum d.c. resistance at 20°C (Ω/km)* | |
|---|---|---|---|
| | | *Aluminium* | *Copper* |
| 1.5 | 0.0023 | — | 12.1 |
| 2.5 | 0.0038 | — | 7.41 |
| 4 | 0.0061 | 7.41 | 4.61 |
| 6 | 0.0092 | 4.61 | 3.08 |
| 10 | 0.016 | 3.08 | 1.83 |
| 16 | 0.025 | 1.91 | 1.15 |
| 25 | 0.038 | 1.20 | 0.727 |
| 35 | 0.053 | 0.868 | 0.524 |
| 50 | 0.072 | 0.641 | 0.378 |
| 70 | 0.104 | 0.443 | 0.268 |
| 95 | 0.144 | 0.320 | 0.193 |
| 120 | 0.182 | 0.253 | 0.153 |
| 150 | 0.224 | 0.206 | 0.124 |
| 185 | 0.281 | 0.164 | 0.0991 |
| 240 | 0.369 | 0.125 | 0.0754 |
| 300 | 0.463 | 0.100 | 0.0601 |
| 400 | 0.592 | 0.0778 | 0.0470 |
| 500 | 0.746 | 0.0605 | 0.0366 |
| 630 | 0.963 | 0.0469 | 0.0283 |
| 800 | 1.23 | 0.0367 | 0.0221 |
| 1000 | 1.55 | 0.0291 | 0.0176 |

curved segmental sections. Succeeding layers may consist of wires or flat strips, the latter improving both compactness and flexibility. For 18/30 kV cables, shaped conductors are oval rather than sectoral; circular conductors only are used at all higher voltages.

## 31.2.2 Insulation

*31.2.2.1 Thermoplastic and elastomeric materials for wiring cables*

In the general wiring-type cable field and for many power cables the major insulants in general use are either thermoplastic or elastomeric materials. In making the choice, several factors have to be considered. No insulant is ideal: a compromise is sought between processability, performance and economics.

An elastomeric material is one which returns rapidly to approximately its initial dimensions and shape after deformation at room temperature by a weak stress. Under such conditions a thermoplastic material shows permanent deformation. Conventional elastomeric compounds need to be cross-linked by vulcanisation, generally by chemical methods, to provide them with the characteristics which were typified by rubber compounds.

Examples of elastomeric materials are natural rubber (NR), ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE), polychloroprene (PCP), chlorosulphonated polyethylene (CSP) and silicone rubber (SR). Of these, EPR and XLPE are the most common because they combine the flexibility and electrical properties of natural rubber with a higher operating temperature limit and easier strippability.

Examples of thermoplastic materials are polyvinyl chloride (PVC), polyethylene (PE) and polypropylene (PP). Until recently, PVC was the most usual insulant because of its uncomplex processability, good general-purpose performance and economic advantage. By adjustment of formulation, PVC compounds can meet a variety of requirements. Their robustness, relative chemical inertness, good ageing and attractive appearance in a range of colours have led to wide use not only as an insulant, but also as bedding for armour wires and for sheathing. PVC hardens at temperatures below 0°C but will recover its flexibility on returning to normal ambient temperatures. General-purpose PVC compounds are limited to a maximum conductor operating temperature of 70°C.

Where electrical properties are paramount, e.g. radio-frequency cables, polyethylene is the preferred insulant. It is also a more effective water barrier where a water-resistant property is important.

Elastomeric compounds are of advantage for long-term operation at temperatures higher than those that PVC can tolerate. EPR and XLPE can operate up to 90°C continuously, and silicone rubber at 150°C continuously. Elastomers are also the first choice where flexibility combined with mechanical ruggedness is required. Applications for this type of material range between flexible cords for domestic flat-irons, fixed wiring and power cables, and flexible trailing cables for mines and quarries.

Where light weight and high operating temperatures are of paramount importance, fluorocarbon tapes or extrusions are adopted, particularly in the aircraft industry. Among the materials used in such high-performance cables are polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), ethylene tetrafluoroethylene (ETFE) and polyimide/FEP tapes. They are characterised by low coefficient of friction, excellent electrical properties, resistance to chemical attack and stability at elevated temperatures. Besides use in aircraft applications, these materials have also been used in specialised radiofrequency cables and equipment wires.

Glass fibre in the form of lappings and braids is the insulation in a range of cables and cords for use, for example, in luminaires.

*Tables 31.4* and *31.5* provide data on physical and electrical properties for a range of thermoplastic and elastomeric insulating materials.

### *31.2.2.2 Thermoplastic and elastomeric materials for power distribution cables*

In the distribution field, PVC is being displaced by the thermosetting material XLPE as the most widely used insulation and, as flexibility is not important, XLPE is more favoured than the possible alternative, EPR. (It is more usual to refer to cross-linking rather than curing or vulcanising; and to thermosetting rather than to elastomeric materials.)

**Table 31.4** Physical properties of polymeric materials

| *Material* | *Type* | *Tensile strength (min.)*(N/mm$^2$) | *Elongation at break (min.)*(%) | *Limiting temperature** (°C) | |
|---|---|---|---|---|---|
| | | | | *Rating* | *Installation* |
| *Thermoplastic* † | | | | | |
| Polyvinyl chloride | TI 1 | 12.5 | 125 | 70 | 0 |
| Polyvinyl chloride | TI 2 | 18.5 | 125 | 70 | 0 |
| Polyvinyl chloride | TI 2 | 10 | 150 | 70 | −10 |
| Polyvinyl chloride | TI 4 | 7.5 | 125–150 | 85 | 0 |
| Polyvinyl chloride | TI 5 | 12.5 | 125 | 85 | 0 |
| Polyethylene LD | PE 03 | 7 | 300 | 70 | −60 |
| Polyethylene LD | PE 2 | 7 | 300 | 70 | −60 |
| Polyethylene HD | | 37 | 500 | 80 | −40 |
| Polypropylene | | 37 | 400 | 80 | −10 |
| LSF‡⇐ | BS 6724 | 10 | 100 | 70 | −10 to 0 |
| *Elastomeric*§ | | | | | |
| General-purpose GP rubber | EI 1 | 5.0 | 250 | 60 | −45 |
| Heat resisting GP rubber | GP 1 | 4.2 | 200 | 85 | −45 |
| Heat resisting GP rubber | GP 2 | 4.2 | 200 | 85 | −45 |
| Heat resisting MEPR rubber | GP 4 | 6.5 | 200 | 90 | −45 |
| Flame-retardant rubber | FR 1 | 5.5 | 200 | 85 | −30 |
| Flame-retardant rubber | FR 2 | 5.5 | 200 | 85 | −30 |
| OFR rubber | OR 1 | 7.0 | 200 | 85 | −30 |
| Silicon rubber | EI 2 | 5.0 | 150 | 150 | −55 |
| Ethylene vinyl acetate | EI 3 | 6.5 | 200 | 105 | −25 |
| Hard ethylene propylene rubber | | 8.5 | 200 | 90 | −40 |
| Cross-linked polyethylene | | 12.5 | 200 | 90 | −40 |
| *Fluorocarbons* | | | | | |
| Polytetrafluoroethylene | | 24 | 300 | 260 | −75 |

* Maximum temperature for sustained operation and minimum temperature for installation.
† BS 6746 for PVC types and BS 6234 for polyethylene types.
‡≰LSF' (low smoke and fume) is a generic term and the characteristics given are typical of the material which is still under active development and improvement to meet stringent performance requirements.
§ BS 6899 for GP rubber types, EPR types, and cross-linked polyethylene.

**Table 31.5** Electrical properties of polymeric materials

| *Material* | *Type* | *Volume resistivity (min.) at* 20°C (Ω-m) | *Permittivity at* 50 Hz | *tan δ at* 50 Hz |
|---|---|---|---|---|
| *Thermoplastic** | | | | |
| Polyvinyl chloride | TI 1 | $2 \times 10^{11}$ | 6–7 | 0.1 |
| Polyvinyl chloride | TI 2 | $1 \times 10^{12}$ | 4–6 | 0.08–0.1 |
| Polyvinyl chloride | TI 2 | $2 \times 10^{11}$ | 6–7 | 0.09–0.1 |
| Polyvinyl chloride | TI 4 | $1 \times 10^{9}$ | 5–6 | 0.07–0.13 |
| Polyvinyl chloride | TI 5 | $5 \times 10^{11}$ | 6 | 0.9 |
| Polyethylene LD | Pe 03 | $1 \times 10^{16}$ | 2.35 | 0.0003 |
| Polyethylene LD | PE 2 | $1 \times 10^{16}$ | 2.35 | 0.0003 |
| Polyethylene HD | | $1 \times 10^{16}$ | 2.35 | 0.0006 |
| Polypropylene | | $1 \times 10^{16}$ | 2.25 | 0.0005 |
| LSF‡ | BS 6724 | $1 \times 10^{12}$ | — | — |
| *Elastomeric†* | | | | |
| General-purpose GP rubber | EI 1 | $2 \times 10^{12}$ | 3–4.5 | 0.01–0.03 |
| Heat resisting GP rubber | GP 1 | $7 \times 10^{12}$ | 3–4 | 0.01–0.02 |
| Heat resisting GP rubber | GP 2 | $1 \times 10^{13}$ | 3–4 | 0.01–0.02 |
| Heat resisting MEPR rubber | GP 4 | $7 \times 10^{12}$ | 3–4 | 0.01–0.02 |
| Flame-retardant rubber | FR 1 | $5 \times 10^{12}$ | 4.5–5 | 0.02–0.04 |
| Flame-retardant rubber | FR 2 | $1 \times 10^{13}$ | 4–5 | 0.015–0.035 |
| OFR rubber | OR 1 | $1 \times 10^{10}$ | 8–11 | 0.05–0.10 |
| Silicone rubber | EI 2 | $2 \times 10^{12}$ | 2.9–3.5 | 0.002–0.02 |
| Ethylene vinyl acetate | EI 3 | $2 \times 10^{12}$ | 2.5–3.5 | 0.002–0.02 |
| Hard ethylene propylene rubber | | $2 \times 10^{13}$ | 3.2 | 0.01 |
| Cross-linked polyethylene | | $1 \times 10^{14}$ | 2.3–5.2 | 0.0004–0.005 |
| *Fluorocarbons* | | | | |
| Polytetrafluoroethylene | | $1 \times 10^{16}$ | 2 | 0.0003 |

* BS 6746 for PVC types and BS 6234 for polyethylene types.
† BS 6899 for GP rubber types, EPR types and cross-linked polyethylene.
‡ 'LSF' (low smoke and fume) is a generic term and the characteristics given are typical of the material which is still under active development and improvement to meet stringent performance requirements.

Although EPR can be produced in a hard grade (known as HEPR) with properties similar to those of XLPE, it is more expensive than XLPE and, as is common with rubber compounds, it contains a large number of ingredients. XLPE comprises merely polyethylene, an antioxidant and a cross-linking agent. The cross-linking can be accomplished by a variety of methods. Until recently the most common has been to mix an organic peroxide (dicumyl peroxide) with the PE and to extrude the insulated conductor into a large catenary tube containing steam under high pressure. For high-voltage cables, where minimum moisture content of the insulation may be important, radiant electrical heating may be substituted for steam and the CCV tube filled with nitrogen.

In the CCV extrusion process there is a wastage when starting and stopping; increasing use is being made of a process by which the extrusion can be in a conventional line, as for thermoplastic materials, and the cross-linking can be accomplished by a different chemical process. A silane and an accelerator are blended with the polyethylene and cross-linking is achieved by immersion of the insulated conductor in hot water. One method requires a separate process for preparing the graft polymer (which has a limited storage life), but in the Monosil process all the ingredients are blended in the hopper of the extrusion machine.

### *31.2.2.3 Impregnated paper*

Layers of paper tapes are lapped around the conductor and the cable is dried and impregnated before application of the metal sheath which is required to keep the insulation dry and undamaged in service. The paper consists of a felted matt of long cellulose fibres derived from wood pulp. Washing of the fibres, both at the pulp stage and after formation of the sheet, is an important factor in the control of the properties of paper for cables. Large quantities of water are used, and for paper intended for the highest-voltage cables this water has to be deionised to ensure minimum power factor.

Impregnants have traditionally been based on mineral oils thickened with gum rosin to limit drainage from the insulation at service operating temperatures and to provide resistance to oxidation. It is now more usual to substitute materials such as microcrystalline waxes to obtain improved non-draining performance. For high-voltage internal pressure cables of the oil filled type it is necessary to use an impregnant with very low viscosity; hence, the highly refined mineral oils formerly used have been replaced by synthetic alkylates of dodecylbenzene type.

The electrical properties of the dielectric are not critical for voltages up to about 10 kV, but, at this level, ionisation in any air spaces becomes important and the impregnation process must ensure that butt gap spaces between paper tapes are well filled with impregnant. Impregnated paper itself, in sheet form, has a high electric strength, around 10 MV/m in short-time a.c. tests.

## 31.2.3 Armour

### *31.2.3.1 General wiring cables*

When cables are not installed in conduit or trunking, they may require armour, most commonly provided by galvanised steel wire (GSW) helically applied in a single layer and known as 'SWA' (single-wire armour).

Pliable wire armour finds application for portable cables in quarries and mines. It consists of stranded seven-wire bunches of GSW applied helically in a similar manner to SWA, but with a shorter lay length, thus providing good mechanical protection with improved flexibility, enabling the cable to be moved without affecting performance.

Braided GSW armour is mainly used in cables for ships and off-shore applications. It has the advantage of easier installation in complex cable runs. For single-core cables in a.c. circuits, where magnetic effects could cause high losses with GSW, tinned phosphor-bronze wires are normally used.

### *31.2.3.2 Supply distribution cables*

Most types of power cable require mechanical protection and/or an earth conductor to carry fault currents. For most distribution cables this is provided by SWA. Cables with aluminium sheaths seldom require armour. Cables with lead sheaths may be armoured with steel tape, which is cheaper, but SWA is preferred in the UK for the heavier, higher voltage cables for 10 kV and upwards because it increases corrosion resistance and the longitudinal strength of the cable for installation purposes. Steel tape is normally protected against corrosion by bitumen, but if better corrosion resistance is required, the tape may be galvanised.

When additional mechanical or tensile strength is needed, as for river crossings, coal mines or long vertical runs, a double layer of steel wires may be employed. Single-core a.c. cables are rarely armoured, but if armour is necessary, it can be provided by non-magnetic tape or wire, normally of aluminium.

## 31.2.4 Oversheaths and protective finishes

### *31.2.4.1 General wiring cables*

The choice of sheathing material depends on its environmental performance. Matters for consideration are: ambient temperature; flexibility; resistance to abrasion, water, oil and other chemicals; performance under fire conditions; and compatibility with other materials with which a cable is in contact during its operational life. The sheathing material must also be chemically compatible with the other materials used in the cable both during and after processing. While insulants are chosen primarily for their electrical characteristics, sheaths are selected on their physical properties. Thus, not all insulants are suitable sheaths. However, in general, insulation and sheath materials are similar: e.g. a thermoplastic sheath protecting thermoplastic insulation.

Elastomeric sheathing materials include natural rubber, used for ordinary-duty domestic flexible cords; and synthetic rubbers such as NBR/PVC, PCP(OFR), CSP(HOFR). PCP is classed as an OFR material (oil resistant and flame retardant), and CSP as an HOFR material (heat resistant, oil resistant and flame retardant). These materials can be specially formulated to meet special requirements, e.g. improved water resistance, extra flame retardance, improved mechanical properties. Most elastomeric materials have a wider operational temperature range than thermoplastics and their superior performance under adverse environments (as found in mines and quarries) makes them first choice for such applications. Not only are they abrasion resistant but also they are flexible over a wide range of temperatures.

In thermoplastic insulated cables, e.g. general wiring cable and radiofrequency cables, the predominant sheathing material is PVC in various formulations. Polyethylene is chosen where cables are in water or operate at subzero temperatures. For more specialised applications nylon and polyurethane are also used. Nylon has application where the cable is likely to be attacked by hydraulic fluids and is also claimed to be a termite barrier. Polyurethane is being introduced into designs which call for a cable having good flexibility, abrasion and impact properties under arduous low-temperature conditions.

Cables with high-performance insulation materials can be sheathed with conventional thermoplastic or elastomeric materials, but more commonly they have sheaths similar to the insulation composition. PFTE, FEP and a combination of PTFE and polyimide/FEP tapes are often used. These are light in weight, and are resistant to abrasion and cut-through, even when applied with small radial thicknesses.

### *31.2.4.2 Distribution cables and transmission cables*

Even when armoured cables are installed indoors above ground, it is unusual for the armour to be left bare, because (a) there are few environments where corrosion will not occur, (b) without an outer covering the armour layer may become disturbed during installation, and (c) few cables are above ground for their whole length. Nowadays, to make cables easy to handle and provide a clean finish, a polymeric sheath is usually applied overall.

Where cables are buried, the soils can be aggressive and cable life may depend on the degree of protection provided. For many years, lead sheathed cables depended on bituminised textiles as a bedding *under* the armour, and a serving of two layers of hessian or a layer of helically applied jute strings *over* the armour. Bitumen is provided over each layer, as well as to flood the armour, and use of the optimum grade of bitumen at each stage is important. Today, extruded sheathing—usually either PVC or sometimes (for toughness) polyethylene—has largely replaced bitumen finishes, even on lead sheathed cables, and all new designs of cable introduced during the last three decades have had PVC or polyethylene oversheaths. The successful introduction of aluminium for sheathing depends entirely on adequate protection with extruded plastic oversheathings.

For exposure to sunlight, plastic oversheaths should be black, but in other situations colours are sometimes used as a means of identification. To this end the sheaths are also embossed with the words 'Electric Cable', the voltage and sometimes further details of the cable construction, the manufacturer and the year of manufacture. Even though very tough, plastic oversheaths can be damaged during installation and, if they protect an aluminium sheath, it is important to carry out an inspection before backfilling. In the case of expensive transmission cables it is usual to test for damage by applying a graphite coating over the plastic and then to carry out a 10 kV d.c. test between this electrode and the metal sheath.

One of the disadvantages of PVC concerns cables in buildings or in tunnels. Although PVC is basically flame retardant, if a serious fire develops, it can transmit flame and will decompose, with evolution of noxious acidic fumes and dense smoke. Alternative synthetic compositions—sometimes known as 'low smoke and fume' (LSF)—are now becoming widely available to overcome this hazard.

## 31.3 General wiring cables and flexible cords

### 31.3.1 Wiring system cables

A wiring system cable is usually regarded as the final link in the transmission network which begins in the power station and ends at the socket outlet in the home, office or factory work-bench. Although rubber was for many years the insulant for wiring cables, it has been superseded almost entirely by PVC, or for some applications by mineral insulated cables. Although several alternatives have been tried, plain annealed copper remains the sole conductor material for wiring cables up to 16 $mm^2$.

PVC was originally developed in Germany in the 1930s. It took many years for PVC to be universally accepted for use in wiring cables. As PVC compounds improved, the thickness of insulation was progressively reduced. It now approaches half of that originally used and is acceptable for twice the operating voltage. The insulation is designed to have a higher tensile strength, resistance to deformation and a higher insulation resistance than the sheath. Sheathing compounds are usually formulated to provide good abrasion resistance and yet have easy-tear properties to facilitate stripping at terminations.

When vulcanised rubber insulation was used with copper conductors, it was necessary to tin the copper to prevent chemical reaction with the rubber. With PVC insulation, plain conductors became universally accepted. The introduction of cables to metric standards in 1969 achieved a greater degree of international alignment.

PVC wiring cables in common use in the UK are of two basic designs. One is the single-core unsheathed cable, used in conduit or trunking, the numbers of cores varying from 2 up to as many as 38. The other is the insulated and sheathed cable, available in single-core, two-core and three-core versions, the two-core and three-core cables (made in a flat formation) having the option of a bare earth continuity conductor.

In the late 1980s the need for improved fire performance wiring cables led to the introduction of an alternative insulating and sheathing material; special characteristics of these cables are the low emission of smoke and corrosive gases when affected by fire and a rapidly increasing use of these materials is foreseen.

Whilst EPR is used as the insulation for flat-twin festoon lighting cables and insulated, textile braided and compounded single-core conduit wire, another elastomeric insulation having low smoke and fume characteristics is now becoming widely available for wiring (conduit) cables (BS 7211). These cables have an upper temperature limit of 90°C, and although voltage drop may limit their advantages in some situations, it is anticipated that they will progressively replace PVC insulated cables in the next decade.

### 31.3.2 Flexible cords

Most flexible cords are designed for and used in domestic premises as the supply lead from the socket outlet to portable, and some fixed, appliances. The range of domestic appliances covers such items as can openers, food freezers, hairdryers, vacuum cleaners, microwave ovens, towel rails and washing machines. There is a flexible cord to suit each one.

The major cable insulants used in flexible cords are natural or synthetic rubber and PVC. Where flexibility is a prime requirement (for instance, on an electric iron), a rubber insulated type is most suitable. However, PVC is less expensive, has an attractive surface finish and is available in a larger range of colours. It is therefore the first choice for the supply lead to most domestic appliances.

Nowadays, many appliances carry the approval mark of the British Electrotechnical Approvals Board (BEAB) for House-hold Equipment, which means that in most cases the supply lead should meet the requirements of BS 6500: Insulated flexible cords. Independent auditing of flexible cords to BS 6500 by the British Approvals Service for Cables (BASEC) provides an assurance of the integrity and reliability of the cablemakers' products. This standard specifies cords having elastomeric, thermoplastic and glass-fibre insulants. These types are designed for a wide range of applications with upper temperature limits varying from 60 to 185°C. The natural rubber insulated types are rated at 60°C and cover the twin-twisted and textile braided cord in use for many years for pendant flexibles. The recommendations for this application are now 85 and 150°C rubber or glass-fibre insulated types. The UDF cord is used on electric irons and consists of rubber insulation and a thin rubber sheath, over which is applied a semi-embedded textile braid.

Currently under technical evaluation are cords employing cross-linked PVC for applications such as electric irons, where the ability to withstand contact with a hot surface is desirable combined with flexibility and abrasion resistance.

The PVC insulated and sheathed cords in BS 6500 are rated at 70°C and are available in light- and ordinary-duty versions for such applications as table lamps, television sets, washing machines and refrigerators. For areas where temperatures are likely to exceed those satisfied by standard PVC, but not in excess of 85°C conductor temperature, BS 6141 defines a range of heat resisting PVC cords. Examples of use are connections to immersion heaters and night storage heaters. For situations involving contact with oil and grease, there is an elastomeric insulated and sheathed flexible cord, rated at 85°C and having an oil resisting sheath. The glass-fibre insulated types in BS 6500 are primarily intended for use with light fittings (luminaires) and other situations where the cord is not subject to mechanical damage or continuous flexing. They can be used at temperatures up to 185°C.

Some flexibles are available in cut and trimmed form as an aid to the handyman, i.e. the cores are cut to length and the sheath and insulation are stripped. A few are also available in coiled extensible form, the most common type being for electric shavers.

There are also flexible cables designed for more harsh industrial environments. Three common types have a copper wire or galvanised steel wire braid, or a spiral steel strip, over the inner sheath, and an outer oversheath. The copper wire braided type is mainly used for portable hand lamps and where a flexible cable is required in certain flameproof installations. The steel wire braided and steel strip types are utilised where both flexibility and mechanical protection are required.

For situations where a limited degree of flexibility at low temperatures is required, special PVC formulations are available. Areas such as temporary supplies to traffic lights and portable tools on building sites are examples.

Some, but not all, designs of flexible cord used in the UK have been harmonised in accordance with the CENELEC procedure and for these the same design is standardised throughout the Common Market countries.

### 31.3.3 Control and instrumentation cables

Whereas power cables are the 'arteries' of industry, control and instrumentation cables are its 'nerves' and are used for the control of equipment and data collection. They range from single-core cables used in the wiring of control panels and switchgear, to the complex control and instrumentation cables used in power stations and petrochemical sites.

At one end of the scale are the single-core cables used within machine tools and switchgear. Where normal ambient temperatures are involved, PVC insulation is employed. At the other end of the scale is, for example, a North Sea oil terminal utilising 500 km of cable and connecting as many as 2000 instruments measuring flow rates or liquid levels in storage tanks. Control cables have copper conductors and are laid up in multicore or multipair formation, each core being separately identified.

Thermocouple cables (*Figure 31.1*) are used for connecting the thermocouple to its measuring instrument. The term 'thermocouple cable' is often used to describe both extension and compensating cables. Extension cables utilise conductors of the same alloys or metals as the thermocouple itself, while compensating cables utilise conductors of cheaper material although having similar thermoelectric characteristics. The normal conductor materials or alloys used are constantan, copper, iron, copper–nickel, nickel–chromium and nickel–aluminium.

Several national standards exist for the colour identification of insulation and sheath. Unfortunately, there is not yet a recognised international standard.

To prevent electrical interference in both control and thermocouple circuits within and between the cables, metallic screens (usually in the form of tapes) are applied over the individual pairs and/or the laid-up cores.

The finish of any type of cable to be buried in a petrochemical environment has to be given special consideration because of the presence of hydrocarbons in the soil. The steel wire armour which is normally applied as a mechanical protection on underground cables is not a barrier to the ingress of hydrocarbons into the heart of the cable: this is best achieved by applying a lead sheath. Thus, such control and instrumentation cables contain a PVC bedding, lead sheath, another PVC bedding, single wire armour and PVC oversheath. BS 5308 gives details of control cables with this type of protection. North American practice is to use an aluminium sheath.

Safety in hazardous areas has to be carefully considered. Intrinsic safety is a protective technique which ensures that any electrical sparking which may occur is incapable of causing an ignition of gas or vapour. Although a cable itself will rarely cause an explosion, it is possible for gas or vapour to percolate along the interstices of cable from a hazardous zone to a non-hazardous one. This problem can be cured by use of a stopper box or sealing gland. Reference should be made to BS 5345 for specific details. The British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA) test and certify intrinsically safe and flameproof equipment.

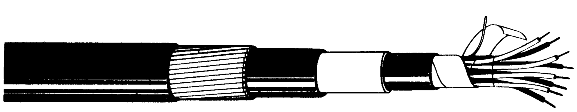


**Figure 31.1** Multi-pair thermocouple cable with PVC insulation, pair screening, lead sheath and wire armour

### 31.3.4 Cables for electronic applications

Cables for electronic applications are single-core and multicore equipment wires, and radiofrequency cables. Equipment wires are usually regarded as insulated single conductors with or without a screen and sheath. They can also be supplied in flat formation as multicores or multipairs, often with a transparent backing. The space between conductors is precisely controlled to ensure consistent electrical characteristics and to assist in termination. Multicore equipment wires generally have PVC or PTFE insulation and sheath in a range of conductor sizes and number of cores, unscreened and screened.

Radiofrequency cables transmit high-frequency signals at minimum loss. Calculation of the optimum cable design involves operating frequency, capacitance, velocity ratio, impedance and attenuation. With the exception of a few twin and special designs, radiofrequency cables are normally *coaxial*; they have an inner conductor, insulation, outer concentric conductor forming the screen, and sheath. Also used for radiofrequency applications are PE and PTFE insulated multipair cables for use in computer interfacing.

For conductors, plain annealed copper is most common but even this is available in several grades, each conferring special properties. It is possible to draw copper to extremely fine sizes because of its good ductility. By leaving copper in the hard-drawn condition, additional tensile strength may be obtained at the expense of elongation. Where d.c. conductivity is of secondary importance, composite conductors incorporating a high-tensile-steel core are employed in miniature cables.

Insulants used in electronic cables vary between PVC, PE, PPE, $PVF_2$, PVF, ETFE, FEP and PTFE (see *Table 31.4*). The choice of insulant is an optimisation of performance and economics. In radiofrequency cables, where electrical performance is paramount, the insulation is usually either PE or PTFE. However, chemical, mechanical and thermal performance must also be considered.

Screens are applied to prevent electrical interference between circuits or to control the amount of pickup by, or leakage from, a cable. Braided and lapped wires, tapes, tubes, foils and films are among the screening materials used, depending on the application.

Sheaths are applied to act as protection. A thermoplastic or fluorocarbon material is most common. In more demanding environments it may be necessary to have additional protection over the sheath in the form of steel wire braids or armour.

Although there are many specifications covering electronic cables, manufacturers have their own standards.

In the optical fibre cable, the signals are transmitted optically rather than electrically. The conductor is made of a high-quality glass-fibre which transmits light. The main advantages of optical fibre cables compared with conventional metallic conductor cables include low weight, small volume, increased system capacity, freedom from electromagnetic interference and improved security.

### 31.3.5 Arc welding cables

BS 638: Part 4 Specification for welding cables, includes single-layer EPR, CSP or CPE (HOFR) 85°C rubber to

BS 6899 and a two-layer covering, EPR and CSP or CPE to BS 6899.

The conductor is made up of a large number of small copper or aluminium wires, usually with a separator between conductor and insulation to make the cable supple. Single-conductor cables meet the majority of requirements for connection to electrode holders, arc-welding guns or leads for both manual and automatically controlled metal arc-welding equipment, or to form extension or return leads. Multicore cables are sometimes required for connections to the distribution boxes of multi-operator equipment.

Because of the variable periods of operation, current ratings have to be derived specifically for arc-welding cables and are contained in BS 638: Part 4. The period during which current flows varies from periodic to continuous, according to the application. The longer the period of use, the greater the conductor heating effect, so that current ratings are reduced as the operating cycle lengthens. The operating (or duty) cycle is defined as the time a cable operates in each 5-min period expressed as a percentage: e.g. up to 1.5 min operation in the 5-min period is 30%. Duty cycles are classified as shown in the table below.

| *Duty cycle* | *%* |
|---|---|
| Automatic | ≤100 |
| Semi-automatic | 30–85 |
| Manual | 30–60 |
| Intermittent or occasional | ≤30 |

Excessive voltage drop can occur when long cable lengths are required between the set and the electrode; conductors of larger current rating must then be selected. For flexibility, the final length of cable to the electrode can revert to the area appropriate to the current rating.

### 31.3.6 Offshore and ship cables

A wide variety of installation conditions and extremes of temperature are experienced in tankers, refrigerated vessels, ferries, trawlers, tenders, passage vessels, dry cargo ships, etc. In the UK the cables used are largely standardised as ethylene propylene rubber (EPR) insulated and chlorosulphonated polyethylene (CSP) sheathed and produced to BS 6883 (*Figure 31.2*). The operating temperature of 85°C provided by this combination has been proved satisfactory over a number of years and has been used extensively for applications on North Sea oil platforms, although in this case braid armoured cable with an outer CSP sheath has been the main standard.

EPR has excellent electrical properties, good corona resistance and good low-temperature flexibility. The CSP sheath provides a tough outer surface which is resistant to weather, oil resistant and flame retardant.

The increasing use of higher power generation on board ship has meant that systems with voltages of 3.3 and 6.6 kv are now in operation. Again the use of suitable designs of EPR insulated CSP sheathed types have proved fully adequate for this service. For oil rig platforms 13.8 kV cables are also in regular operation.

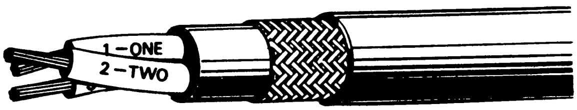


**Figure 31.2** Typical ship wiring cable

The conductors of ship wiring cables are of a more flexible construction than comparable land-based cables because of the problem of installing them through complex structures characteristic of shipboard installations. The reactance of a cable operating in an a.c. system depends on many factors, including, in particular, the axial spacing between conductors, and the proximity and magnetic properties of adjacent steel-work. This latter point is of crucial importance in ships and oil rigs. It is desirable to minimise the effect of magnetic induction by means of adequate spacing between cables and steel-work, minimum spacing between conductors, and the avoidance of magnetic materials between single cores in the same circuit.

There are many classification authorities that will approve cables to international and to some national standards. When a ship installation is contemplated, the local surveyor of the chosen classification authority should be consulted before a decision is taken on the particular design to be used.

### 31.3.7 Aircraft cables

Cables used for wiring aircraft are continuously under development and, as technology improves, new materials are used in this most exacting of applications. The ambient temperature variation within an aircraft is wide and provision has to be made for cables to operate down to −75°C and up to 260°C. In addition, various special fire resisting cables are needed for use in aircraft-engine fire zones.

For the lower temperature a combination of special PVC, glass braid and nylon has been used where a conductor temperature of 105°C is deemed appropriate. Since the mid-1960s, when a miniature range of cables was introduced both for multicore and screened versions, much development work has been undertaken and greater attention has been paid to the effect of cable weight on the performance of the aircraft; as a result, cables with polyimide insulation are being widely used in the aircraft industry for general airframe wiring. This material has been chosen because of its excellent mechanical and electrical properties and its resistance to the various chemical contaminants present in aircraft. Depending upon the type of conductor and coating used for colouring purposes, polyimide insulated cables are approved to operate at conductor temperatures of 150 and 210°C.

The higher temperature ranges of cable consist largely of combinations of PTFE, glass and polyimide, and when using a nickel plated conductor, are approved for operation at conductor temperatures up to 260°C.

Special fire resisting cables for engine-bay wiring are available and comprise combinations of silicone rubber, glass-fibre, quartz fibre, polyimide and PTFE to ensure that circuit integrity can be maintained for a short period during a fire.

### 31.3.8 Cables for railways

The main application for general wiring cables for railway use is for track signalling. Multicore signalling cables are laid along the trackside. The insulation is a combination of natural and synthetic rubber. A natural rubber layer is applied next to the conductor to provide electrical integrity, and the outer layer is of polychloroprene (PCP) to give each insulated conductor some oil resistant properties. The cores are collected together and covered overall with a thick

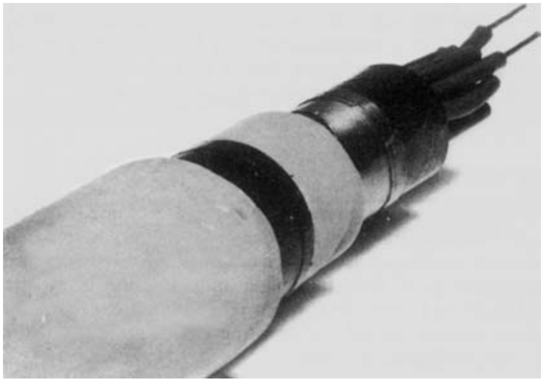


**Figure 31.3** Multi-pair signalling cable with materials and construction for optimum flame retardance and freedom from smoke and fumes in a fire

sheath of heavy-duty PCP compound specially chosen for toughness, and weather and abrasion resistance.

Cables for track power feeds on electric systems at medium and low voltage are insulated with EPR and sheathed with chlorosulphonated polyethylene (CSP). Cables for traction and rolling stock are conventionally of EPR/CSP composite insulation, but recent developments have resulted in new materials having low smoke properties and greater resistance to the oils and fluids used in traction and rolling stock.

In the underground system operated by London Transport Executive particular emphasis has been placed on minimising hazards resulting from fire. Designs are now approved which, in a fire, give off fewer toxic products and far less smoke than did previous designs (*Figure 31.3*).

Two-way communication between a control centre and moving trains is now becoming common, even when the trains are in tunnels. It is accomplished by installing suitably designed electric cables near to the track, either at ground level or overhead, to act as elongated aerials. The most common cable for this purpose is the so-called 'radiating coaxial' or 'leaky feeder'.

### 31.3.9 Cables for mines and quarries

Cables for metalliferous mines and quarries have been standardised for many years. They are essentially flexible and tough, as they need to withstand all the rigours of service in a rugged and rough environment. The range of cables, given in BS 6116, incorporates ethylene propylene rubber (EPR) as insulation, a rubber undersheath, a layer of stranded galvanised steel wires applied as an armour, and a tough weather resistant outersheath of polychloroprene (PCP). Cables are available for 600/1000 V, 3.3 kV and 6.6 kV systems. Some higher voltage installations have been made using cables with individually screened cores and a thick overall PCP sheath, but their use is subject to permission from the relevant authorities.

Cables for use by equipment connection in underground coal mines are manufactured to specifications issued by British Coal and use an EPR compound insulation specially formulated to give good impact strength and crush resistance. Individual core screening is the norm as part of the safety measures necessary for operation at the coal face. The sheath is of PCP, which has excellent mechanical properties and is flame retardant. Low-voltage pliable armoured cables similar to those in quarries are also used for portable supply cables to conveyor loaders, etc., and similar cables suitable for 3.3 kV and 6.6 kV systems are used for connection to transformers.

Thermoplastic insulated cables are also widely used for power, lighting and signalling purposes, and British Coal has now standardised power cables insulated with XLPE and EPR.

An increasing demand for improved communication services in mines and quarries is reflected in the expanding use of two-way mobile radio, radio paging and radio control systems. However, mines and quarries often present situations where free-space propagation is not possible: for instance, propagation in tunnels can be restricted to only a few hundred metres. One solution is the radiating cable or leaky feeder in which signals radiate from the cable rather than from a conventional aerial. Radiating cables have special screens which provide and control the electromagnetic field around the cable so that signals can be picked up by nearby mobile receivers, with communication in the reverse direction also possible. These cables use low-permittivity dielectrics, which, with the special screens, ensure good radiation and transmission characteristics unaffected by the arduous external environmental conditions encountered in mines.

### 31.3.10 Mineral insulated metal sheathed cables

Mineral insulated metal sheathed cables generally consist of copper conductors insulated with compressed mineral powder, typically magnesium oxide (MgO), and enclosed in a copper sheath.

The traditional method of manufacture is to position the required conductors within a large-diameter tube and fill them with powder using a ramming process, the filled cable then being drawn to the required final diameter by cold drawing through numerous dies with inter-stage and final furnace annealing. More recently, continuous manufacturing methods have been developed in which the sheath is produced from rolled and welded strip into which powder and conductors are introduced, the assembly being reduced to its final diameter by rolling or a combination of rolling and die drawing with inter-stage and final annealing by induction. The annealing of the copper is carried out to restore ductility and conductivity, lost due to work hardening. Moisture ingress into the dielectric is inhibited by control of the chemical activity of the powder, or by additives.

Normally, mineral insulated cables need no further protection over the copper sheath, will withstand high service temperatures, and are impervious to oil and water. Being composed of inert inorganic materials they are incombustible and non-ageing. However, for aesthetic appeal, identification or corrosion protection of cables buried underground or inaggressive industrial environments a thermoplastic outer covering may be applied, which may be typically PVC, but more recently low smoke and fume sheathing materials have been introduced.

Mineral insulated cables are made with 1, 2, 3, 4, 7, 12 or 19 conductors in light-duty (500 V) or heavy-duty (750 V) grades, with conductor areas ranging from 1 to 400 $mm^2$, and current ratings of 11 A to over 1000 A depending on the cable size and installed conditions.

The current rating of mineral insulated cables, unlike other types of cable, is not determined by the temperature withstand of the insulation, but by the temperature attained by the copper sheath. For normal applications and where the cable has an outer covering, the limiting temperature is

70°C. As for other types of cable installed in buildings, the published ratings are based on an ambient temperature of 30°C with adjustments being needed for other ambient temperatures and grouping as detailed in Section 31.6.

However, bare mineral insulated cable with a copper sheath can operate continuously at sheath temperatures up to 250°C, depending on the type of end seal applied, and when so rated the current rating capacity is greatly increased. At temperatures above 250°C, progressive oxidation of the copper sheath occurs, although the cable can function for limited periods with sheath temperatures in the region of 1000°C.

To make connections the copper sheath is removed at each end and seals provided by the cable's manufacturer are used to seal the face of the insulant and to insulate the exposed conductor tails. The copper sheath provides an excellent low resistance circuit protective conductor, connection to which is achieved by use of compression glands or by use of special end seals with integral earth tails.

For specialised applications such as thermoelectric cables, heating cables, down-well and other transducer cables or for continuous operation at temperatures higher than 250°C, stainless steel or alloy sheaths are also used with nickel, steel, alloy and many other special conductors.

### 31.3.11 Cables in fire hazard

An area of electric cable technology where much research and development work has been concentrated in recent years is that of the behaviour of cables in fires. Although they may overheat when subject to current overloads or mechanical damage, electric cables in themselves do not present a primary fire hazard. However, cables are frequently involved in outbreaks of fire from other causes which can eventually ignite the cables. The result can be the propagation of flames and production of noxious fumes and smoke. This result, added to the fact that cables can be carrying power control circuits which it is essential to protect during a fire to ensure an orderly shutdown of plant and equipment, has led to a large amount of development work by cablemakers. This work has included investigations on a wide range of materials and cable designs, together with the establishment of new test and assessment techniques.

Although PVC is essentially flame retardant, it has been found that, where groups of cables occupy long vertical shafts and there is a substantial airflow, fire can be propagated along the cables. Besides delaying the spread of fire by sealing ducts at spaced intervals, an additional safeguard is the use of cables with reduced flame propagating properties. Attention has also been focused on potential hazards in underground railways, where smoke and toxic fumes could distress passengers and hinder their rescue. Initially, compounds with reduced acidic products of combustion were incorporated in cables which have barrier layers to significantly reduce the smoke generated. In the meantime, other cablemaking materials have been developed which contain no halogens and which also produce low levels of smoke and toxic fumes as well as having reduced flame propagating properties. These are now incorporated in British Standards such as BS 6724 and BS 7211.

A different requirement in many installations, such as in ships, aircraft, nuclear plant and the petrochemical industry (both on and off-shore), is that critical circuits should continue to function during and after a fire. Amongst the cables with excellent fire withstand performance, mineral insulated metal sheathed cables are particularly suited for use in emergency lighting systems and industrial installations where 'fire survival' is required. As fire survival requirements on oil rigs and petrochemical plants become more severe, new control cable designs have been developed to meet fire tests at 1000°C for 3 h with impact and water spray also applied, and also to have low smoke and low toxic properties.

**Figure 31.4** Heat sensor cable

Another novel approach to fire protection in power stations and warehouses is the use of fire detector cables (*Figure 31.4*). These are used in a system which both detects and initiates the extinction of a fire in the relatively early stages of its growth. These cables have also been installed in shops, offices and public buildings, where the cables can be used to operate warning lights or alarms.

The present position in relation to materials is that problems due to smoke and objectionable fumes are dealt with in the case of insulation by heavy additions of aluminium trihydrate in EPR and EVA. For beddings and oversheaths similar addition may be made to ethylene acrylic elastomer, but such compounds do not have the toughness and oil resistance of CSP and PCP compounds.

For aircraft engine components, where cable weight is important, the cable construction is based on silicone rubber plus quartz with PTFE coverings.

For ships' cables, silicone rubber is also used, and where a glass braid is also included, the silica ash enables the IEC 331 test at 750°C to be met. By use of special EPR compounds, the withstand temperature may be increased to 1000°C. The use of mica/glass tapes on conductors provides good high-temperature insulation which is cost effective in comparison with silicone/glass and mineral insulated designs.

## 31.4 Supply distribution cables

For underground public supply systems and mains distribution in factories, paper insulation has given way to synthetic insulation, except for certain sectors of the public supply.

Since the early 1960s, PVC has been the major insulant for industrial cables up to 3 kV, but this is now changing and XLPE is increasingly finding favour because of its potentially higher operating temperature (90°C). Similarly, for higher voltage industrial applications, XLPE is now the preferred dielectric.

In Europe and elsewhere, consumers are supplied at around 240 V single-phase and 240/415 V three-phase, as required. From the outset, the system for urban areas has been underground with direct burial of multicore cables, and three-phase transformers feeding large groups of consumers through cables along the whole length of every road. The step-down from the transmission grid has moved towards voltages of 19/33 kV and 6.35/11 kV, but international standardisation for cable specifications caters for a full range of 0.6/1, 1.8/3, 3.6/6, 6/10, 8.7/15, 12/20 and 18/30 kV r.m.s. The rounding off of voltages to whole numbers allows for the fact that the designs cater for 20% variation of voltage.

In the USA, and other countries following American practice, cable designs and voltage standards are the same, but the types favoured and the practical utilisation tend to be very different. The supply to the consumer caters for both 110 and 220 V or thereabouts, and except for the innermost areas of cities the distribution is largely by overhead lines. Instead of three-phase transformers, the local supply is from single-phase units at 10–15 kV or higher, using appropriate transformers to obtain the dual consumer voltages. Conventionally, such transformers are pole mounted, and small, as they feed only a few consumers.

Undergrounding on the American system tends to be a replica of the overhead practice by continuation of the use of similar small transformers and merely adding insulation to the overhead line conductors. Extruded polyethylene or XLPE is convenient for this purpose for both low-voltage and high-voltage requirements, and this is why the interest first developed on the American continent. Very simple single-core cable constructions meet the requirement and much high-voltage cable has been installed in which the neutral conductor comprises copper wires applied over the insulation with no outer sheath. In recent years a concerted effort has been made to get away from the unsightly poles and overhead distribution lines with emphasis on 'underground residential distribution' (URD). This embraces the concept of small single-phase transformers outlined above but more emphasis is now being placed on direct burial of cables instead of installation in ducts. With the dual voltage requirement for consumers, the URD concept, together with the use of single-core cables, provides a way of undergrounding overhead networks at minimum cost. It seems unlikely that it will be adopted in countries where systems have long been geared to other practices.

### 31.4.1 Paper insulated cables

From its introduction at the end of the last century, impregnated paper has given excellent service to the cable industry. Under normal conditions, users have been able to install the cables and then forget about them. Ultimate lives of 50–60 years are common, and the majority of cables have been replaced only because they became too small for the load. The UK supply industry depreciates paper cables over a 40-year life—surely towards the maximum for any industrial plant.

While the basic dielectrics have changed little throughout this century, there have been considerable improvements in quality of materials and manufacturing techniques, and these have led to successive reductions in thickness over the years.

#### *31.4.1.1 Belted and screened constructions*

In multicore cables a greater insulation thickness is required between conductors than from conductor to metal sheath. The most economic construction, therefore, is to apply part over the individual conductors and then a small thickness as a 'belt' over the laid-up cores (*Figure 31.5*). The spaces between the cable cores under the belt are filled with jute or paper, but whereas the main insulation consists of paper tapes applied in a controlled manner, the filler insulation has to be softer and less dense to be compressed into the space available. It is therefore weaker electrically, and it will be seen from the pattern of flux distribution in *Figure 31.6* that significant stresses arise in the filler spaces. An even more important effect, to be seen in *Figure 31.6* is that, in addition to the radial stresses through the layers of paper, there is also a tangential stress component along the paper surface. In the tangential direction the electric strength of impregnated paper is only one-tenth of that radially.

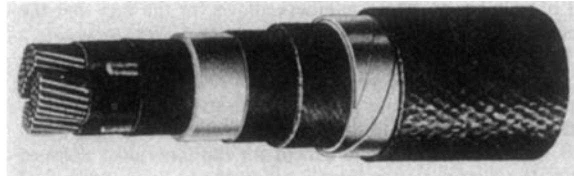


**Figure 31.5** Four-core, 1 kv, paper insulated, lead sheathed cable

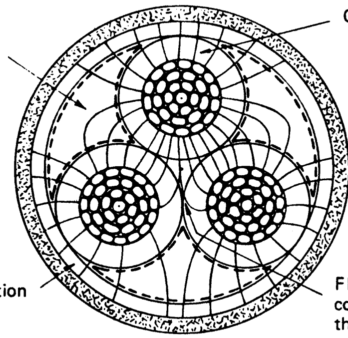



**Figure 31.6** Flux distribution in paper insulated belted cable with top conductor at peak potential

When supply voltages were increased to 22 kV and 33 kV in the 1920s, many cable failures occurred due to lack of appreciation of this fact. Hochstädter identified the need for an earthed metallic layer over the insulation to create a purely radial field, a construction subsequently known as 'H'-type or screened. Very little metal is required for the purpose, and while thin copper tapes have been used, the most common form nowadays for multicore cables is a layer of thin aluminium tape or of metallised paper, consisting of aluminium foil on a paper backing. The latter is usually pinpricked to facilitate passage of oil during impregnation. The cores and fillers are held together by a binder of 'copper woven fabric tape' (CWF) containing a few thin wires woven into the weft. This gives protection against scuffing and provides electrical contact between the screen and the metallic sheath. Another construction, used mainly in continental Europe, is the 'HSL' or 'HSA' type, which denotes three lead or aluminium sheathed single cores laid up together and then armoured overall.

The screened construction is optional at 11 kV, but mandatory for higher voltages. Because the dielectric has much better electric field distribution the operating temperature can be increased and higher current ratings obtained. Some 11 kV users find that these factors justify the somewhat greater expense and the extra skill required in jointing.

#### *31.4.1.2 Insulation*

The insulation comprises layers of paper tapes, of thickness in the range 0.7–1.9 mm, carefully applied to maintain controlled butt gap spacings and optimum registration between layers. The stress is highest at the conductor surface and may be increased locally, owing to the conductor profile or lack of smoothness. To improve this situation at voltages of 6.35/11 kV and above, a layer of semiconducting carbon paper is applied over the conductor to exclude from the field the small spaces between the wires of the outer layer which otherwise could be sites for discharge.

The thickness of insulation has to be determined by both mechanical and electrical requirements, the former being dominant at the lower voltages, e.g. to withstand bending and to resist damage due to impact. Similarly, at 11 kV, while impregnated paper itself has an a.c. breakdown strength of the order of 10 MV/m, the actual cable design stress is only 2 MV/m, the effects in butt gap spaces being one of the most important factors.

The impregnation of the paper is carried out before application of the metallic sheath by the 'mass-impregnation' process. The cores, on drums or rewound into trays, are inserted into large tanks. These are first evacuated to remove all the moisture in the paper. Hot impregnating compound is then admitted, and the tank is maintained under pressure for a period which depends on voltage, and then cooled slowly to ensure that contraction voids are not present within the insulation.

To obtain good impregnation, the compound viscosity at 120°C should be low, but in the operating temperature range of the cable it needs to be as high as practicable, so that no drainage occurs into the inevitable space under the metallic sheath and into joints. Traditionally, the compound consisted of mineral oil thickened with gum rosin. A problem with such compounds was that the viscosity at maximum operating temperature was not high enough to prevent drainage when cables were installed vertically or on hilly routes, thus leaving the already relatively weak butt gap spaces devoid of impregnant. In the 1950s, BICC developed the 'mass-impregnated non-draining compounds' (MIND) which subsequently became standardised in the UK. In these compounds the viscosity control is obtained by the addition of such materials as microcrystalline waxes and polyethylene to mineral oil.

When single- or three-core cables are operated at 11 kV or higher, some discharge may occur in the space between the insulation and the inside of the metallic sheath. Although this is not unduly detrimental, it is eliminated by the inclusion of a carbon paper over the insulation.

#### *31.4.1.3 Lead sheath*

Unalloyed lead is suitable for the majority of armoured cables but is prone to fatigue cracking if subjected to vibration or to high expansion and contraction, as when cables are suspended on hangers or are in manholes. In the UK, when moderate improvement of fatigue strength is required, it is usual to adopt alloy 'E' to BS 801 (0.4% tin, 0.2% antimony). Alloy 'B' (0.85% antimony) has higher fatigue strength and is desirable for conditions involving severe flexing, such as aerial cable installations and cables on bridges. Other alloys are available and are preferred in some countries.

The use of very high-purity lead is detrimental because it can give rise to large grain size and low fatigue strength. Hence, it is always preferable to use lead with impurities up to the limit of 0.1% as permitted by BS 801. Tin and antimony are frequently added for this reason.

#### *31.4.1.4 Armour*

The use of armour fulfils a variety of functions, primarily to supply mechanical protection during cable handling and installation, and subsequently in service. Steel taping is the most common, but in the UK a layer of galvanised steel wire is often applied for 11 kV and higher to increase the longitudinal strength of the cable. Galvanised steel tape is popular in tropical countries to provide greater resistance to corrosion; narrow steel strips are often preferred in continental Europe. In general, the resistance to damage is proportional to the armour thickness, and steel strips or tapes are less effective than steel wire.

#### *31.4.1.5 11 kV aluminium sheathed cables*

The replacement of a lead sheath by an aluminium sheath with good corrosion protection, such as an extruded plastics oversheath, provides a very economic cable construction eliminating armour. For cables of a type offering other advantages, e.g. to provide a concentric conductor as in the Consac CNE type cable described later, and h.v. cables operating under internal pressure, aluminium sheaths have been widely used since the mid-1960s.

For other types of paper insulated cables, however, aluminium sheaths have not found favour, one factor being the somewhat greater skill required for sheath plumbing when joints other than the cast resin type are used. An exception is that in the UK, the public supply authorities did standardise almost universally in the mid-1970s on 11 kV aluminium sheathed cables and, until recently, XLPE insulated cables were unable to compete on price. There are now clear signs that XLPE will be increasingly used on electricity company networks at 11 kV. However, whilst they were using aluminium sheathed cables, there was a variation of design, some preferring a smooth sheath, whilst others favoured the corrugated form. With a weight reduction of 50% compared to lead sheathed and armoured cables, both types were easy to handle, although there was a problem with pulling 240 and 300 $mm^2$ cables with smooth sheaths into ducts. Subsequently the preference was for corrugated sheaths.

A significant factor is the effect of thermomechanical forces at straight joints. With the flexible corrugated sheath the position does not greatly differ from that with lead sheathed cables. However, if full load is to be carried regularly, it is desirable with smooth aluminium sheathed cable to employ joints filled with cast resin to overcome possible problems at the plumbs and buckling of cores within the joint sleeve. Most of the 11 kV cable installed by the public supply authority in the UK operates at less than maximum rating because of factors of which the most pertinent is that the cable network is in open rings and is only required to carry full load when the ring is closed because of a fault near to the transformer.

Typical 11 kV aluminium sheathed constructions as used by some authorities are shown in *Figure 31.7*; the design

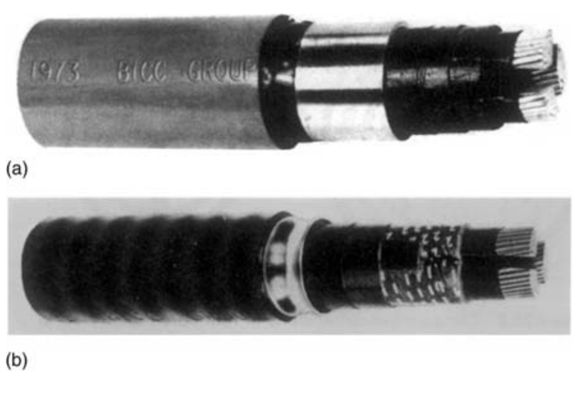



**Figure 31.7** Smooth (a) and corrugated (b) aluminium sheathed, 11 kV, paper insulated cables

which was finally standardised was a belted version with corrugated aluminium sheath. In this construction there is a large space between the outside of the insulation and the inside of the sheath. It is important that this should be partially (but not completely) filled with impregnating compound.

## 31.4.2 CNE cables for PME systems

In this heading CNE denotes a 'combined neutral and earth' conductor in cable construction and PME signifies 'protective multiple earth' applied to a network.

### *31.4.2.1 PME systems*

Traditional practice in UK buried systems involved earthing of the neutral conductor at one point only, at the substation. This meant that the supply cables along the streets required five conductors, three phases, one neutral and one earth (the lead sheath). Consumers normally obtained a satisfactory earth by connection to buried lead water pipes, but when conditions were difficult, as with overhead line sections in rural areas, a practice of multiple earthing of the neutral (MEN) was introduced in the 1940s by burying suitable metal adjacent to poles. This gradually extended to the PME concept, which basically implies that consumers are provided with an earth terminal connected to the supply neutral conductor.

In the 1950s further problems arose when lead water pipes began to be replaced by plastic pipes. One solution was to earth consumers' plant to the lead sheath of the supply cable, but this was only satisfactory if across all straight and branch joints the lead sheaths were plumbed to the jointing sleeves. In many cases, however, the joints were of the mechanical grip type in cast-iron boxes, and these had such a high resistance that the earth path to the substation was inadequate. By additional earthing of the neutral conductor, nowadays usually only at the remote end of the run, and by using this conductor also as the protective earthing conductor, the consumer earthing problems were overcome. Moreover, the supply cable required one fewer conductor and by developing a new range of cables very considerable savings were obtained. *Figure 31.8* shows the much lower material utilisation achieved with one form of CNE cable.

Initially, PME systems with CNE cables were kept separate from the existing networks, but by appropriate and simple bonding between neutral conductors and lead sheaths, all existing systems can be converted to PME. The UK network has largely been modified in this way. CNE cables can, therefore, be installed indiscriminately for replacements and additions. A point requiring attention is that, if consumers are given a PME earthing facility, all exposed earthed metal within the installation which may be touched must be suitably bonded to provide an equipotential background.

### *31.4.2.2 CNE cable types*

The Consac cable (BS 5593), first introduced in the mid-1960s and shown in *Figure 31.9*, maintains the use of paper insulation. Aluminium sheathing provides the neutral. The use of solid aluminium conductors with 1 kV paper insulation had already become established with four-core PILS cables before the development of Consac. Because of the total use of aluminium as conductor metal and the small amount of other material, Consac has a very economic construction, but in the early days some of the cost advantage was lost by the extra difficulty of plumbing the aluminium sheath. This was later overcome by the simple techniques involving the use of mechanical fittings and cast resin filling.

One of the important features in the design of any CNE cable is that, in the event of cable failure, there should be no loss of the important protective neutral conductor. It has also to be recognised that, with the growing use of mechanical excavating equipment, the main source of cable failures is now third-party damage. If the PVC oversheath on Consac is damaged, local corrosion of the aluminium sheath will follow and water entering the insulation will produce detectable cable failure before there is any severe reduction in conductance of the neutral.

The Waveform cable type (*Figure 31.10*) is also known as Waveconal and Alpex. Although introduced some years after Consac, and a little more expensive, it has become more extensively used than Consac, because of its simple jointing techniques. The XLPE insulation represented the first departure by the UK regional electricity companies from paper insulation for mains cables. In Waveform cable the neutral conductor comprises aluminium wires applied with a sinusoidal lay, and, as with all modern cable designs, there is an outer PVC oversheath. For making service joints, no cutting of the neutral is involved and the wires can readily be formed into two bunches for mechanical jointing. A key point in the design is that the wires are spaced and encapsulated between two layers of unvulcanised rubber so that each wire is separately embedded in the rubber. In the event of local damage to the oversheath, the entry of groundwater is thus limited; again an important factor in preventing loss of the neutral conductor. In Germany this form of sinusoidal lay neutral construction is

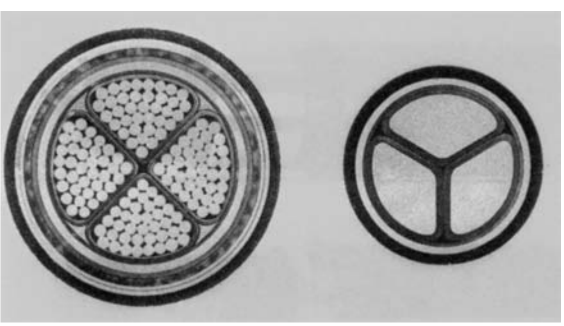


**Figure 31.8** Comparative dimensions of four-core PILS/STA and Consac CNE cables of equal rating

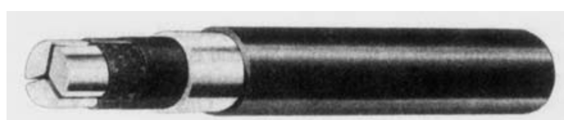


**Figure 31.9** Consac cable

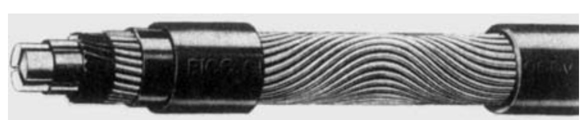


**Figure 31.10** Waveconal cable

known as 'Ceander', but has only been employed with copper wires and without the rubber bedding. The use of copper wires as the neutral together with a single layer of unvulcanised rubber has recently found favour with the distribution companies in the UK, and many of those currently using Waveconal and Consac have now indicated their intention to adopt the cable having a copper wire neutral.

In Scotland some use has been made of 'Districable', a type which is also found in France. This is a four-core construction, again with XLPE insulation on the phase cores, but the neutral/earth circular or shaped conductor has a lead sheath to protect it from corrosion. Two thin galvanised steel tapes are applied as a binder and to provide a metal screen in contact with the neutral/earth conductor. A PVC sheath is applied overall.

Ultimate simplicity in CNE cable design and ease of jointing can be achieved by the use of four shaped aluminium conductors, insulated with XLPE and then provided with a PVC or polyethylene oversheath with no outer metallic protection. This type has already replaced all other public supply mains cable types in Germany. In the UK it has been rejected, however, even though a metallic envelope is not mandatory below 650 V and spiking tests have shown that danger from flash or shock is little greater than with the Waveconal, Consac, Districable or lead sheathed paper cables. The reason is that, in the event of mechanical damage, there could be exposure of the aluminium in the neutral to groundwater, with the possibility of undetected loss of this conductor. Damage to phase conductor insulation could also give rise to currents in the ground, flowing through other buried metalwork.

### 31.4.3 Service cable

Prior to the introduction of CNE mains cables, the service cables were of the three-conductor split-concentric type. This design is still used for consumers where it is not practicable to provide a PME earth terminal connected to the supply neutral/earth. The single-core (or multicore for three-phase supply) phase conductors are insulated with PVC or XLPE. In a helically applied concentric layer around the phase core or cores, some of the copper wires are bare to form the earth conductor and some have a thin layer of PVC coating to comprise the neutral conductor, the two portions being separated by PVC strings.

For a PME system, the construction is further simplified to a two-conductor design, the concentric layer consisting of bare copper wires.

As an alternative design of service cable, some users of Waveform mains cable prefer to adopt the same construction, i.e. sinusoidal lay aluminium wires embedded in rubber, as the neutral/earth conductor.

In addition to use for house service, all these cables find applications for such requirements as street lighting, traffic signs and complete individual routes for motorway lighting.

### 31.4.4 PVC insulated power cables

Although used for public supply cables in some overseas countries, PVC insulation has never been adopted in the UK for this purpose, other than for the service cables described above. The reason is associated with its thermoplastic nature and resultant softening at elevated temperatures. Thus, at 1 kV, ratings are restricted by a maximum temperature of 70°C, whereas paper can be operated to 80°C and XLPE to 90°C. More important, however, is that, in the event of a short overload, severe thinning may occur due to deformation by conductor thrust at bends, whereas paper or XLPE insulation would be relatively unaffected.

Close fusing to give cable protection is usually impracticable in public supply systems, but presents no great problem in industrial applications. From the late 1950s, therefore, PVC insulated cables were almost universally applied in this sector for voltages up to 3.3 kV. More recently, XLPE, with its superior overload characteristics has become increasingly more popular. Close fusing was defined by the 14th edition of IEE Wiring Regulations as an excess-current operating device which operates within 4 h at 30% excess rated value for cables direct in the ground, or 50% excess for cables in ducts or in air. In the 15th and recent 16th editions the whole concept has been changed (see Section 31.6.7).

*Figure 31.11* shows typical 1 kV cable and 6 kV cable, the latter as used in coal mines.

As PVC insulated cables are little affected by moisture, no metal sheath is required, and this contributes greatly to ease of handling as well as simplifying jointing and terminating procedures. No precautions have to be taken to prevent entry of moisture.

BS 6346 caters for conductors of stranded copper or solid aluminium, but not stranded aluminium. The solid form was chosen because it provides the most economic cable construction and is particularly suitable for manufacture with PVC insulation. Solid conductors are also very much better for either soldering or mechanical jointing techniques. Stranded aluminium conductors are often preferred by overseas users and are also used for power supply cables in coal mines, as they facilitate coiling for taking the cables down the mine shafts.

Except for the smallest sizes, the conductors are shaped, and uniform thickness of insulation is obtained by extruding the PVC as a slightly oversize tube which is made a snug fit on the conductor by a combination of conductor feed speed control and internal vacuum. For multicore cables, the cores fit tightly together, leaving few gaps, but when these are of larger size, non-hygroscopic fillers are included so that the laid-up cores are reasonably circular.

For the armour bedding, there is a choice between PVC tapes and a layer of extruded PVC. The latter is more expensive but provides a robust cable which is preferred for cables with circular conductors, for cables laid

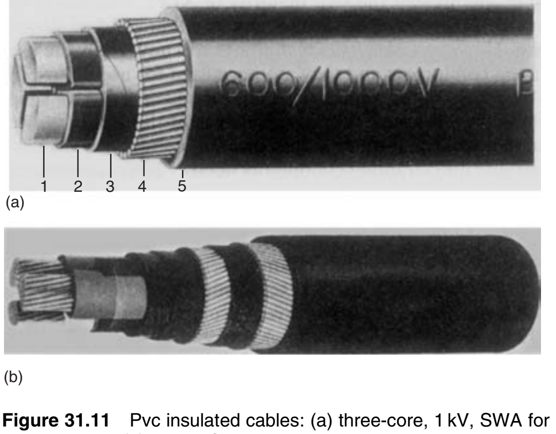



**Figure 31.11** Pvc insulated cables: (a) three-core, 1 kV, SWA for industrial use; (b) British Coal three-core, 6.6 kV DWA

underground, and when it is desirable for terminating glands to provide a seal on to the bedding.

While any form of armour can be supplied (e.g. steel tape or strip, aluminium strip or galvanised wire (GSW)), BS 6346 covers only GSW or aluminium strip. GSW is normally preferred, as it gives optimum mechanical protection and adequate earth conductivity. Aluminium strip armour is now usual only when extra earth conductance is required and it is then important that suitably designed aluminium terminating glands be used. Aluminium armour is also necessary for single-core cables, because steel armour, being magnetic, increases losses, with an adverse effect on ratings.

A PVC sheath is usually applied overall and no bitumen is normally included over the armour. When this was done in the early years, following conventional practice with textile servings, it was found that the bitumen extracted plasticisers from the PVC, creating a mobile black liquid which would bleed from the cables at terminations below vertical runs.

The early choice of PVC by British Coal for mining cables operating at 3.3, 6.6 and, to some extent, at 11 kV was associated with the fact that the resilience of the insulation was found to provide better resistance than paper insulation to damage by rock falls. Although PVC is also satisfactory for higher voltages and has been used extensively in Germany at 20 kV, the electrical losses tend to be high. Better materials such as XLPE are now available when polymeric insulation is preferred.

Although the relative hardness of PVC at ambient temperature can be modified considerably by the choice and proportion of the plasticisers used, these cannot exert a significant effect on deformation at maximum operating temperatures. Heat resisting grades are defined in BS 6746, and such grades can even be formulated to allow PVC to operate for limited periods up to around 100°C without serious degradation due to chemical factors. However, they do little to improve deformation resistance and not much use has been made of them for power cables.

### 31.4.5 XLPE insulated cables up to 3.3 kV

Polyethylene has never found much application outside the USA for power cables, largely because PVC became established and polyethylene suffered from the same disadvantage of thermal deformation. XLPE completely overcomes this problem, and in the voltage range up to 3.3 kV it provides an advantageous alternative with cable constructions which are essentially identical. The main difference is that, as it is a much tougher material, the insulation thickness can be reduced, in the case of 1 kV cables to the minimum which can be extruded satisfactorily.

XLPE has now firmly established itself as an attractive alternative (both technically and economically) to PVC for industrial cables in the UK. XLPE has positive advantages because it is a better insulating material with much lower dielectric loss factor; more particularly, it can be operated satisfactorily to 90°C, with corresponding improvement in cable ratings. These factors have clearly provided an incentive for XLPE to be considered as a competitive material throughout the whole range of power cables up to the highest voltages and it is now being used in all spheres of application. There are competitors, such as ethylene propylene rubber, which may have advantages for specific cable types, but are unlikely to be economic over the whole range.

Up to 3.3 kV, therefore, XLPE is now superseding both paper and PVC insulation. In comparison with PVC, the continuous current rating advantage is usually more apparent than real, because cable size is dictated by voltage drop rather than current rating. The short-circuit rating based on 250°C instead of 160°C is likewise a bonus only infrequently required. Where XLPE does gain is in that, when ambient temperature is high, such as in tropical countries, the benefit from a smaller derating factor can be substantial. XLPE is not flame retardant, as is PVC, but as flame retardancy is governed more by the oversheath than the insulation, this is not normally significant.

In comparison with paper insulation, XLPE also has a small continuous rating benefit, but the main advantage is the absence of a metallic sheath and the availability of cable which is much cleaner and easier to handle in laying and jointing, together with lower permissible bending radii. The simpler jointing techniques, without any need for plumbing, provide strong attraction for developing countries where such skills are not readily available, and, to date, this is probably the area where XLPE has made the greatest impact.

Another field for XLPE is for self-supporting 240/415 V cables for overhead distribution, as a replacement for bare conductors. Four insulated circular stranded aluminium conductors are twisted together with a long lay and used with special fittings. Following widespread use in Europe, this application has now proved to be an economic alternative in the UK.

Some European countries have extended this application for higher voltages (up to 15 kV), but so far the only use in the UK has been in pilot schemes at 11 kV.

### 31.4.6 PE and XLPE cables for 11 kV to 45 kV

The excellent dielectric properties of PE and XLPE brought these materials into prominence in the early 1960s for higher voltage applications and an increasing scale of effort has been devoted to them ever since. In some countries, particularly the USA, they came into regular use at 10–20 kV at an early stage, and, in spite of a very poor initial service performance in comparison with paper insulation, they have since virtually replaced it for many years at voltages up to 45 kV.

The most important single factor which has caused problems is that, as with paper insulation, internal partial discharges occur at voltages of 5 kV upwards at any irregularities within or at the surface of the insulation. However, whereas paper insulation has fairly good resistance to such discharges and the effects in butt gap spaces can be minimised by oil or gas pressure, polyolefines such as PE and XLPE are particularly weak. Both PVC and EPR are rather better, but have other limitations.

While it was recognised that the insulation must be extremely clean and free from voids, and that screening at both surfaces of the insulation was necessary, many cables were put into service without adequate testing to ensure freedom from discharge. It was also not until the mid-1970s that ideal forms of screening were developed which could be readily removed for jointing and adequately deal with thermal expansion and contraction. Then, in the succeeding years, the final problem was to identify and find solutions to problems caused by effects of water in contact with the insulation. Water has minute solubility in PE and XLPE, but ‘tree-like’ structures were found in the insulation and it was eventually established that these could lead to electrical breakdown.

Although UK manufacturers supplied some of the first cables used in the early 1960s, the acceptance of XLPE at home has been slow to come. Three main reasons account for this. First, for the types of cable used, there was, until recently, no clear economic incentive in comparison with paper insulation. Second, in the countries where polymeric materials were quickly adopted, one of the prime reasons was to enable jointing to be carried out with less-skilled resources. In the UK this was not necessary. Third, the higher operating temperature of cross-linked insulation has particular benefit in reducing the derating penalty in countries having high ambient temperatures. Nevertheless, cable manufacturers export a large proportion of their production and so have been obliged to produce competitively.

In the problems that have arisen, polyethylene has no advantages over XLPE and, because it is a thermoplastic material, has great disadvantages in current ratings. Even in the USA, where the use of PE was substantial, it has now given way to XLPE. The remainder of this section refers to XLPE only.

For many years, IEC Specification 502 formed the basis for cable construction for UK manufacturers. However, the issue of BS 6622, which generally follows IEC 502 but is somewhat more demanding, covers the voltage range from 6.6 kV up to and including 33 kV. Above this voltage there is no international specification, but for cables above 30 kV and up to 150 kV, IEC Specification 840 gives detailed requirements for their test performance.

### *31.4.6.1 Conductors*

Up to the present the vast majority of XLPE insulated cables have employed circular conductors in either solid or stranded form. However, extrusion techniques will now allow the use of shaped conductors and they are permitted for use up to 11 kV in BS 6622. At the moment there is limited demand for shaped conductors. Because of the importance of the screen between conductor and insulation, a smooth conductor surface is desirable and stranded conductors need to be well compacted.

### *31.4.6.2 Conductor screens*

Many of the early cable failures were due to imperfections resulting from the use of semiconducting fabric tapes as conductor screens. A thin layer of extruded semiconducting polymeric material is now mandatory, and to ensure a clean interface it is normally extruded in tandem with the main insulation and cured with it. In the case of stranded conductors, a semiconducting tape may be applied between the conductor and extruded screen to prevent penetration between the wires and facilitate removal for jointing.

### *31.4.6.3 Insulation*

Extrusion and curing can be carried out by a variety of processes, but a cardinal feature of all of them is that good material handling to avoid dirt and contamination is vital. The most common method of extrusion for cables up to 20 kV is the Monosil (or similar) process, whilst for 30 kv and above it is the continuous catenary vulcanising (CCV) method in which the curing is carried out by radiant heating and nitrogen under pressure (although it has limitations, curing is sometimes carried out by the application of steam pressure and cooling in water).

As explained earlier, the Monosil type process involves curing the cores in hot water; despite this the insulation performance and subsequent dielectric moisture content is equivalent to that of a 'dry-cured cable'.

### *31.4.6.4 Insulation screen*

One of the main factors concerning the dielectric screen is that it should be easily removed for jointing. A layer of semiconducting polymeric material, compatible with the insulation, can readily be extruded and cured in the same operation and techniques and materials are now readily available to enable the manufacturer to produce either a firmly bonded screen or a 'strippable' screen, which—although in intimate contact with the insulation—can readily be removed without recourse to special tools. Up to 33 kV the majority of cables use strippable screens, whilst bonded screens are occasionally used for 33 kV and almost always for higher voltages.

The older, taped, form of insulation comprising a layer of semiconducting varnish followed by an easily removed semiconducting tape is now used less often.

Both forms of semiconducting screen are usually followed by either a copper tape, applied helically, or a concentric layer of copper wires. The amount of metal in these screens must be related to what is required for earth fault current-carrying capacity; if tapes are used for three-core cables the metal tapes can be supplemented by copper wires in the filler spaces.

### *31.4.6.5 Finish*

A typical three-core cable is shown in *Figure 31.12*, in which the copper taped cores are laid-up, then provided with a PVC extruded bedding, galvanised steel wire armour and PVC or PE oversheath. A single-core cable would have a

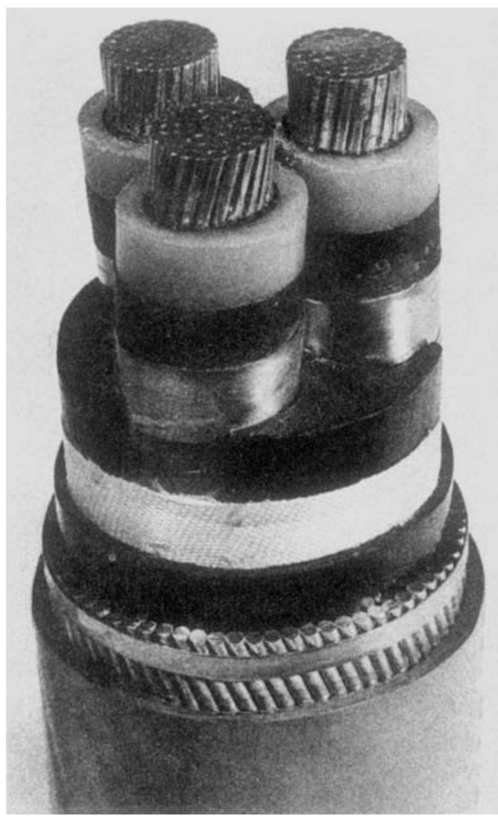


**Figure 31.12** Three-core 8.7/15 kV XLPE insulated steel wire armoured cable

PVC or PE bedding over the concentric copper earth wires, then aluminium wire armour and PVC or PE oversheath.

Bearing in mind the faults that can be experienced due to contact between groundwater and insulation, and acknowledging the fact that plastic oversheaths may be damaged during installation or subsequently, new designs with components or special layers to restrict movement of water within cables are being produced. These will utilise some form of conductor blocking, usually in conjunction with blocking (swelling) tapes applied radially under the outer layers. Other designs use a powder which swells on contact with moisture.

*31.4.6.6 Dielectric deterioration by treeing phenomena*

No discussion on polymeric insulation at high voltage would be complete without some reference to deterioration caused by treeing mechanisms. These are related to a prebreakdown characteristic which gradually spreads through the dielectric under electrical stress through paths which, when visible or made visible, resemble the branch structure of trees. Trees are of two basic types:

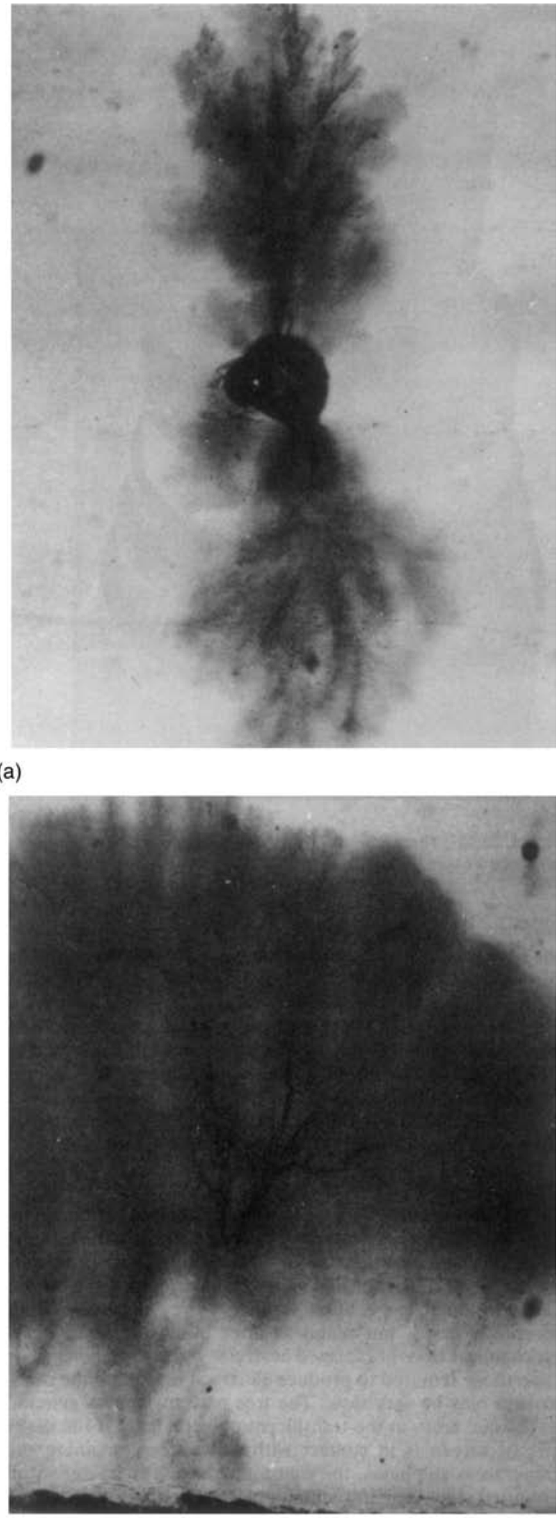
(1) *Electrical trees* These are trees in a dielectric consisting of permanent channels having dendritic or branching patterns due to partial discharges during application of a.c., d.c. or impulse electrical stresses. The channels originate at sites of high stress due to non-uniform electrical fields from imperfections such as protrusions at an insulation interface, a void or a contaminant.

(2) *Electrochemical trees* This is a class of tree generated in a dielectric during application of electrical stress in the presence of liquid water or water vapour—hence, often known as 'water trees'. They consist of fine water channels which can be seen under a microscope after staining. They disappear if the sample is dried, but reappear after boiling in water. Electrochemical trees are formed at stresses which are much lower than those required to produce electrical trees, and the rate of growth may be very slow. The tree patterns appear generally at opaque areas in the translucent polyethylene. If the dielectric or screen is in contact with soil water containing such minerals as sulphides, the water may have a characteristically coloured stain. The initiation of electrochemical trees is at the same types of site as indicated above for electrical trees. Characteristic names are often given to them according to origin, e.g. 'bow-tie' trees from contaminants (*Figure 31.13*(*a*)) and 'bush' or 'broccoli' from surface imperfections. *Figure 31.13*(*b*) shows an electrical tree which is developing in an area where electrochemical treeing has become extensive.

It is this treeing phenomenon which is the important reason for the insulation to be free from all irregularities and for the surfaces to be smooth and in good contact with the screens. Cables may operate for many years before a tree size is generated which will contribute to ultimate breakdown. The presence of water is a requisite for treeing to be initiated, but a very small amount suffices, and for the highest voltages it is desirable to ensure that all moisture is excluded, e.g. by provision of a metallic sheath.

## 31.4.7 Cable tests

Full details of the tests and procedures required are given in the cable standards listed at the beginning of the section. IEC 55, IEC 502 and IEC 840 are the most relevant documents and values quoted below are taken from these standards. A complete summary would be lengthy and it is



(a)

(b)

**Figure 31.13** (a) Bow-tie tree at an inclusion; (b) Electrical tree in an area of extensive water tree development only possible to give a brief outline to illustrate the general basis for the more important tests.

*31.4.7.1 Manufacturing tests*

Tests during manufacture are restricted to those which are not possible on finished cables and comprise a.c. spark tests on polymeric insulation and sheaths.

*31.4.7.2 Tests of completed cables at works*

Tests of completed cables at works comprise the following:

(1) Measurement of the thickness of insulation and other prescribed components.
(2) Conductor resistance test.
(3) An a.c. test for 5 min (30 min for cables above 30 kV) at a voltage which is usually 2.5 $U_0 + 2$ kV for cables rated up to 3.6/6 kV, and $2.5U_0$ for cables of 6/10 kV and above. For multicore non-screened cables the test is required between conductors and also between any conductor and sheath. For cables with individually screened cores it is from conductor to sheath only.
(4) For paper insulated cables with rated voltage $U_0$ of 8.7 kV and above, a dielectric power factor/voltage test is required to determine compliance with prescribed limits for maximum power factor at 0.5 times $U_0$ and maximum difference in power factor from 0.5 to 1.25 times $U_0$ and from 1.5 to 2.0 times $U_0$.
(5) A partial discharge test is required for cables insulated with PE and XLPE of rated voltages above 1.8/3 kV and on cables insulated with EPR and PVC of rated voltages above 3.6/6 kV. The magnitude of discharge at $1.5U_0$ must not exceed (a) 20 picocoulombs (pC) for EPR, PE and XLPE for cable up to 30 kV, (b) 10 pC for PE, EPR and XLPE above 30 kV and up to 150 kV, and (c) 40 pC for PVC.

*31.4.7.3 Tests after installation*

(a) Paper cables: a 15 min d.c. test at a voltage of 70% of the values given in (3) above.
(b) Polymeric cables: a 15 min d.c. test at a voltage of approximately $4U_0$ for cables up to 30 kV and $3U_0$ for cables above 30 kV up to 150 kV.

*31.4.7.4 Special and type tests*

(1) A bending test at a radius much more severe than stipulated for installation, followed by a voltage test. For paper cables the diameter of the test cylinder varies, according to the cable rated voltage and type, from 12 to 25 times the diameter of the cable plus the diameter of the conductor $(D+d)$. Three cycles of bending are required and maximum limits are stipulated for tearing of individual paper tapes. For polymeric cables up to 30 kV two cycles of bending are required over a test cylinder of $20(D+d)$ for single-core cables and $15(D+d)$ for multicore cables. For polymeric cables above 30 kV and up to 150 kV three cycles are required over a test cylinder of $25(d+D)+5\%$ for cables with metal sheaths and $20(d+D)+5\%$ for others.
(2) A drainage test for non-draining paper cables at the maximum continuous operating temperature for the cable. The maximum permissible drainage is 2.5–3% of the internal volume of the metal sheath.
(3) A dielectric security test for paper cables comprising sequential bending, impulse and a.c. tests. The impulse withstand requirement is 95 kV for $U_0 = 8.7$ kV, 125 kV for $U_0 = 12$ kV and 170 kV for $U_0 = 18$ kV. The a.c. application is $4U_0$ for oil/resin impregnation and $3U_0$ for non-draining impregnants.
(4) A power factor/temperature test for paper cables of $U_0 = 8.7$ kV and above to a temperature 10°C above rated temperature. Limits are 20–60°C, 0.0060; 70°C, 0.0130; 75°C, 0.160; 80°C, 0.0190; 85°C, 0.0230.
(5) An electrical test for PE and XLPE cables above 1.8/3 kV and PVC or EPR cables above 3.6/6 kV. This requires sequential application and/or measurement of partial discharge, bending, power factor/voltage, power factor/temperature, load cycles, partial discharge, impulse withstand and a.c. high voltage. For synthetic insulated cables above 30 kV and up to 150 kV the sequential application and/or measurement is bending, partial discharge, power factor/temperature, load cycles, partial discharge, impulse withstand and a.c. high voltage. The impulse requirement is $U_0 = 3.6$ kV, 60 kV; $U_0 = 6$ kV, 75 kV; $U_0 = 8.7$ kV, 95 kV; $U_0 = 12$ kV, 125 kV; $U_0 = 18$ kV, 170 kV; $U_0 = 26$ kV, 250 kV; $U_0 = 36$ kV, 325 kV; $U_0 = 64$ kV, 550 kV; $U_0 = 76$ kV, 650 kV; and $U_0 = 87$ kV, 750 kV. The a.c. test comprises 4 h at $3U_0$ for cables up to 30 kV and 15 min at $2.5U_0$ for cables above 30 kV up to and including 150 kV.
(6) Tests on the component materials before and after ageing and, in the case of polymeric cables, on the complete cables after ageing.

## 31.5 Transmission cables

### 31.5.1 Historical development sequences for a.c. transmission

*31.5.1.1 Problems due to partial discharges within paper insulation*

Reference has already been made to the work by Hochstädter which led to the 'H' type or 'screened' radial field design. Such constructions were quite satisfactory at 33 kV and to a limited extent at 66 kV. Failures at 66 kV and higher voltage were found to be due to discharges in minute vacuous voids formed by expansion of the impregnating compound with insufficient subsequent contraction to fill all the space available. Emanueli in the late 1920s pioneered the first solution, which was the oil filled cable. The basic requirement was either to eliminate completely the possibility of voids being created, as in the pressurised oil filled cable, or to ensure that they were always under a high gas pressure. Gas may be admitted directly into the insulation or exerted externally on a flexible sheath over the insulation, in which case the void suppression principle is more akin to that of the OF cable.

As the void formation mechanism was also clearly related to the temperature excursions of the insulation, the operating temperature limit of the solid (i.e. non-pressure) insulation could be raised from 65 to 85°C for gas filled cables and 90°C for oil filled cables, with consequently much improved cable ratings. Even more important was the fact that the a.c. operating electrical stress of impregnated paper insulation could be increased from 4 MV/m to about 16 MV/m and reductions in dielectric power factor were achieved.

*31.5.1.2 Types of paper-insulated pressurised cables*

Many different types of pressuring are possible and may be classified into the two basic constructions indicated in *Table 31.6* which lists those currently in service.

**Table 31.6** Pressure cables and voltage in commercial service

| *Design* | *Voltage range* (kV) |
|---|---|
| *Fully oil impregnated* | |
| Lead or aluminium sheath | |
| Low-pressure OF | 30–525 |
| Steel pipe | |
| High-pressure OF | 30–500 |
| External gas pressure with diaphragm sheath | 30–275 |
| *Internal gas pressure* | |
| Lead or aluminium sheath | 30–275 |
| Steel pipe | 30–132 |

OF, oil filled.

A fact which emerges from *Table 31.6* is that oil pressure can be used up to the highest voltages at present required (525 kV). Gas pressure has a limitation primarily related to a lower electrical breakdown strength. Although gas pressure cables have some advantages in terms of the associated accessories and equipment, the oil pressure cables are usually more economic.

### *31.5.1.3 Transmission system requirements*

When Emanueli first developed the pressure cable technique, he was fulfilling a need for the requirement of the early 1930s to transmit in the range of 30–132 kV with conductor sizes of around 200 $mm^2$. With the growth in the usage of electricity during the next 30 years, cable voltages and ratings had to keep pace with and match the overhead-line circuits. Developments quickly proceeded to find solutions for the higher voltages with conductors up to 2500 $mm^2$.

Bulk transmission in the UK began in the 1930s with a circuit requirement of 110 MVA at 132 kV; 275 kV followed in the late 1950s with a winter circuit rating of 760 MVA; and by the late 1960s the circuit demand had increased to 2600 MVA at 400 kV. To obtain this from a single cable circuit meant that design had to be pushed towards the limit for paper insulation in relation to electrical features, diameter and coiling on drums. To match the increases in overhead-line ratings, it has become necessary for the heat generated in cables to be removed by more sophisticated engineering means involving cooling pipes.

### *31.5.1.4 Alternatives to impregnated paper insulation*

The oil filled cable has been most successful in meeting all requirements up to 525 kV. At some future date (possibly not until the next century in the UK, but earlier in some other countries) there will be a need for undergrounding parts of transmission lines operating at 800–1000 kV. To produce cables within a diameter (say 160 mm) which is practicable for manufacture and handling, and to keep losses within an economic limit, it seems essential to use higher stresses (possibly 25 MV/m) and dielectrics with lower power factor and permittivity than can be achieved at present with impregnated paper. Possibilities are discussed later.

There has been much recent interest in materials such as polyethylene and XLPE, which have good potentialities for very high voltages and other advantages for the lower voltage range. To date, the enthusiasm has stemmed not primarily from low losses, but from the possibility of a much simpler cable construction, the promise of less complicated jointing requirements and, above all, the elimination of pipework and pressurising equipment. In some overseas countries, where installation and maintenance skills are not readily available, this is an important factor which could well justify a higher intrinsic cable cost. Location and repair of oil leaks can be troublesome. However, some of the problems with polymeric insulation for distribution cables have been discussed, and for voltages greater than 132 kV the usage so far of PE and XLPE cables has been relatively small.

## 31.5.2 Types of cable

### *31.5.2.1 Basic requirements*

Apart from absolute consistency and freedom from defects, the essential requirements of high-voltage dielectrics are:

(1) High impulse strength, because this is the ultimate design stress requirement and determines dimensions.
(2) Low dielectric power factor in order to keep the heat generation to a minimum. When conductor size is at the maximum possible, much expense may have to be devoted to means of cooling the cable to obtain an economic circuit.
(3) Low permittivity to reduce both the electrical losses and charging current.
(4) Ease of bending during installation without sustaining damage which could affect service life.

Impregnated paper under oil pressure is the only dielectric which so far has met all these requirements up to about 525 kV. In relation to electrical losses, however, it is reaching its limit at this voltage without forced cooling. Impregnated paper with gas pressure is technically satisfactory up to 275 kV but is not generally economically competitive with oil filled cables.

Low-pressure oil filled cable (*Figure 31.14*) is used almost universally in the UK throughout the voltage range and it is predominant throughout the world. High-pressure OF cable is favoured in the USA.

The influence of the impulse strength requirement on design stress can be seen from *Table 31.7*.

Conventional oil filled cable has a safe impulse stress of around 100 MV/m and a.c. stress of 30 MV/m, a ratio of about 3/1. This has to be compared with the service performance requirement of between 10.2/1 and 6.2/1 according to voltage, i.e. cables must be designed on an impulse breakdown stress basis and then they will have a large safety margin for a.c. performance. The reverse would soon lead to breakdown. *Table 31.7* also illustrates that, because the impulse/a.c. ratio reduces with increasing voltage, higher design stresses can be adopted as voltage increases: typical

**Table 31.7** Working and impulse voltages

| *System voltage* (kV) | *Working voltage* (kV) | *Impulse-test voltage* (kV) | *Impulse/working ratio* |
|---|---|---|---|
| 33 | 19 | 194 | 10.2 |
| 66 | 38 | 342 | 9.1 |
| 132 | 76 | 640 | 8.4 |
| 275 | 160 | 1050 | 6.6 |
| 400 | 230 | 1425 | 6.2 |

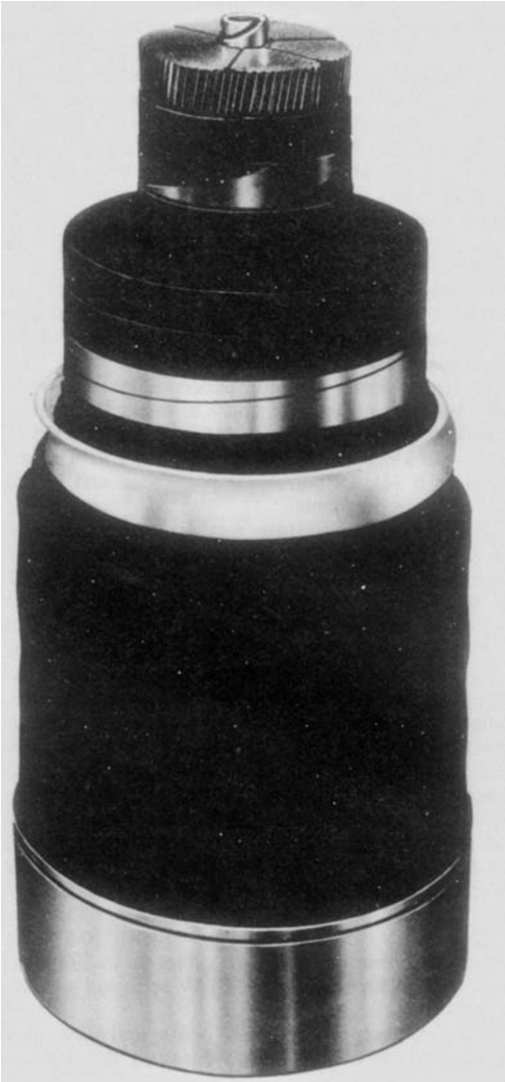


Figure 31.14 A 400 kV single-core oil filled cable

values are 7.5 MV/m at 33 kV; 12 MV/m at 132 kV; and 15 MV/m at 275–400 kV.

### *31.5.2.2 Low-pressure oil filled*

Right from the beginning the low-pressure oil filled cable has been well to the fore and has been the only type of cable widely used in the UK at 275 and 400 kV. Single- and three-core designs are available from 33 to 132 kV but, because of diameter limitations, only single-core cables can be produced for the higher voltages. *Figure 31.15* illustrates how oil channels are provided within the cable. In single-core cables the oil flow is normally through a duct in the centre of the conductor, but for short lengths used to terminate three-core cables the design may incorporate an annulus formed by the provision of longitudinal ribs on the inside of the lead sheath. In triple-core lead sheathed cables and aluminium sheathed cables with circular conductors, a duct is placed in the fillers between the cores. Alternatively, with a corrugated aluminium sheath (CSA) it is possible to omit the ducts and fillers. At 33 kV the conductors may be of oval shape and the construction is known as ductless shaped oil filled, whereas for higher voltages with circular conductors it becomes ductless circular oil.

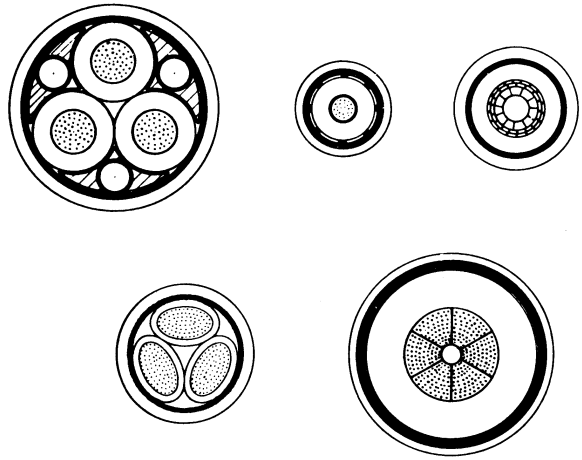


Figure 31.15 Cross-sections of typical oil filled cables

As the cable heats, the oil expands and is forced out of the cable through pipes at joints or terminations into a tank reservoir having internal pressurised capsules so designed that, on cooling, there is a feedback of oil into the cable. *Figure 31.16* illustrates the system. Tanks are of sizes to suit the route length and volume of oil in the cable. They are pressurised to take into account variations in height along the cable route. By the inclusion of stop joints between lengths of cable the circuit may be split into several oil sections. The designed static pressure within the cable is 5.25 bar, but transient pressures up to 8 bar can occur during periods of rapid heating due to increasing load. Optimum planning of the oil feed and sectionalising arrangements is a very important part of the economic design of a cable system.

From the time the cable is filled with oil during manufacture, the oil pressure must be continually maintained. A small tank is fitted on the cable drum; it remains connected during cable laying and even during jointing a flow of oil is maintained. When cables are installed in vertical shafts, e.g. for pumped storage stations, special arrangements are necessary. The Cruachan 275 kV pumped storage scheme in Scotland has a vertical head of 325 m with a consequent hydrostatic pressure of approximately 30 bar. The cable had to be partially drained under vacuum to limit the oil flow while making the lower stop joint, and reimpregnated before making the upper sealing end.

Lead sheaths will not withstand significant internal pressures, and are reinforced to withstand a continuous pressure of 5.25 bar for normal installations by the helical application of bronze tapes. In spite of the reinforcement, the lead sheath is subject to some expansion under creep stress. British practice favours the use of $\frac{1}{2}$C alloy (0.2% tin, 0.075% cadmium). Aluminium sheaths have technical and economic advantages and nowadays they are of corrugated design. This enables the thickness to be reduced and also provides greater flexibility for handling.

To maximise the efficiency of oil flow and the length of individual oil sections, the viscosity of the oil needs to be as

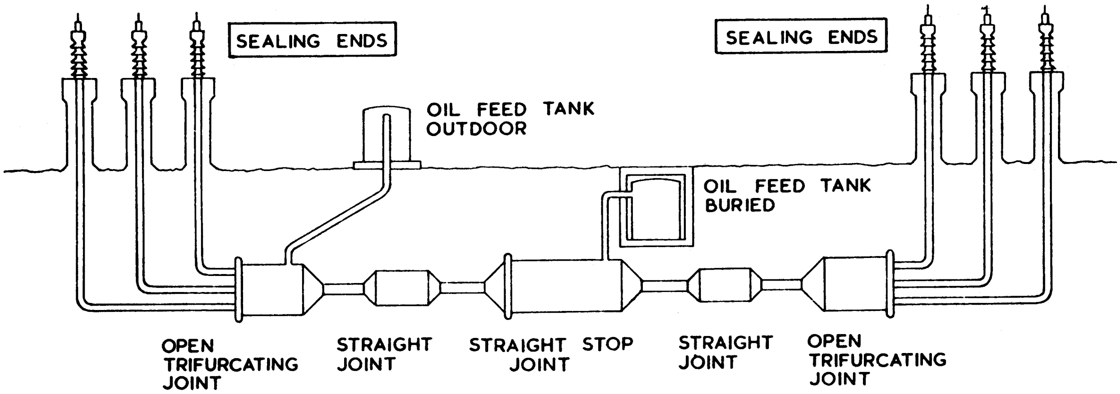



**Figure 31.16** Diagrammatic layout of a typical three-core OF cable system

low as possible, consistent with low power factor and electrical strength. Until recently, mineral oils were used with a viscosity of about 12 centistokes maximum at 20°C. However, current practice is to use synthetic alkylates of dodecylbenzene type which have better gas absorbing properties under electric stress. Such impregnants are intermediates in detergent manufacture.

Apart from the impregnant, the insulation for oil filled cables also differs significantly from that for lower-voltage paper cables. To keep the power factor as low as possible, the paper needs to be more thoroughly treated to remove impurities. For example, the water used in papermaking and washing for very-high-voltage cables may be deionised. For electrical stress reasons, and to obtain good bending performance without disturbance of the dielectric by wrinkling, etc., the papers tapes are graded from thin adjacent to the conductor (where the electrical stress is highest) towards much thicker and wider on the outside (to withstand the higher mechanical stress). With the large insulation thickness (up to 30 mm) required for the highest-voltage cables it is necessary to control the design and paper lapping parameters to allow individual paper layers to slide over one another on bending. This is done by shrinking the papers by predrying before lapping, and carrying out the lapping in a low-humidity atmosphere with careful control of tension.

### *31.5.2.3 High-pressure oil filled cable*

The high-pressure oil filled cable is a type of cable (*Figure 31.17*) developed in the USA and used extensively only in a few countries. It evolved from the predominant American practice of installing cables in buried ducts, the steel pipe being essentially a duct which can be installed a short length at a time without need for long trenches to be kept open. Either the cable cores have a temporary lead sheath which is stripped off as the cable is pulled into the pipe, or the unsheathed cable is delivered to site on a specially sealed and protected drum. So that the cores are not damaged during the pulling operation, D-shaped skid wires are applied helically over the insulation. After jointing, the pipe is evacuated and filled with oil to a pressure of 14 bar and the pressure is maintained by automatic pumping stations. The relatively large volume of oil and the high pressure enable a viscous impregnant to be used.

Pipe type high-pressure oil filled cables tend to be more expensive than self-contained oil filled cables laid directly in the ground, but in built-up inner city areas, or where robustness is desirable, they can be advantageous. Except

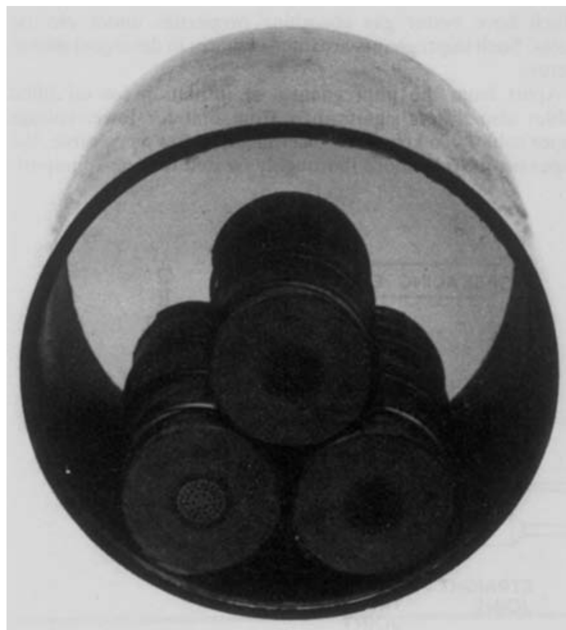


**Figure 31.17** Pipe type 230 kV high-pressure OF cable

for terminations, they always consist of three single-core cables pulled into a single pipe. The proximity of the cores and the high electrical losses in the pipe impose lower ratings than for self-contained cables.

### *31.5.2.4 Gas pressure cables*

During the 1930s–1940s, many designs became established to utilise the principle of gas pressure to suppress partial discharge in voids.

In the 'internal gas pressure' cable and in one form of pipe type cable the gas was admitted directly into the cable insulation and held by the metal sheath or steel pipe. The 'gas compression' cable worked on a different principle. Insulated oval conductors were sheathed with either lead or polyethylene and the individual cores or the three laid-up cores were then covered with a pressure retaining metallic sheath or pulled into a steel pipe. The space between the inner sheath and the outer pressure retaining member was filled with high-pressure gas, usually nitrogen. Expansion and contraction of the relatively viscous impregnating compound was compensated for by the inner sheath acting as a diaphragm.

With one exception, gas pressure designs are obsolete mainly because they cannot match the technical performance of oil filled cables through the voltage range. At 275 kV and above, low power factor and high breakdown strength (a.c. and impulse) become increasingly important, and oil filled cables can be operated to higher design stresses.

The exception is the 'pre-impregnated gas filled cable', useful for applications where problems exist in creating practicable oil sections, e.g. on hilly and undersea routes. Other advantages are: (a) there is no need for specialised oil equipment and (b) long continuous lengths suitable for submarine use can be manufactured. The total length for installation is determined by what can be coiled down in a ship, as joints between lengths can be made either in the factory or on the ship. In this gas filled cable system the paper is impregnated with a special greasy compound before being lapped on to the conductor. With modern designs the impregnated cores are covered by a smooth aluminium sheath and gas is admitted directly into the insulation after installation. There is a minimum of impregnating compound, and although voids do exist from the outset, the high nitrogen pressure provides good electrical strength. As with other forms of gas cable, however, operating voltages are usually limited to 132 kV.

#### *31.5.2.5 Cables with polymeric insulation*

Mention has already been made of the increasing use of polymeric insulation, largely XLPE, for distribution cables up to 33 kV. The low power factor of around 0.0005 which is attainable with such cables is also clearly attractive in comparison with the minimum of about 0.002 which is possible with the best oil filled cables. It seems likely that a new phase of cable transmission is emerging. Incentives are simpler jointing techniques, and reduced maintenance as pressurising equipment and oil leaks are avoided. An economic consideration relates to the voltage limit above which it is desirable to have a metal sheath over the insulation to prevent contact with water.

It was reported in 1988 that 230 km of lead sheathed 225 kV cable with thermoplastic polyethylene insulation was in satisfactory service in France, the first lengths having been installed in 1969. Electricité de France also claimed that the overall economics were favourable. This is despite the use of a lead sheath and limitation with straight polyethylene of the operating temperature to 70°C compared with 90°C with paper insulation.

Following consolidation of satisfactory experience at 33 kV, it is at around 132 kV that large-scale experience will first be obtained and it is now generally accepted that for voltages of 66 kV and above, a metallic sheath is required. XLPE is now well established as a dielectric at 132 kV and long length installations at 275 kV are just beginning. Many small installations at 132 kV are in service with a design stress of 7–9 MN/m. The problems have been enumerated in Section 31.4.6 and are primarily concerned with the production of clean insulation and screen interfaces plus possible incidence of water treeing in service. The French experience with straight polyethylene indicates that the former can be overcome, and only time will prove whether a metal sheath is necessary to prevent degradation by water tree mechanisms.

Much development work is proceeding on the optimum method of curing XLPE. Although dry-cured material has a lower content of microvoids than steam-cured material, there is little difference between the two levels in water tree growth if water is in contact with the insulation. If kept dry, treeing ceases to be a problem and the improved short-term breakdown strength of the dry-cured material enables it to be operated at a higher stress.

### 31.5.3 Submarine power cables

The engineering of submarine cable links is complex. Apart from the choice between a.c. and d.c. transmission, cable design has to take account of the maximum depth on the projected route, the potential hazards caused by shipping, corrosion and possibly marine borers. There are many submarine power cable installations giving satisfactory service at voltages up to ±400 kV d.c. and 420 kV a.c.

The choice of cable for a submarine crossing is influenced by the system voltage, the maximum depth and the length of the crossing. Solid type paper insulated cables are suitable for voltages up to 400 kV d.c. and 33 kV a.c. For deep-water installations special design features are necessary to enable this type of cable to resist the external water pressure. Solid type cable has been used successfully at 550 m depth on a d.c. link between Norway and Denmark. For higher voltages self-contained pressure assisted cables (oil filled and gas filled) are used, the internal pressure being maintained above the external water pressure at the deepest part of the route. Although not so far used for major submarine transmission schemes, polymeric insulated cables may be attractive for future a.c. links.

It is preferable that the cable be manufactured in continuous lengths without joints. As this is not always possible, proven techniques have been developed for the construction of flexible joints in all types of power cable, to facilitate laying in a continuous operation. Manufacture has to be arranged so that the cable can be coiled down on land and then reloaded directly into the cable laying vessel.

Experience on the ±100 kV d.c. cable circuit between England and France (1961) and on the Sweden–Denmark ('Konti-Skan') ±250 kV d.c. link (1965), indicates that cables laid directly on the sea-bed across busy shipping lanes or fishing zones are liable to suffer frequent impact damage caused by dragging anchors and trawls. A significant increase in circuit security can then be obtained by embedding the cables. Techniques have been developed for cutting trenches in the sea-bed and for accurate positioning of the cables within the trenches. On many cable routes adequate security can be obtained by burying the cable at the shore approaches only.

### 31.5.4 D.c. transmission

*Table 31.8* indicates the main d.c. schemes in operation, all of them being submarine. There are advantages in cable cost, but expensive terminal conversion stations may make such schemes uneconomic unless there are other overriding considerations. These arise when large national systems need to be interconnected and occasionally when large blocks of power have to be transmitted within a network. Most of the existing schemes are for submarine links where the charging currents for a.c. cable systems would be excessive.

D.c. cables can be operated at much higher design stresses than a.c. cables. For example, a typical 250 kV oil filled cable could have a maximum design stress of 33 MV/m, whereas a comparable 275 kV a.c. cable would have

**Table 31.8** D.c. cable schemes

| *Link* | *Voltage* (kV) | *Approximate installation date* | *Type of cable* | *Approximate route length* (km) |
|---|---|---|---|---|
| Gotland (Sweden) | 100 | 1954 | Solid | 100 |
| UK–France (Cross Channel Link) | ±100 | 1965 | Solid | 52 |
| Sardinia–Corsica (Italy) | ±200 | 1965 | Solid | 104 |
| Cook Strait (New Zealand) | ±250 | 1965 | Gas filled | 40 |
| Mainland to Vancouver Island | ±300 | 1969 | Solid | 26 |
| Mainland to Vancouver Island | ±300 | 1976 | Oil filled | 36 |
| Skagerrak (Norway–Denmark) | ±250 | 1977 | Solid | 127 |
| Tsugaru Strait (Japan) | ±250 | 1978 | Oil filled | 45 |
| Sweden to Gotland | 150 | 1983 | Solid | 90 |
| UK–France (Cross Channel Link) | ±270 | 1985 | Solid | 45 |
| Sweden to Finland | ±400 | In progress (1991) | Solid | 200 |
| Hawaii to Maui Alenuihaha Channel | ±300 | Planned (1991) | Oil filled | 61 |

a design stress of 15 MV/m. Although the partial discharge in voids mechanism does not apply in d.c. operation, there are other factors, such as stress distribution and transient voltages arising from rectifier malfunction, which have to be taken into account.

In a.c. cables the stress distribution in the insulation is determined by the geometry and the permittivity of the dielectric. It is usual to assume a uniform permittivity, as this property is affected only to a minor degree by changes in cable temperature and voltage. In d.c. cables, however, the steady state stress distribution is dependent on the geometry and resistivity of the dielectric. If the latter remains uniform, the stress distribution is the same as that for a.c. However, the resistivity of the dielectric is highly dependent on the dielectric temperature and to a lesser degree on the applied stress. When the cable is carrying load, there is a temperature gradient across the dielectric, the effect of which is to reduce the stress adjacent to the conductor and to increase it at the outside. It is possible to arrive at the conditions where the stress at the outside exceeds that at the conductor and the insulation must be designed to cater for these changing stress conditions. *Figure 31.18* illustrates the principles involved.

Nevertheless, as pressurising of the insulation is not so necessary and does not give much advantage in direct voltage and impulse breakdown strength, it is possible to use mass impregnated solid type cables for much higher equivalent direct voltages. This assumes that the dielectric is not weakened by migration of impregnating compound, i.e. the insulation is 'non-draining'. For the highest voltage levels, oil filled cables are used and, as with a.c. but for a different reason, clean paper obtained by the use of deionised water is desirable. Excessive conductivity due to ionic impurities can lead to thermal instability and breakdown.

A power of 500 MW can be transmitted by *three* single-core a.c. cables with 1000 mm$^2$ conductors at 275 kV. The same power can be conveyed by *two* single-core 800 mm$^2$ d.c. cables at ±250 kV. To transmit 1500 MW would require a double circuit comprising *six* naturally cooled 2000 mm$^2$ a.c. cables, but still only *two* d.c. cables, reducing by two-thirds the number of substantially identical cables required.

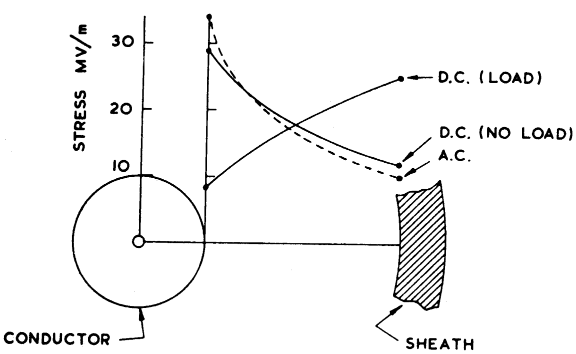



**Figure 31.18** Stress distribution in d.c. and a.c. cables

### 31.5.5 Cable ratings and forced cooling

The considerations in the general section on current carrying capacity are applicable also to transmission cables, but because of the much greater power carried, the effects of heat dissipation in the ground are of particular importance. First, it is necessary to inspect the soil to determine its thermal resistivity: 1.2°C m/W is taken as a representative value, but it may be much higher in sand, shingle or made-up ground, or if the soil is likely to be permanently dry. The moisture content is a significant factor in ground thermal resistivity; this became apparent when cables were loaded continuously so that moisture could not seep back during reduced load periods. If the ground surrounding the cable reaches a temperature of around 50°C, there is a considerable danger, with certain types of soil, of reaching a 'runaway' condition: complete drying out, high thermal resistivity, excessive temperature rise in the cable and breakdown.

When there is doubt about the thermal properties of the backfill, it is safer to surround the cable with imported material having known thermal resistivity in the dry condition. This means creating a dense mass with little air space by a controlled mixture of sand and gravel, particle sizes being blended to obtain good packing. Laboratory control of composition and compaction is important. An alternative is to use a mixture of selected sand and cement in the proportion of 14:1.

During the early 1960s, following the first failure due to ground drying out, several installations were completed in the UK with cooling pipes laid adjacent to each cable, water being circulated through a closed heat exchanger. The latter was air cooled or in some locations water cooled by supplies from bore-holes. Initially, aluminium was used for the pipe but this was later changed to high-density polyethylene.

In these later installations four pipes were used with an internal bore of approximately 66 mm. Specially selected sand was used around the cables and pipes. Some 160 circuit km of 275 kV with a winter rating of 760 MVA was installed in this way. It was later found that this rating, together with 1100 MVA at 400 kV, could be achieved by naturally cooled cables with a stabilised backfill and more realistic assumption of ambient ground parameters.

Separate pipe cooling came back into prominence in 1977 when overhead line ratings were further increased by raising the operating temperature to 65°C. This required a winter rating of 2038 A, equivalent to 970 MVA at 275 kV and 1410 MVA at 400 kV, which could not be achieved with the 2500 $mm^2$ maximum conductor size and stabilised backfill. A similar need for additional cooling also arose with the 400 kV cables in the Dinorwic pumped storage scheme in North Wales. Improved water pipe systems were adopted, the emphasis being on the use of larger pipe diameters and special arrangements for water cooling of the joints (*Figure 31.19*).

A rating factor which is particularly important with high-voltage single-core cables is to prevent the very high losses in metallic sheaths and reinforcement if these were solidly bonded at both ends of a feeder. The losses accrue from currents induced in the low-impedance sheath circuit and are related to the conductor current and separation between phases. Without elimination of such losses the use of aluminium sheaths would not generally be economic. In some cases it may be possible to bond earth at one end only, but modern practice is to employ a transposition method (*Figure 31.20*) in which the metallic sheaths are interrupted every few hundred metres with cross-connection at jointing positions. Voltages are then balanced at every third joint and usually kept below 65 V under full-load conditions. High transient voltages can occur; and to check that the sheath insulation is satisfactory, a 10 kV d.c. test is carried out after laying.

When two circuits are laid on a common route, the current rating will be reduced by mutual heating unless thermal independence can be obtained by a separation of about 2 m at 132 kV, with progressive increases for higher voltages. To obtain the most economic solution, it is necessary to examine the cost of larger conductor cable, extra trenching and external cooling. In the case of a single-core circuit the mutual heating effects between the phase cables must also be taken into account. With single-point bonding and cross-bonding to eliminate sheath circulating currents, a flat formation with spacing between cables of 150–300 mm is usually beneficial to avoid unduly high sheath voltages. If single-core cables are bonded and earthed at both ends, it is necessary to install the cables in trefoil formation, because with wide spacing the increase in sheath losses would more than offset the reduction in mutual heating.

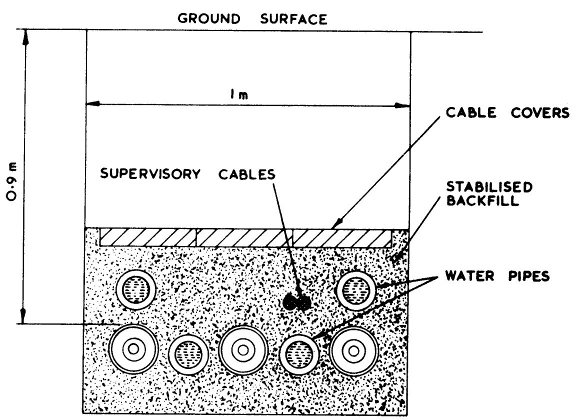



**Figure 31.19** Typical layout of cables and water cooling pipes in a trench

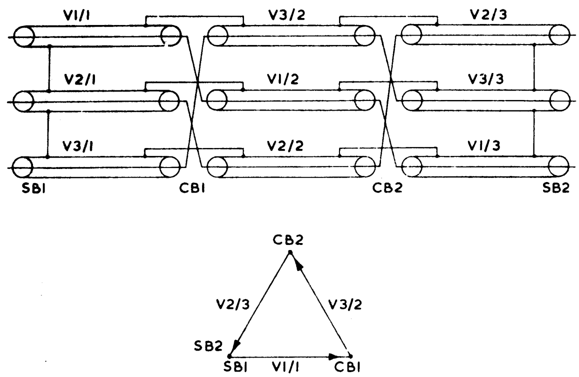



**Figure 31.20** Cross-bonding of cable sheaths to provide transposition for reducing sheath losses

### 31.5.6 Future development

It was mentioned earlier that the low-pressure OF cable was nearing its limit of performance at the present maximum service voltage of 525 kV. However, overhead lines will soon be in operation at around 1000 kV, and at some future date there will be a need for cables to match them.

A major factor in the development of such cables is the need to keep the diameter of the cables down to a size that will enable drums of completed cable to be transported on existing road systems. As 525 kV cables are already approaching this limit, only a small increase in insulation thickness can be permitted. This will result in the insulation of the higher voltage cables operating at a much higher electrical stress. Experimental work has shown that this should be feasible provided the minimum oil pressure is substantially increased.

While higher design stresses are possible with impregnated paper insulation, they create problems insofar as dielectric losses are concerned. The dielectric loss of a cable which occurs whenever the cable is energised can be expressed as follows:

$$\text{Dielectric loss} = 27.7\, V f d s \varepsilon \delta \times 10^{-4}\ (\text{W/m})$$

where $V$ is the phase voltage (kV), $f$ is the frequency (Hz), $d$ is the conductor screen diameter (mm), $s$ is the maximum design stress (kV/mm), $\varepsilon$ is the relative permittivity of the insulation, and $\delta$ is the dielectric loss angle.

For a given conductor size, frequency of supply and insulation characteristics, the dielectric losses are proportional to the product of the operating voltage and design stress. The increase in the dielectric loss means that the current dependent losses, i.e. the current rating, must be reduced to prevent the maximum design temperature being exceeded. At a voltage of approximately 850 kV, the cable reaches its maximum design temperature purely by voltage energisation and, therefore, has no current rating.

To overcome these problems, designers have been looking for alternative materials which have lower dielectric losses than paper but which have the required mechanical and physical characteristics. Although much research work has been devoted to insulation consisting of all-plastic films, the material now being introduced into commercial service is a laminate consisting of a film of polypropylene between two layers of paper (PPL). The proportion of paper to polypropylene is approximately 50:50. It has been found that this type of laminate overcomes many of the problems associated with all-plastic films.

The use of PPL reduces the dielectric loss to about 25% that of conventional paper insulation and extends the useful operating voltage range above 1000 kV. It is also beginning to find use in low- and high-pressure oil filled cables with voltage ratings down to 345 kV.

Polymeric insulation such as XLPE also has very low dielectric losses and, therefore, is attractive for the higher operating voltages. Until recently these insulations operated at much lower electrical stresses than paper insulation and therefore were not suitable for use in cables at voltages in excess of 275 kV. However, much development work has been undertaken with the object of increasing the operating stress. This has been mainly directed at reducing the contaminant level in the insulation and providing extremely smooth conductor and dielectric screens. Short lengths of 500 kV cable are now in service to obtain operating experience.

A completely different approach is to make use of superconduction: very large currents can be carried by small conductors without the generation of much heat. Until recently, it was necessary to use liquid helium to cool the conductor to the required temperature.

The engineering problems are not inconsiderable, but experimental cables have been made and trials undertaken to demonstrate the practicability of such schemes. It has, nevertheless, been established that the economics are such that this form of transmission can only be justified for ratings of the order of 5–10 GVA. In the UK such requirements are several times what can immediately be envisaged.

The subject has attracted renewed interest with the recent discovery of high temperature superconduction. At the time of writing discoveries are still taking place and, therefore, it is not possible to assess its full impact on underground transmission. It would appear that with these new superconductors, liquid nitrogen is a possible coolant which is considerably cheaper than liquid helium. However, the materials so far discovered are of a brittle nature and will require special designs of conductors.

## 31.6 Current-carrying capacity

The continuous current rating of a cable is dependent on the way heat generated in the conductor, insulation and metallic components is transmitted through the cable and then dissipated from its external surface. For convenience the conductor temperature is taken as the reference datum for the cable. A notional maximum cable rating can then be calculated from the permissible temperature rise from a standard base ambient or ground temperature to the maximum temperature that the particular type of insulation will withstand with a reasonable margin of safety. Adjustments to this notional rating have to be applied to cover many factors, which include a different base temperature and variations in heat dissipation from the cable surface: e.g. dissipation from a cable in a duct is lower than from a cable in free air.

The difference between conductor temperature and external or ambient temperature is directly related to the total heat losses and the law of heat flow, using a conduction current analogue. This analogy may be extended into the type of circuit diagram in *Figure 31.21*, which shows how the heat input at several positions has to flow through

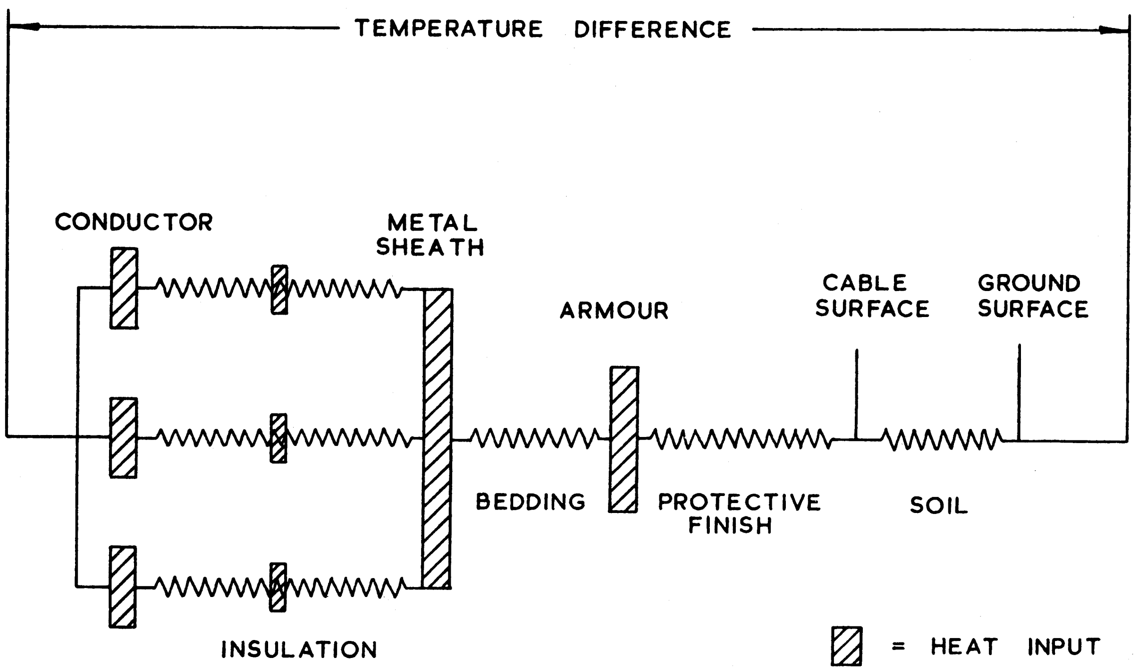



**Figure 31.21** Equivalent circuit diagram for the heat flow in a three-phase belted cable

various layers of different thermal resistance. To make calculations, values of thermal resistivity have to be measured for all the materials involved. Thermal resistivity is defined as the difference in degrees Kelvin between opposite faces of a metre cube caused by the transference of 1 J/s of heat; the SI unit is kelvin-metres per watt (K-m/W).

### 31.6.1 Availability of continuous ratings

Cable users frequently need to ascertain the rating for a particular type of cable at a given voltage and with a range of copper or aluminium conductor sizes. The most common sources of reference are:

(1) The IEE Regulations for the Electrical Equipment of Buildings. This source covers cables of all standard types (up to 1 kV). A difference from the others listed below is that the ratings quoted are lower, as they are calculated from a base ambient temperature of 30°C (compared with 25°C) and, hence, a lower permissible temperature rise. Only 'in air' ratings are included.
(2) Report ERA 69-30 (8 parts), published by ERA Technology Ltd, provides ratings for paper cables up to 33 kV, PVC cables up to 3.3 kV and thermosetting insulated cables up to 3.3 kV. Guidance is also provided for cyclic and emergency ratings, together with further information relating to cables in typical specific installation conditions.
(3) Manufacturers' catalogues.
(4) Lower ratings may be selected for specialised installations because of particular environmental conditions. For example, the IEE Regulations for the Electrical and Electronic Equipment of Ships stipulate an ambient temperature of 45°C and somewhat lower maximum temperatures for continuous operation (80°C for thermosetting insulation).
(5) The above cover installations based on British cable practice. When USA types of cable and system are applicable, reference may be made to ICEA publications.
(6) IEC Publications 364-5-523 and 287 (*Table 31.1*): 364-5-523 provides ratings for unarmoured cables and 287 gives the basic methods for calculating ratings using the standard data included. Values prepared by all other bodies are almost always derived in accordance with this specification.

In general, these documents provide tabulated figures for copper and aluminium conductor cables installed in air, in ducts and buried directly in the ground. The data quoted are for standard conditions, and multiplying factors are given for variations in the conditions.

A feature of USA practice is that data provision is made for limited periods of operation with emergency overload for a specified number of hours per year to a higher temperature. While it is recognised that such operation could affect the life of the cable, the conditions are chosen to ensure that only limited ageing is likely to occur. British practice has not yet included this feature in published recommendations.

Another important aspect relates to the fact that the published ratings are quoted for 'continuous' or 'sustained' operation. Few cables are loaded for the whole of their life to full rating, and allowance is made for this. Nevertheless, the derivation of ratings is a most complex subject and many large users, such as the UK distribution companies, have developed ratings which allow for their own circumstances, such as cyclic operation and the emergency conditions which can arise with 11 and 33 kV cables normally installed as open rings (Electricity Council Engineering Recommendation P 17—Current Rating Guide for Distribution Cables).

A standard rating for the particular cable and specified installation conditions having been determined, factors have then to be applied to obtain the actual rating for the individual conditions. The references quoted provide these factors for variations such as ambient or ground temperature, depth of laying, thermal resistivity of soil and mutual heating due to cables being installed close together.

### 31.6.2 Factors in cable ratings

#### *31.6.2.1 Temperature*

As previously mentioned, ratings are governed primarily by the permissible temperature rise from a declared base temperature to a maximum for the particular cable design. The base temperature is normally 15°C for buried cables and either 25 or 30°C for cables in air. At the maximum continuous temperature the heat generated in the cable equates with the heat dissipation from it, which is dependent on the thermal resistance of the cable components and the surroundings.

The internationally recognised limits for conductor temperatures with the common types of insulation and cable design are shown in *Tables 31.9* and *31.10*.

In the case of the insulation materials, it is not usually chemical degradation which is the main aspect. With paper insulation the permissible temperature is reduced with increasing voltage and this ensures that there is not undue expulsion of impregnating compound for the duty required.

**Table 31.9** Paper cables: conductor temperature limits

| *Rated voltage, $U_0/U$* (kV) | *Design* | *Temperature** (°C) |
|---|---|---|
| 0.6/1, 1.8/3 and 3.6/6 | Belted | 80 |
| 6/10 | Belted | 65 |
| 6/10 | Screened | 70 |
| 8.7/15 | Screened | 70 |
| 12/20 and 18/30 MIND | Screened | 65 |

* For continuous operation. Temperature for short-circuit conditions is 160°C, except for 0.6/1 kV cable, for which the limit is 250°C, subject to the accessories being suitable.

**Table 31.10** Polymeric cables: conductor temperature limits

| *Insulating compound* | *Temperature** (°C) | |
|---|---|---|
| | *Continuous* | *Short-circuit* |
| Polyvinyl chloride | 70 | 160† |
| Polyethylene | 70 | 130 |
| Butyl rubber | 85 | 220 |
| Ethylene propylene rubber | 90 | 250 |
| Cross-linked polyethylene | 90 | 250 |

* Temperature limits are based on intrinsic properties and do not take account of variations in cable and accessory design. Short-circuit ratings are affected by (a) reduction of thickness of PVC and PE by thermomechanical forces; (b) conductor and core screens; (c) design of accessories (e.g. soldered conductor joints are unsuitable).
†140°C for conductors above 300 mm².

Similarly, screened paper cables are more independent of compound effects in the filler spaces and can be operated to a higher temperature. Thermoplastic insulation softens significantly with increasing temperature and the limit is governed by deformation. Thermosetting materials can withstand much higher temperatures without undue deformation. Limitation by ageing effects is a factor with natural rubber compounds.

#### *31.6.2.2 Conductor losses*

With the exception of some higher voltage transmission cables, the $I^2R$ conductor losses represent the major source of heat produced. These also have to be dissipated through the longest radial path in the cable. When the conductors are large, the effective resistance may also be increased because of skin effect. The increase is negligible for sizes up to about 185 $mm^2$ and can be reduced by the use of the Milliken construction described earlier.

Proximity effects may be caused by the interaction of magnetic fields associated with adjacent current-carrying conductors and these, too, can cause further redistribution, as with skin effect. The proximity effect occurs with small spacing and so is most significant for low-voltage cables of large conductor size.

#### *31.6.2.3 Dielectric losses*

Dielectric losses are reasonably negligible for paper and XLPE cables up to about 60 kV and for PVC cables up to 6 kV. They are mainly of importance for high-voltage transmission cables. One reason that PVC has not found much application in the 10–20 kV field is that the losses are high in comparison with paper and XLPE. Even so, they represent only around 6–8% of the conductor losses in 11 kV cables. With XLPE the figure is around 0.1%.

#### *31.6.2.4 Sheath and armour losses*

Losses in metallic sheaths are of great importance for large conductor single-core cables bonded and earthed at both ends. As explained in Section 31.5.5, they can be avoided by cross-bonding. Although they make some contribution to total losses, the effect is not very significant for multicore cables. Similar remarks apply to armour, but losses due to magnetic effects are dominant for single-core cables and it is usually necessary to use non-magnetic armour material.

#### *31.6.2.5 Internal thermal resistance*

Thermal resistance within the cable is related to: (a) cable design and construction, e.g. the number of separate layers and the volume; and (b) the thermal resistivities and thicknesses of the individual materials. Values (in Km/W) included in IEC 287 are:

| | |
|---|---|
| Impregnated paper, solid cables | 6.0 |
| Oil filled cables | 5.0 |
| Polyethylene, XLPE | 3.5 |
| Polyvinyl chloride | 5.0/6.0 |
| Ethylene propylene rubber | 3.5/5.0 |
| Bituminous textiles | 6.0 |

#### *31.6.2.6 External thermal resistance*

For cables in free air the heat dissipation is related to the degree of exposure and to the surface emissivity, which depends on surface condition. Published ratings assume shading from the sun, and if this is not provided, derating may be necessary.

### 31.6.3 Sustained ratings

*Table 31.11* indicates a typical example of published ratings for one type of cable installed in air, in ducts and buried directly in the ground. When cables are installed in ducts two other thermal resistances are introduced—namely, an air space between the cable and the duct, and the duct itself. As can be seen from *Table 31.11*, these cause a heavy rating penalty. *Table 31.11* also illustrates that while ratings for cables in air and buried direct in the ground are broadly similar, in air they are lower for small conductor sizes and higher for larger sizes. These differences are related to heat dissipation as a function of surface area.

Cables installed under water have the lowest external thermal resistance and highest ratings. However, there is always a danger that in time a layer of silt may build up, and investigations in canals have shown that such layers can have high thermal resistivity.

### 31.6.4 Short-time and cyclic ratings

A cable on load will show an exponential temperature rise/time relationship and, if starting from a low temperature, may take many hours to reach stable condition at maximum temperature. It can, therefore, carry more than maximum continuous rating for a limited time, the factor for overload depending on the extent of initial loading.

For cyclic loadings some increase of rating, compared with continuous, may be applied to an extent which will vary with the shape of the load curves. Calculations to take advantage of this possibility are rather tedious, but guidance may be obtained from ERA 69–30: Part IV (published by ERA Technology Ltd).

### 31.6.5 Short-circuit ratings

Often the conductor size necessary is related to short-circuit current rather than continuous current requirements. The

**Table 31.11** Sustained current ratings and volt drop for triple-core copper, 0.6/1 kV, XLPE insulated, armoured cables

| *Conductor area* ($mm^2$) | *Rating, dg* (A) | *Rating, sd* (A) | *Rating, air* (A) | *Volt drop* (mV/A/m) |
|---|---|---|---|---|
| 16 | 119 | 96 | 107 | 2.5 |
| 25 | 152 | 124 | 134 | 1.7 |
| 35 | 182 | 149 | 165 | 1.2 |
| 50 | 217 | 177 | 201 | 0.87 |
| 70 | 266 | 218 | 256 | 0.60 |
| 95 | 319 | 263 | 316 | 0.45 |
| 120 | 363 | 300 | 369 | 0.37 |
| 150 | 406 | 338 | 423 | 0.30 |
| 180 | 458 | 382 | 489 | 0.26 |
| 240 | 529 | 442 | 582 | 0.21 |
| 300 | 592 | 496 | 672 | 0.19 |

Depth of laying, 0.5 m.
Soil thermal resistivity, 1.2 Km/W.
Ground temperature, 15°C.
Ambient air temperature, 25°C.
Maximum conductor temperature, 90°C.
Rating: dg, direct in ground; sd, in single-way ducts; air, in free air.

short-circuit current, which may be 20 or more times normal, produces thermal and electromagnetic effects proportional to the square of the current. So far as the cable insulation itself is concerned, much higher conductor temperatures can be allowed because the heating and cooling are very rapid and the full temperature will not be sustained for significant time by the insulation. Figures are included in *Tables 31.9* and *31.10*.

Short-circuit ratings are not published for individual cables in any official documents, because of the large number of the cable types and sizes involved and the fact that they have to be related to the duration of short circuit which applies to the particular circuit. *Figure 31.22* illustrates a typical example of the graphs available from manufacturers to provide information on a basis of a maximum conductor temperature with a range of durations.

Other factors may dictate a lower rating for a particular design of cable or installation condition. A short circuit in a cable produces electromagnetic forces which could burst the cable if the cores are not adequately bound together (single-core cables are a special case of this). The accessories must also be designed to withstand both electromagnetic and thermomechanical forces; and accessories must be compatible with the cable in this respect. Soldered joints impose limitation of the short-circuit temperatures to 160°C.

The method of installation may also limit permissible short-circuit current. Local pressure due to clamping may lead to high forces, with deformation of cable components. Longitudinal expansion can also be considerable and has to be absorbed uniformly. When cables are buried, the cable is restrained and these forces must be accommodated by joints and terminations.

### 31.6.6 Voltage drop

Voltage drop may be of great significance for 0.6/1 kV cables but is not usually important at higher voltages. A typical

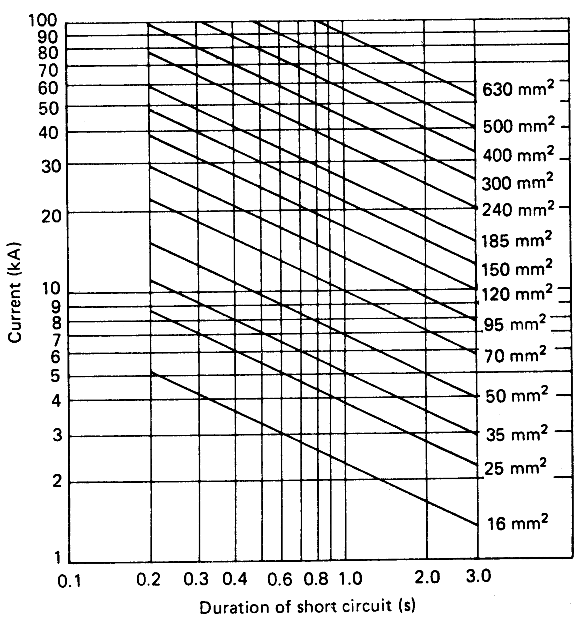



**Figure 31.22** Short-circuit ratings for copper conductor XLPE insulated cables (temperature rise 90 to 250°C)

requirement in the IEE Regulations is that the voltage drop in a cable run should be such that the total drop in the circuit, of which the cable forms a part, does not exceed 4% of the nominal voltage.

As the actual power factor of the load is seldom known, a practical approach is to assume the worst condition, i.e. where the phase angle of the load is equal to that of the cable. Cable manufacturers issue tabulated figures for volt drop, as in *Table 31.11*, based on this assumption. If the actual current differs greatly from the tabulated current the figure may be approximate only. From a table such as this, a suitable cable size may be selected but it must also be able to carry the current.

### 31.6.7 Protection against overload current

For some types of cable, particularly wiring cables, the required current rating of the cable must be determined by the overload protective device rather than the circuit current. The rating of the device must not be less than the circuit current and, of course, such ratings are in discrete steps. In the 16th edition of the IEE Wiring Regulations the protective device must satisfy the requirements of:

$$I_B \le I_n \le I_z$$
$$I_2 \le 1.45 I_z$$

where (a) the nominal or current setting $I_n$ shall not be less than the design current $I_B$ of the circuit; (b) $I_n$ does not exceed the lowest of the current-carrying capacities $I_z$ of any of the conductors in the circuit; (c) the current causing effective operation of the protective device $I_2$ does not exceed 1.45 times the lowest of the current-carrying capacities $I_z$ of any of the conductors of the circuit.

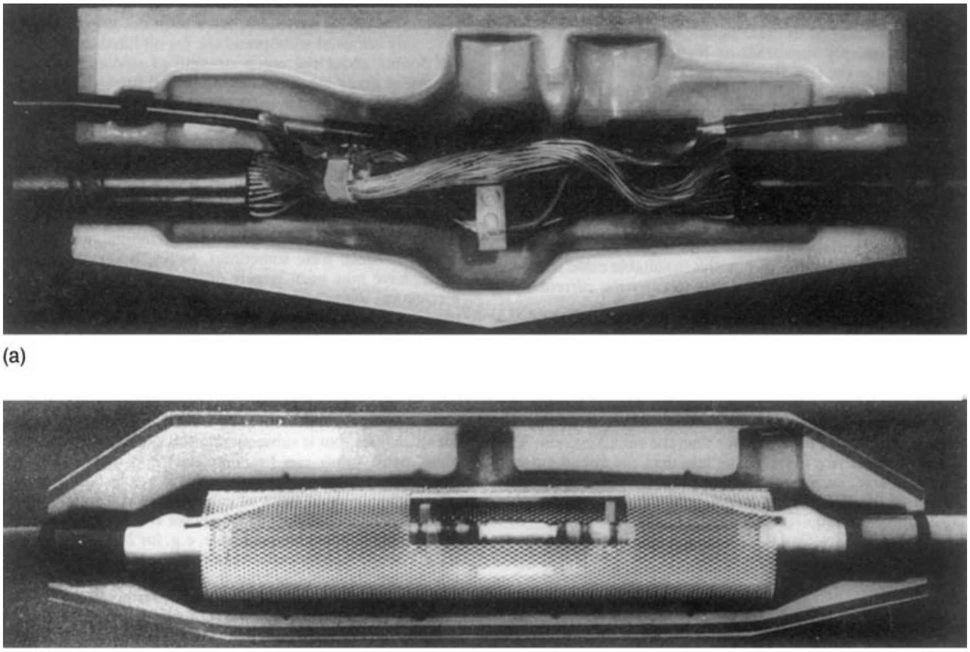
## 31.7 Jointing and accessories

### 31.7.1 Aluminium conductor jointing

The technique involving a flux for soldering with aluminium is essentially the same as for copper, but more care is required and strict observance of temperature limits is important. A special flux is necessary to remove the oxide skin and its composition should be without dermatitic risk. Solid conductors have an advantage in that a tinned layer can more readily be produced by the abrasion tinning procedure.

Problems with aluminium conductors, however, have largely been overcome by development of improved and simple compression methods suitable for both solid and stranded conductors. Probably the only remaining difficulty is that, when making straight joints on multicore tables, the larger separation necessary between cores for inserting the tool head makes the joints more bulky. Test requirements are given in BS 4579: Part 3.

Reference has been made to the problems with aluminium conductors in the tunnel type terminations of house-wiring fittings and these emphasise the care necessary in designing any mechanical fittings for aluminium. Suitable approved fittings are available for specific requirements such as the concentric neutral conductor in Waveform distribution cable, and for aluminium conductors in house-service cut-outs. Alternatively, for terminations, fittings are available for connecting a short piece of copper to an aluminium conductor.



(a)

(b)

**Figure 31.23** Cast resin type joints before resin filling: (a) service joint on Waveconal cable; (b) straight joint on paper insulated cable

Where maximum strength and minimum volume of joint are essential, welding techniques have been developed, but they have only achieved widespread use for oil filled cables. There are doubts about the creep strength of soldered joints and jointing is made more difficult by the oil flow which must be maintained. The metal inert gas (MIG) welding procedure, which is essentially a casting process, proved to be practical and reliable.

### 31.7.2 Joints for distribution cables

The traditional practices of the past, which required highly skilled jointers for soldering and plumbing and involved materials which were sometimes, heavy, bulky and cumbersome, have now been largely dispensed with. By the use of mechanical joints and cast resin filling into simple shell type plastics moulds, all the components can be packed as a convenient complete kit and only simple tools are needed on site. The resin is poured while cold, and when mechanical fittings are used, no heating of any kind is required. At the time of mixing on site, the resin is fluid and penetrates well to fill all cavities, but it subsequently sets quickly to a hard solid mass. Most joints can be completed in $1$–$1\frac{1}{2}$ h and can be energised immediately. The basic principles of cast resin jointing apply to all types of cable for all voltages up to and including 10 kV. *Figure 31.23* shows two typical examples. Where 'live' jointing is practicable, e.g. for 240/415 V services, it can equally well be carried out with these designs. The main advantages, however, accrue from the lower skill demanded and the short time required for jointer training.

*Figure 31.24* shows a cross-section of a service joint on CNE cable taken through one of the phase connectors. With this type of connector it is not necessary to remove

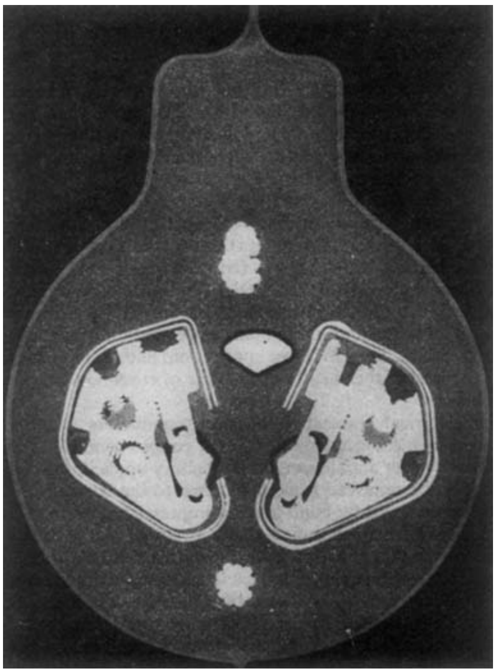


**Figure 31.24** Section of cast resin service joint on Waveconal cable, showing the insulation piercing phase conductor connector

the insulation from the phase conductor, even if it consists of XLPE, because knife edges on the connector pierce the insulation and establish firm contact with the conductor.

### 31.7.3 Joints for transmission cables

Special fittings are required to joint and terminate transmission cables, the detailed design of which depends on the type of cable system employed. The following description of those used for low-pressure oil filled cables gives an indication of the important categories.

*Straight joints* The main requirements for joints connecting adjacent lengths of cables are: (a) to provide electrical continuity for the cable conductors; (b) to maintain the electrical insulation; (c) to provide an oil-tight connection between the sheaths; (d) in the case of cross-bonded single-core installations, to provide an insulating barrier between adjacent cable sheaths with facilities for cross connection; and (e) to maintain the insulation of the sheaths in the case of cross-bonded cable installations.

The electrical connection between conductors is usually provided by a compression ferrule for copper conductors and MIG welding for aluminium. As the factory-applied insulation has had to be removed to permit access to the conductors, it has to be replaced by hand-applied impregnated paper tapes and rolls. These are not electrically as strong as the factory-applied insulation and must be built up to a greater diameter. The different diameters for the cable and hand-applied insulation introduce longitudinal electric stresses in the joint. The stresses (and, hence, the shape of the boundaries) must be carefully controlled, as the electric strength of paper insulation along the laminations is only about 1/15 of that normal to the surface of the paper. *Figure 31.25* illustrates a typical straight joint for 33 kV triple-core cable.

*Trifurcating joint* This type of joint resembles a straight joint but is used to connect a three-core cable to three single-core cables, usually for terminating purposes.

*Stop joint* A stop joint provides all the functions of a straight joint but, in addition, separates the two adjacent cables hydraulically. It is used to limit the hydraulic pressure in a cable system installed when there are significant changes in elevation. This requirement has a major effect on the design, as it is necessary to introduce a different material in the electrical insulation to be capable of withstanding the hydraulic pressure difference. In modern designs of stop joint, this function is carried out by a moulded barrier of epoxy resin with a mineral filler. A

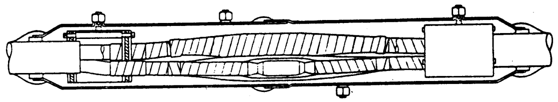


**Figure 31.25** Straight joint for a 33 kV, three-core, OF cable

stop joint for 132 kV single-core cable is shown in *Figure 31.26*.

*Outdoor termination* The termination is enclosed in a porcelain housing, which retains the oil pressure and provides protection against climatic conditions. The porcelain has a long creepage path to allow for contamination by dirt, rain, fog and snow. As for straight joints, care must be taken to control the longitudinal stresses in the paper insulation. In very-high-voltage cable systems this is usually provided by means of a 'capacitor cone' similar to that used in high-voltage bushing.

*Oil immersed termination* This is similar to an outdoor termination but is used to make connection to oil immersed equipment. As there is no surface contamination from the atmosphere the length of the termination is appreciably shorter than the equivalent outdoor form.

*$SF_6$ immersed termination* Increasing use is now being made of $SF_6$ gas instead of oil for insulation. *Figure 31.27* shows a cable termination into $SF_6$ insulated metal-clad equipment. The cable is of the single-core 132 kV oil filled type with a copper conductor. The insulator is of the plug-in connector type, which employs a solid cast-in electrode, unpierced by the need for seals. The electrical stress control is of the capacitor cone type and is composed of cylinders of aluminium foil embedded in oil impregnated paper rolls.

## 31.8 Cable fault location

Irrespective of the type of cable, fault location demands a systematic approach if time and cost are to be minimised. Current practice is to adopt the four-step approach of diagnosis, preconditioning, prelocation and pinpointing.

### 31.8.1 Diagnosis

Diagnosis is used to confirm the existence of a fault and to determine its character. The dividing line between low- and high-resistance faults is based on the assumption that prelocation will be by a modern technique such as the

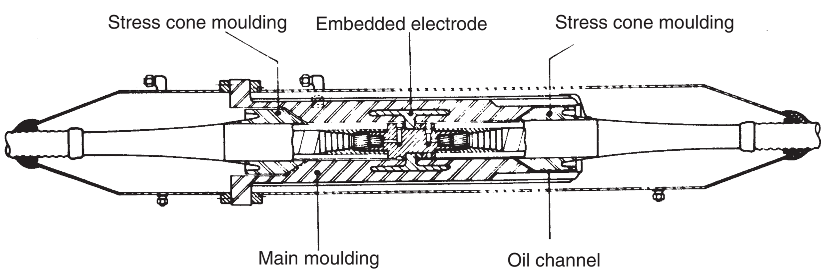



**Figure 31.26** Single-core, 132 kV, OF cable stop joint

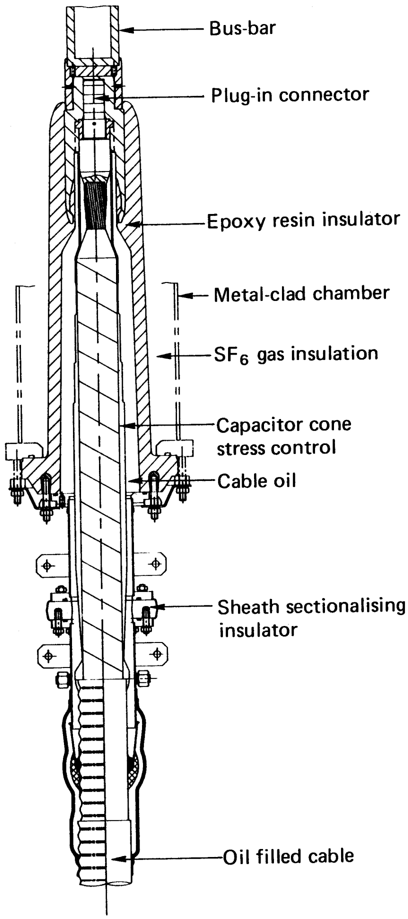



**Figure 31.27** $SF_6$ plug-in sealing end for 132 kV OF cable

pulse-echo method, rather than by any of the classical bridge methods. It is essential that the fault resistance be measured using an ohmmeter and not an insulation tester such as a 'megger'. Cable continuity may be checked using a pulse-echo set, rather than an ohmmeter, with the advantage that breaks in the cable sheath as well as in the cable cores will be detected.

### 31.8.2 Preconditioning

Preconditioning (often referred to as 'fault burning') is used to change high-resistance faults to low-resistance ones which can then be prelocated using the pulse-echo method. Fault burners are usually designed to give various combinations of voltage and current output at ratings of up to 5 kVA. While reasonably successful on paper insulated cables (except on flashing and intermittent faults), fault burning has not proved to be effective on cables employing polymeric insulation, particularly XLPE. Prelocation techniques, such as the impulse current method, described below, have eliminated the need to precondition faults.

### 31.8.3 Prelocation methods

Prelocation is the application of a test at the terminals of a cable to give an indication of the distance of the fault from the test point. While the measurement should be as accurate as conditions allow, the primary purpose of the terminal tests is to give an indication, as quickly as possible, of the vicinity in which to commence the final pinpointing tests.

For many years cable fault prelocation methods were based on d.c. or low-frequency measurements of conductor resistance or capacitance. Most of these tests were performed using some form of bridge circuit which, when balanced, would indicate the ratio of the resistance, or capacitance, of the faulty conductor to that of a healthy one in the same cable. Versions of these 'classical' methods are still in use today but they have been largely replaced by 'modern' methods which are based on travelling-wave phenomena—the first to appear being the pulse-echo or radar method.

#### *31.8.3.1 Pulse-echo method*

Pulse-echo fault locators generate a short-duration pulse which is injected into the cable and which travels to the fault point at $D$ (metres) and back in a time $t$ (microseconds):

$$t = \frac{2D}{v}\,(\mu s)$$

where $v$ (m/μs) is the speed at which the pulse travels along the cable and is determined almost totally by the permittivity of the cable dielectric $\varepsilon$, according to the formula:

$$v = \frac{300}{\sqrt{\varepsilon}}\,(m/\mu s)$$

where 300 m/μs is the velocity of light in vacuo.

The advantages of the pulse-echo method, compared with bridge methods, are that it requires access to only one end of the cable and it is not necessary to perform any 'equivalent length conversions', provided the cable insulation is the same throughout the whole cable route. It is thus far less dependent on accurate cable records than are the bridge methods.

In the earliest instruments, the injected pulse and its reflection(s) were displayed on a cathode-ray tube but modern versions now use dot-matrix liquid crystal display (LCD) panels. Simplified instruments, for cable-length checking as opposed to cable fault location, may not provide a graphical display of the 'echogram', but only give an (automatic) readout of the time/distance to the reflection from the end of the cable.

Pulse-echo fault locators do, however, have one serious limitation in that the amplitude of the reflection produced by a fault depends on the ratio of the fault resistance $R_f$ to the surge impedance of the cable $Z_0$, as shown in *Figure 31.28*. Series faults, i.e. faults affecting the continuity of one or more conductors of a cable, generally present no difficulty as they are generally complete open circuits producing 100% reflections (of the same polarity as the injected pulse). Shunt faults, i.e. faults affecting the cable insulation, produce (reversed polarity) reflections with amplitudes of less than 5% if the fault resistance is greater than 10 times the surge impedance of the cable. A reflection amplitude of 5% is about the smallest which can be easily identified from amongst the other 'background' reflections which arise on a jointed cable route. Comparison of the trace obtained from the faulty phase with that from a healthy phase in the same cable can simplify the interpretation and

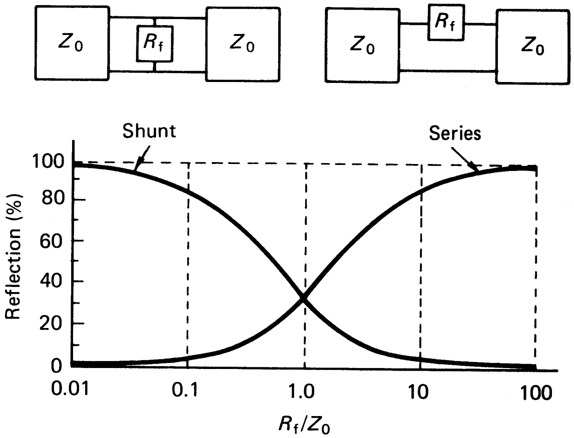



**Figure 31.28** Relative amplitude of reflective pulse as a function of the ratio of fault resistance ($R_f$) to surge impedance ($Z_0$) for both series and shunt faults

extend the sensitivity to possibly 1%. With typical power cable surge impedances lying in the range 15–50 Ω, it is frequently impossible to locate shunt faults without the use of 'fault burning' or 'fault re-energisation'.

## 31.8.4 Cable fault characteristics

Representing cable faults simply as resistors is misleading, and a more realistic equivalent circuit, where the fault resistance is paralleled by both a spark gap and a capacitor, is shown in *Figure 31.29*. The values of all the elements of the equivalent circuit can vary widely and are completely independent of each other. The breakdown voltage $V_b$ of the spark gap is determined by the distance between the two metallic boundaries of the fault which may be bridged by carbonised insulation in the case of a shunt fault or air spaced for an open circuit series fault. The value of the resistance is directly related to the degree of carbonisation of the insulation, whilst the value of the capacitance varies with the amount of moisture present. Based on the equivalent circuit shown in *Figure 31.29*, and the '5% reflection' limit for the pulse-echo method, cable faults can be conveniently classified as shown in *Table 31.12*.

The existence of the fault 'spark gap' has been well known for many years, and it has been extensively exploited

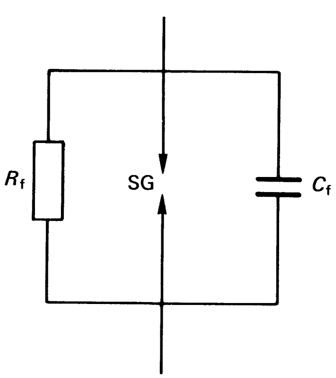



**Figure 31.29** Equivalent circuit of a cable fault. SG, spark gap

**Table 31.12** Classification of cable fault types

| *Fault type* | $R_f$ | *Spark gap* |
|---|---|---|
| Series | $\rightarrow\infty\Leftarrow$ | Breakdown under impulse or d.c. |
| Low resistance | $<10\times Z_0$ | Breakdown under impulse, provided $R_f$ is not too low |
| High resistance | $>10\times Z_0$ | Breakdown under impulse |
| Flashing | $\infty\Leftarrow$ | Breakdown under impulse or d.c. |
| Intermittent | $\infty\Leftarrow$ | Breakdown under prolonged d.c. |

in the acoustic method of pinpointing—based on applying a high-voltage impulse to the cable to create an audible flashover at the fault point.

### *31.8.4.1 Impulse-current method*

The impulse-current method of fault location also exploits the existence of the spark gap, but in this case it is the electrical transient created by the breakdown, rather than the acoustic transient, which is of interest. This method overcomes the limitation of the pulse-echo method since it is applicable to every type of fault. Faults are located by detecting and recording the current signals flowing in the impulse generator circuit using a high speed digital transient recorder.

Low resistance shunt faults and open circuit series faults are located by identifying the direct reflections of the applied impulse in much the same way as with a standard pulse-echo instrument—albeit with reversed reflection polarities. Most faults, however, are located from the transients created by the flashover of the spark gap at the fault point which always occurs some time after the arrival of the voltage impulse due to a phenomenon known as 'ionisation delay'.

*Figure 31.30(a)* shows how a typical current transient is created under the application of an impulse voltage from a capacitor discharge generator where the impulse reflects from the open circuit end producing 'voltage doubling' which (eventually) results in breakdown of the fault spark gap. An actual recorded transient, produced under the conditions illustrated in *Figure 31.30(a)*,is shown in *Figure 31.31*. The transient can sometimes be simplified by increasing the applied voltage sufficiently to reduce the ionisation delay so that the fault breaks down before the reflection from the open-circuit end arrives back at the fault point—this is shown in *Figure 31.30(b)*. On flashing or intermittent faults, an even simpler transient can be produced by closing the impulse generator contactor and raising the voltage on the cable and the generator capacitor at the same time until flashover occurs, thereby producing the transient shown in *Figure 31.30(c)*.

The impulse-current method has now been adopted by every cable fault location equipment manufacturer in Europe, and is in widespread use throughout the world. As a method, it can accommodate a far wider range of fault and cable types than the pulse-echo method and requires only a simple and inexpensive 'linear coupler' to connect the recording instrument to the impulse generator. In one respect, however, it is inferior to the pulse-echo method, since the transient phenomena are far more complex and

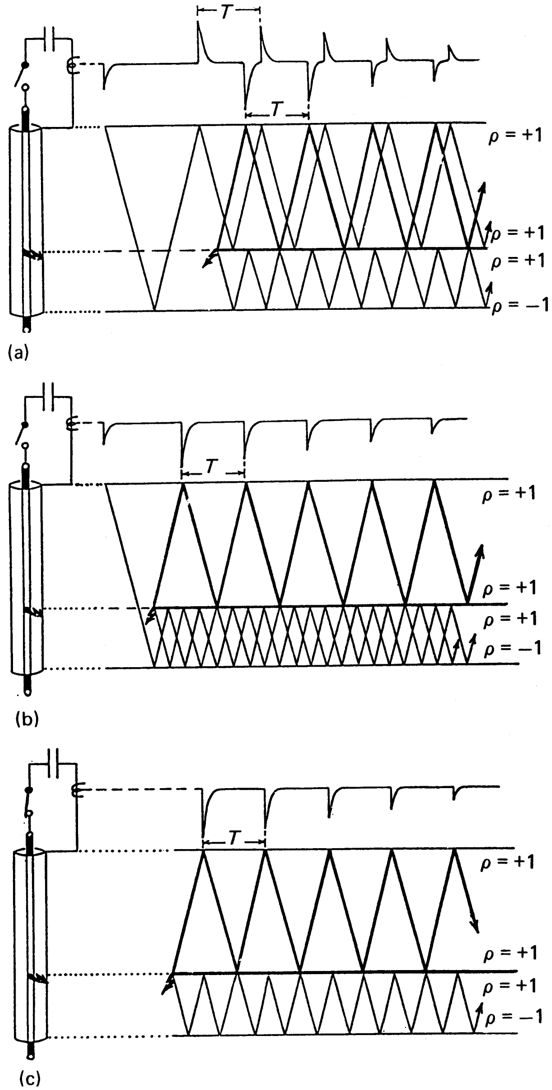



**Figure 31.30** Current transients created by the application of an impulse voltage from a charged capacitor: (a) voltage doubling induced breakdown; (b) fault breakdown before reflected pulse; (c) simpler transient produced by closing the generator contactor

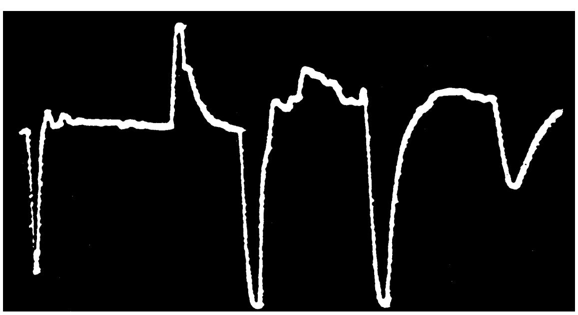


**Figure 31.31** Recorded transient corresponding to the condition shown in *Figure 31.30*(*a*)

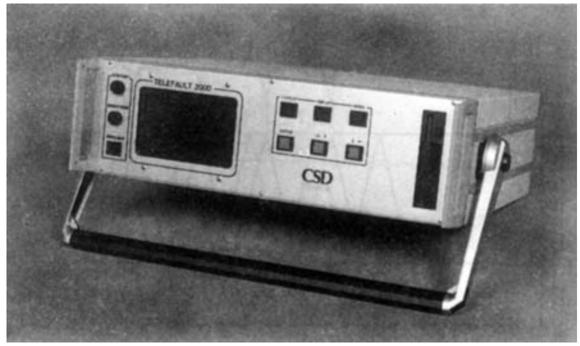



**Figure 31.32** Cable fault analyser

require more experience to interpret. One solution to this problem has been the introduction of computer-aided equipment such as the cable fault analyser shown in *Figure 31.32*.

### *31.8.4.2 Secondary-impulse method*

An alternative solution to the problem of the complexity of impulse current waveforms has been the development of the secondary-impulse method. Here the high voltage impulse generator is used to create a flashover of the fault spark gap and then, whilst current is still flowing through the ionised fault, a (second) low-voltage signal from a digital pulse echo instrument (*Figure 31.33*) is applied to the cable via a special high-voltage isolation and filter unit.

The secondary-impulse method cannot cope with as wide a range of cable and fault types as the impulse-current method, but interpretation of the waveforms is much simpler—a very important aspect when locating faults on the multi-branched networks frequently used in low-voltage distribution systems. A further complication of fault location on low voltage cables is that consumers' loads must often be assumed to be still connected to the cable, thereby precluding the application of any abnormal voltage


**Figure 31.33** Digital pulse echo instrument

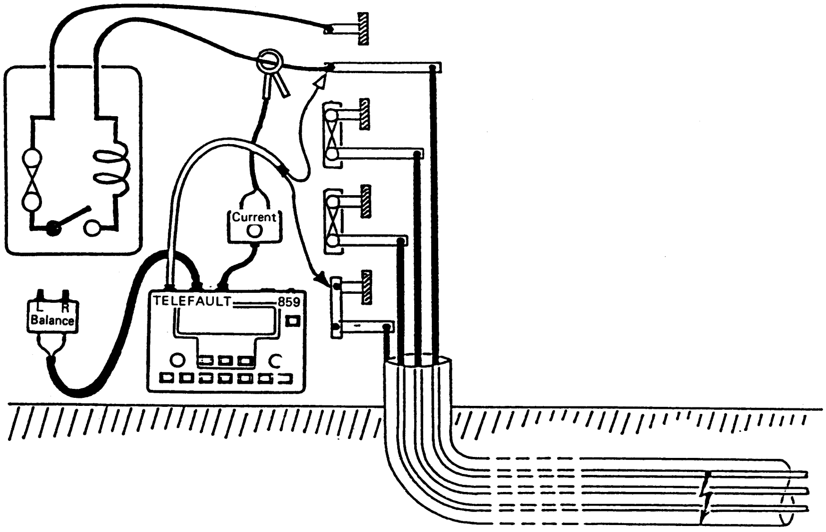



**Figure 31.34** Test lead connected to the cable termination

to 'condition' faults—many of which may only be 'active,' and therefore detectable, when the cable is energised.

Connecting a pulse-echo set to an energised low-voltage power cable requires careful attention to safety, e.g. the provision of suitably fused test leads, and to methods of reducing the complexity of the waveforms—particularly the unavoidable mismatch which exists where the test lead is connected to the cable termination (*Figure 31.34*). A second test lead is connected to a 'balancing network' which is adjusted to present a complex impedance as close as possible to that created by the stray inductance of the main test lead connections onto the cable tails in combination with the surge impedance of the cable under test. The signals produced on the test lead connected to the cable are subtracted from those produced on the test lead connected to the balancing network by a hybrid transformer. With an effective method of removing the outgoing pulse, and its associated 'ringing' within the test lead connections, it is possible to increase the width of transmitted pulse without any loss of short-range discrimination. Wide pulses propagate further than narrow pulses as they not only contain more energy but also the spectral distribution of the energy is shifted towards lower frequencies where the cable attenuation is also less.

When using the secondary-impulse method to locate unstable faults on low-voltage power cables, it is necessary that the pulse echo set injects its signal into the faulty cable after the fault arc has been established. During the arc the effective resistance of the fault will be almost zero, producing a reflection amplitude approaching 100%. Before the arc is struck, or after it has extinguished, there is no reflection from the fault, but the reflections from all the other points of mismatch along the cable remain the same. One method of detecting when the fault arc exists is to use a clip-on current transformer, as shown in *Figure 31.34*. For convenience, and safety, the cable should be re-energised via a switching device which must include a series 'wavetrap' to prevent the injected pulse from reaching the substation busbar, and thereby all the other cables connected to it. When the re-energising device closes, there is usually a delay before the fault responds and the cable termination triggers the pulse-echo set. As can be seen from *Figure 31.35*, the

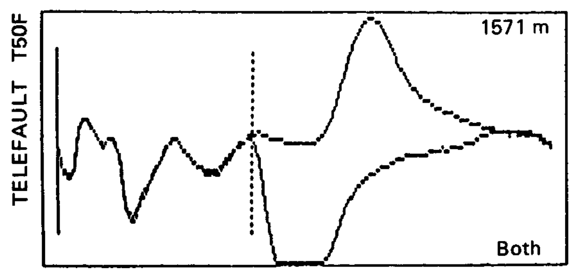



**Figure 31.35** Typical secondary impulse method result

operator's task is simply to compare the waveform recorded during the time when fault current is flowing with a waveform obtained when fault current is not flowing.

### 31.8.5 Pinpointing

Pinpointing is essential on direct buried cables if the location and repair of a fault is to be accomplished with a

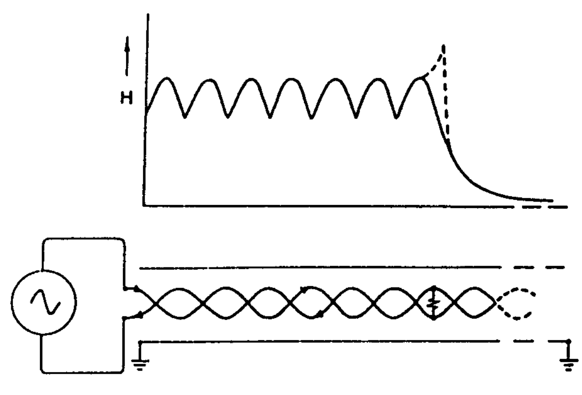



**Figure 31.36** The AF induction method

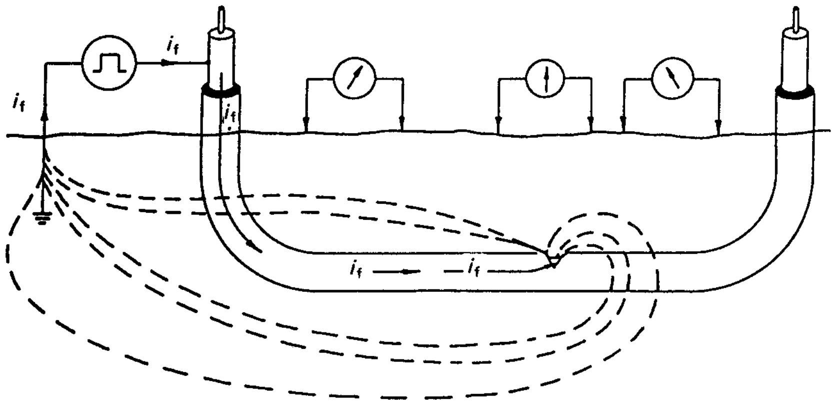


**Figure 31.37** Pool of potential method for serving fault location

single excavation. The majority of faults on high-voltage power cables are pinpointed by detecting the acoustic signal generated when the fault spark gap breaks down either from the application of a voltage impulse from a surge generator or a high direct voltage from a pressure test set. In some cases the acoustic signal can be detected without any special equipment but, in general, it is an advantage to use a 'ground microphone' and amplifier to pick up the mechanical shock wave. The importance of the pinpointing stage cannot be overemphasised, and anything which might jeopardise the generation of the acoustic signal, such as prolonged preconditioning, should be avoided.

Once a fault develops into a very low-resistance 'welded' condition, it will 'short out' the spark-gap, making it impossible to generate an acoustic signal. Multiple excavations may then be unavoidable unless the fault is between two conductors or both conductors are welded to the cable sheath. If a low-resistance path exists between one conductor and another, it is possible to pinpoint the fault using the 'AF induction' or 'Bimec' method (*Figure 31.36*). Between the signal generator and the fault the signal induced in the search coil exhibits a characteristic rise and fall owing to the lay of the cable cores, while beyond the fault the signal either disappears completely or, more likely, becomes constant. The lay effect is the only positive means of identifying that the received signal is emanating from the faulty cable and is not caused by re-radiation from other adjacent buried metallic services. The induction method of pinpointing can be applied, subject to the necessary fault conditions, without any prior knowledge of the cable route and without prelocating the fault. As the appropriate fault conditions for the 'induction' method occur relatively infrequently, the main use of the technique is in cable route tracing when an artificial core-to-core fault is applied at the far end of the cable.

Both the acoustic and the induction pinpointing techniques require a complete metallic path in which the signal currents can flow. An alternative approach, used in pinpointing serving faults on insulated sheath transmission cables, is to apply a signal between the metallic sheath and the general mass of ground so that a voltage gradient is established in the earth in the vicinity of the fault. The voltage gradient or pool of potential is detected using a sensitive voltmeter connected to a pair of probes and the fault position is pinpointed accurately (*Figure 31.37*). Probing over the complete length of a long transmission cable is time consuming, and many serving faults are sectionalised, using a magnetometer to trace the current flowing in the sheath up to the fault point.

When cables are accessible, being installed above ground or still on the drum prior to installation, it is often possible to pinpoint faults by exploiting their 'microphonic' characteristics. A high-gain amplifier, a.c. coupled to a faulty cable, will pick up the small 'noise' voltages generated when the fault is subjected to mechanical vibration. Partially broken conductors can be detected and pinpointed by circulating constant d.c. through the cable; insulation faults can be detected using a high-voltage source to pass a small polarising current through the fault resistance.

## Acknowledgements

The author is grateful to his past colleagues at BICC for their assistance in the preparation of this chapter, and in particular to Tony Arkell for his help in updating the section on transmission cables.

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