9

Cables, Wires and Cable Installation Practices

Cables provide a highly reliable and compact method of transmitting power from its source to its consumer. Cables are installed in open air on racks or ladders, in the ground, or underwater as in the case of submarine cables. Power at all the voltages normally encountered in the oil industry i.e., less than 100 V and up to 33 kV, can be transmitted efficiently by single and multi-core cables.

Over the last 30 years there has been a progressive improvement in the materials used in the construction of cables, especially in the non-metallic materials. This has been due to several necessary requirements e.g.,

a) To maximise the conductor temperature and hence the power transmitted.
b) To provide high resistance to mechanical wear and tear, both during the laying of the cables, and in their on-going use when they may be disturbed in the future.
c) To withstand the effects of chemical attack from their environment e.g., when laid in polluted ground.
d) To withstand the damaging effects of steady state and transient overvoltages.
e) To withstand the impact of heat from the environment when exposed to fire and high radiant temperatures.
f) To withstand freezing temperatures and embrittlement.
g) To be resistant to ultraviolet light when exposed to bright sunlight.

Not all of the above requirements are needed for a particular plant. The specification of the cable and its materials should take account of the changes in its environment throughout a one-year cycle. The conductor current rating should be based on the worst-case conditions if the cable is to be fully utilised and expected to give a long life time of service.

9.1 ELECTRICALLY CONDUCTING MATERIALS USED IN THE CONSTRUCTION OF CABLES

References 1 and 2 give detailed information about the metallic materials used in cables. Some of the more commonly used data are presented herein.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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9.1.1 Copper and Aluminium

Copper and aluminium are used in their highly refined form for the power conductors of cables. The total impurities contained in high conductivity copper should be less than 0.1% and for aluminium less than 0.5%. The measured conductivity of these metals will have its highest value when they are annealed. Hard drawn conductors will have conductivity that is several percentage points lower than the annealed value. Note that castings made of these materials will generally have conductivity slightly lower than their rolled and drawn forms.

The presence of oxygen in the form of oxides is the most common impurity. It slightly reduces the conductivity, malleability and ductility of the metal.

Table 9.1 shows some of the electrical and physical properties of these two metals. For use in most power cable applications these metals are formed into annealed conductors.

Copper is generally the preferred material for cable conductors used in the oil industry. Aluminium is seldom chosen for conductors. It is sometimes used for the armouring of single-core cables that carry AC, or DC, if a substantial AC ripple is present e.g., DC, motors fed from a thyristor controlled power source.

9.1.2 Tin

Tin metal is occasionally specified to provide a thin layer on the outer surface of copper conductors. Historically this tin layer gave protection against corrosion of the copper surface from rubber insulation, which contained substances such as sulphur. Large proportions of sulphur were added during the vulcanising process to increase the hardness and tensile strength of the rubber. The modern use of ‘plastic’ insulation instead of rubber compounds means that the layer of tin is no longer required in most applications. Tin is beneficial in situations where soldered lugs are used to terminate the copper conductors, although modern methods of crimping lugs onto their conductors has tended to make the use of tin unnecessary.

Table 9.1. Electrical and physical properties of cable conductors

Property	Copper		Aluminum	
	Annealed	Hard drawn	Annealed	Hard drawn
Resistivity at 20°C (ohm-m × 10^{-8})	1.72	1.78 to 1.80	2.80	2.83
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.00393	0.00393	0.00403	0.00403
Coefficient of linear expansion per unit per °C	17.0×10^{-6}	17.0×10^{-6}	23.0×10^{-6}	23.0×10^{-6}
Approx. 0.1% proof stress, tons/sq inch	4.0	20.0	2.0	10.0
Thermal conductivity W/mK	384.0	384.0	209.4	209.4
Density kg/m^3	8.89×10^{-3}	8.89×10^{-3}	2.71×10^{-3}	2.71×10^{-3}
Specific heat kJ/kg K	0.394	0.394	0.904	0.904
Modulus of elasticity lbs/sq inch	–	18.0	9.6	10.0

Tin is also used as a coating for copper armour wires or armour braiding where rubber compounds are used in the inner or outer sheathing.

9.1.3 Phosphor Bronze

Phosphor bronze is an alloy of mainly copper, 5 to 10% tin and approximately 0.1% phosphorous. The alloy has superior mechanical strength when compared with copper. It is also very resistant to corrosion, particularly in the presence of water.

Phosphor bronze is used as wire in the armouring of cables to provide moderate protection against mechanical damage. It is formed into a tightly woven braid to form a non-magnetic, highly conductive, armoring and electromagnetic screen.

It is a practical alternative to tinned copper braid in many applications where steel wire should not be used.

The alloy is also used in the form of a thin tape for the purpose of repelling insects e.g., ants, termites and marine teredo worms. The tapes are placed underneath the main armouring and on top of the inner sheathing. Table 9.2 shows some of the electrical and physical properties of phosphor bronze.

9.1.4 Galvanised Steel

Galvanised steel is used for the cable armour where a high degree of mechanical protection is required, and where high pulling forces are experienced during the installation of the cable, especially in the laying of submarine cables. The armour wires are formed into a helical cage to give the highest protection or as a braid when flexibility is required during the installation and a lesser level of protection can be accepted.

Mild steel is used for the armouring of cables laid on land. For submarine cables the material can be specified as carbon steel, which has a higher tensile strength.

The depth of the galvanising is specified in the international standards. The cross-sectional area of each armour wire (in a helix and not in a braid) varies from typically 0.9 mm for small power and control cables e.g. 1.5 and 2.5 mm^2 conductors, to 2.5 mm for 400 mm^2 low voltage high

Table 9.2. Electrical and physical properties of phosphor bronze

Property	Phosphor bronze
Resistivity at 20°C ohm-m	9.50×10^{-8}
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	Similar to copper
Coefficient of linear expansion per unit per °C	18.0×10^{-6}
Thermal conductivity W/mK	75.0
Density kg/m^3	8.92×10^{-3}

Table 9.3. Electrical and physical properties of galvanised steel wire

Property	Mild steel	Carbon steel
Resistivity at 20°C (ohm-m × 10^{-8})	13.2	15.9
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.0045	0.0045
Coefficient of linear expansion per unit per °C × 10^{-6}	12.2	12.2
Thermal conductivity W/mK	59.4	51.9
Density kg/m^3	7.86×10^{-3}	7.86×10^{-3}

power cables. For submarine cables the wire diameter can be up to 6.0 mm and for some deep ocean applications two layers of armour wires are used. Table 9.3 shows some of the electrical and physical properties of mild steel and carbon steel, see also volume 1 of Reference 1.

Steel wire armour as opposed to steel wire braid has lower electrical impedance for a given length of cable. This is an important benefit in networks that are solidly earthed at their power source. Some special applications that require as low an impedance as is practical to achieve in the cable have some of the armour wires replaced by copper wires. Hence the parallel circuit consisting of the steel and copper wires has a lower total impedance than the steel wires on their own. The impedance of the armouring, with or without the copper wires, is predominantly resistive and so the inductive reactance at the power frequency can therefore be ignored.

9.1.5 Lead

Metallic lead is occasionally used as an extruded sheath to provide protection against chemical corrosion where it is necessary to bury cables in polluted or aggressive soils. Examples of these are found in chemical plants, refineries, storage tank farms and areas that have high water tables.

The lead is often alloyed with small amounts of tin and antimony to improve its ability to withstand mechanical fatigue, such as fatigue experienced in long distance transportation to site. Lead sheathed cables should not be installed where regular cyclic physical movement will be experienced. Table 9.4 shows some of the electrical properties of metallic lead used for sheathing cables.

Table 9.4. Electrical and physical properties of metallic lead sheathing

Property	Lead sheathing
Resistivity at 20°C (ohm-m × 10^{-8})	20.6
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.00336
Coefficient of linear expansion per unit per °C × 10^{-6}	29.0
Thermal conductivity W/mK	34.3
Density kg/m^3	11.3×10^{-3}

9.2 ELECTRICALLY NON-CONDUCTING MATERIALS USED IN THE CONSTRUCTION OF CABLES

9.2.1 Definition of Basic Terminology

Some terms are used loosely in various engineering disciplines e.g. plastic, rubber. However, they have particular connotations in electrical engineering, especially in the field of cable manufacturing.

9.2.1.1 Rubber

Rubber is obtained in two basic forms, natural rubber and synthetic rubber. Natural rubber is the sap of the particular species of trees called *Hevea brasiliensis*, see References 3 and 4, which is sticky when at tropical temperature, reasonably hard at low temperatures and oxidises when exposed to the atmosphere. Natural rubber is a naturally occurring compound of carbon and hydrogen, and is of little use as a basic material. It is therefore mixed with other chemical compounds, filler materials such as carbon black and then vulcanised to produce 'vulcanised rubber' or more generally called simply 'rubber'. The vulcanising process requires sulphur to be added and the application of heat and pressure. The molecules of rubber are formed in long chains. Individual chains are not bonded to adjacent chains; hence the chains can slide alongside each other with little resistance to movement. This gives processed rubber the ability to recover without permanent deformation. Natural rubber does not necessarily recover to its original shape, since its stability depends on its ambient temperature. Vulcanising or 'curing' causes the sulphur to cross-bond adjacent chains, which stiffens the material thereby making it more useful. By increasing the sulphur content or extending the vulcanising time, or a combination of both functions, the rubber becomes progressively harder with higher tensile strength. Increasing additives such as carbon black can reduce the dielectric strength, thereby making the rubber a poorer insulator. Carbon by itself is of course a conductor.

Synthetic rubbers are also composed of carbon and hydrogen molecules, but they are combined by manufacturing processes. A synthetic rubber, which closely resembles natural rubber, is polyisoprene, which has the same chemical composition.

Reference 5 also describes many types of insulating materials.

9.2.1.2 Elastomer

The term 'elastomer' is the most appropriate technical term for rubber, and is generally applied to synthetic rubbers, e.g. ethylene propylene rubber. It derives its name from the well-known elastic property of rubber.

However some non-rubber compounds are also called elastomers if they exhibit a non-deforming elastic property similar to rubber at room temperature, even if the compound is relatively hard. The two main groups of non-rubber elastomers are thermoplastics, e.g., polyvinyl chloride, polypropylene and thermosets, e.g., ethylene propylene rubber, cross-linked polyethylene. These two groups are also covered by the term 'plastic'.

9.2.1.3 Polymer

A polymeric compound contains several different molecules e.g., carbon, hydrogen, oxygen, silicon, chlorine, sulphur. These molecules combine in small groups usually with a carbon molecule in the middle. The group is repeated linearly many times in the form of a chain.

Polymers can be natural or synthetic materials, which include but are not limited to rubbers, elastomers and plastics.

When two polymers are combined the resulting compound is called a copolymer.

9.2.1.4 Plastic

This is a very widely used term to describe typical household, automobile and industrial components that are moulded from man-made chemical compounds. In the electrical engineering field the term has a more specific definition, especially where insulation materials are being described.

Plastic materials are those that are formed from synthetic compounds e.g., polymers or natural compounds that have previously been modified, for example hydrocarbons refined from crude oil, natural gas or derivatives of ethane, methane and naphtha. By definition the manufacturing of a plastic component should include a viscous flowing process that usually requires heat and pressure, for example extrusion or injection moulding.

Two important groups of insulating and sheathing materials that also come within the definition of plastic are the thermoplastic and thermoset polymeric compounds.

9.2.1.5 Resin

The preferred term for synthetic polymers is resin polymers or simply resins. Hence the two main groups are thermoplastic resins and thermoset resins.

9.2.1.6 Thermoplastic resins

Thermoplastic resins (elastomers and polymers) are plastics that retain their flexibility and chemical composition when heat is applied and removed. The applied heat is only sufficient to steadily melt the resin.

The most widely used thermoplastic resins used in cables are polyvinyl chloride (in various forms), polyethylene (in several forms), polypropylene and polytetrafluoroethylene.

In general these resins in their basic forms do not have sufficiently good properties to make them attractive as materials for cables. The necessary properties for insulation are usually different from those required for sheathing and bedding, even though the same basic resin may be used for these purposes. Other substances are polymerised or mixed with the basic resin during its manufacture. These substances are used to improve or provide:-

- High dielectric strength.
- Low dielectric loss angle.
- High insulation resistivity.

- High melting temperature.
- High tensile strength and resistance to mechanical impact.
- Good flexibility.
- Good handling properties for installation and termination.
- Good resistance to ultraviolet light.
- Good dimensional stability.
- Long service life.
- Low water absorption.
- Low emission of smoke and acid gases during fire situations.
- Low flammability.
- Low solubility in mineral oils (drilling mud), acids, alkalis, organic compounds and solvents.
- Good extrusion performance.
- High resistance to ozone.

Not all of the above can be optimised for a particular type of cable. Some sacrifices need to be made when a particular property or overall performance is to be obtained. For example good performance during a fire inside a building where people are present and smoke and gas must be minimised.

9.2.1.7 Thermoset resins

Thermoset resins do not melt when heated, and are irreversibly changed after the heat is removed. They are produced from a two-stage chemical process. The second stage is called ‘cross-linking’, and is similar to vulcanising. The process requires heat, pressure, catalysts, or irradiation, or a combination of these additives to produce the desired material.

Thermoplastic resins can be further processed by ‘cross-linking’ techniques to produce thermosets.

The thermoset elastomers most frequently used for cables are ethylene propylene rubber and cross-linked polyethylene.

Additives are used in a similar manner to produce the same improvements as listed in subsection 9.2.1.6.

Thermosets are widely used as sheet type insulating materials, adhesives, jointing compounds for cables and solid mouldings such as post insulators.

See Table 9.5 for electrical and physical properties of thermoset resins.

9.2.1.8 Electrical and physical properties of thermoplastic and thermoset resins

There are many thermoplastic and thermoset resins but only a few developed for use in manufacturing cables. Table 9.5 summarises the main properties of the more frequently used resins.

Table 9.5. Electrical and physical properties of thermoplastic and thermoset resins as insulators

Property	PVC	EPR	XLPE	PP	PE	PCP	CSP	PTFE
Dielectric relative permittivity at 50 Hz	4 to 7	3.5	2.2 to 5.0	2.25	2.35	—	10	2.0
Dielectric strength used for continuous service MVrms/m 15 kV × 25 mm^2 single core	3.5	3.8	3.8	—	4.5	—	—	—
Volume resistivity at 20°C ohm-m × 10^9	10^2 to 10^4	2×10^4	10^4 to 6×10^4	10^7	10^7	—	30	10^7
Loss angle tan δ at 50 Hz	0.1	0.005	0.0005 max	0.0005	0.0006	—	0.06	0.003
Temperature in °C at which distortion or softening occurs	120	180	130	120	90 to 100	—	160	300
Density kg/m^3		1.2 to 1.5	0.92		0.95 to 0.97	—	—	—
Tensile strength kg/cm^2 or N/mm^2	12.0 to 14.0	4 to 8	12 to 18	37	37	10	10 to 20	22
Water absorption Note a)	3	9	9	9	9	3	4	—
Conductor maximum continuous temperature °C	70	85 to 90	90	80	70 to 75	75	85	260
Minimum environmental temperature °C	Zero Note b)	−40	−50	−10	−50	−10	−30	—
Thermal resistivity Km/W	5.5	4.5	3.5		3.5	5.5	—	—
Max conductor temp °C for 5 sec short circuit IEC 502	160	250	250	150	130	—	200	300
Resistance to heat Note a)	5	9	5	5	1	9	5	9
Flame retardance Note a)	9	9	1	1	1	8	9	9
Resistance to acids and alkalis Note a)	5	(3)	9	9	9	8	5	9
Resistance to mineral oils Note a)	5	1	1	9	1	7	7	9
Resistance to weather Note a)	5	9	5	7	1	—	7	9
Resistance to abrasion Note a)	7	5	3	9	7	7	7	3
Resistance to ozone Note a)	9	7	5	9	9	—	9	5
Emission of acid gas Note a)	9	1	—	—	—	—	4	—
Low oxygen index %	25 to 35	20 to 40	18	18	18	40	30 to 40	95

Note a) 1 denotes poor performance.
4 denotes an average performance.
9 denotes excellent performance.
Note b) For special compounds the minimum temperature can be as low as 30°C.

9.3 COMPOSITION OF POWER AND CONTROL CABLES

The composition of a power cable is dependent upon the rated voltage at which it will be expected to operate continuously without breakdown.

IEC60038 gives the standard voltages for electrical equipment. However, for cables the AC rms voltages are defined for example in IEC60502, in terms of their line-to-earth and line-to-line values.

See Tables 9.6 and 9.7. Table 9.7 is derived from BS6622.

Note that occasionally u_o is quoted as the value obtained by dividing u by 1.732 and rounding to one decimal place. u_o is derived from IEC60038.

IEC60502 covers the construction and factory testing of polymeric solid insulated cables in the voltage range 1000 to 30,000 volts. IEC60183 gives guidance on the selection of cables for high voltage systems. BS6622 is similar to IEC60502 but is restricted to cables operating at voltages between 6600 and 33,000 volts, with screened XLPE or EPR insulation. BS5467 covers unscreened thermosetting insulated cables that operate between 1000 and 3300 volts; hence the standard is reasonably applicable to low voltage systems e.g. 380, 400, 415, 440, 600 and 750 volts (line to

Table 9.6. IEC standard rated voltages of power cables

Line-to-earth voltage u_o	Line-to-line voltage u	Maximum value of the highest system line-to-line voltage u_m
600	1,000	—
1,800	3,000	3,600
3,600	6,000	7,200
6,000	10,000	12,000
8,700	15,000	17,500
12,000	20,000	24,000
18,000	30,000	36,000

Table 9.7. UK standard rated voltages of power cables

Line-to-earth voltage u_o	Line-to-line voltage u	Maximum value of the highest system line-to-line voltage u_m^* Note a)
600	1,000	—
3,800	6,600	(8,000)
6,350	11,000	(13,200)
8,700	15,000	(17,500)
12,700	22,000	(26,400)
19,000	33,000	(39,600)

Note a) This column is not shown in BS6622 but is included to be consistent with Table 9.6 where a 20% upward margin is added to u to obtain u_m before rounding is applied.

Note b) A method of rounding numbers upwards or downwards is given in Appendix B of IEC60502.

line). BS5468 is similar to BS5467 but only applies to XLPE insulated cables in the same voltage range. BS6746 specifies the requirements of PVC for insulation and sheathing of cables. BS6469 specifies factory-testing methods for insulation and sheathing compounds. IEC60227 and 60245 give the manufacturing and factory testing requirements for PVC and EPR in insulated cables respectively, for voltages up to 1000 volts.

9.3.1 Compositional Notation

A commonly used notation for indicating the main components within a power or control cable uses abbreviations, listed from left to right, that represent the core and its surrounding components, e.g. STR CU/EPR/CSP/GSWB/CSP. This list denotes the following:-

- Conductor is stranded copper, STR CU.
- Insulation is ethylene propylene rubber, EPR.
- Inner sheath is chlorosulphonated polyethylene, CSP
- Armouring is galvanised steel wire braid, GSWB
- Outer sheath is chlorosulphonated polyethylene, CSP

See Appendix A for abbreviations used in specifying cables.

There may be additional materials within the cable such as semiconductor screens for the core-insulation interface; jute, hessian or bitumen for giving extra water resistance to the wire armouring; bronze tape for repelling insects.

Some of the international standards that are frequently used in the specification of cables in the oil industry are, BS801, BS2627, BS4066, BS5308, BS5467, BS5468, BS6234, BS6360, BS6387, BS6469, BS6622, BS6724, BS6883, BS7622, BS7629, BS7655, BS7835, BSEN10257, IEC60227, IEC60245, IEC60331, IEC60332, IEC60502, IEC61034, see Table 9.8 which summarises where the standards are particularly suited to components within a cable. Appendix B gives the titles of these standards.

It can be seen from the above examples that many standards can be used. In fact a particular cable may have its various components specified from different standards. Some standards attempt to cover all aspects of cables that are suitable for certain situations or industries e.g. BS6883 for marine and offshore structures; BS5467, BS6622, IEC60502 for land based plants. Care should be taken when preparing a purchasing specification for a particular project. It is necessary to avoid requirements that may be conflicting between the international specifications that are quoted in the project specification. Such conflicting requirements could lead to a cable that is unnecessarily difficult to manufacture and expensive to purchase or replace. See also Chapter 19.

9.3.2 Conductor

The conductors are usually copper or aluminium. Aluminium is seldom used in the oil industry because it work hardens during installation, has higher losses, has high volt-drop at rated current and requires special attention during termination.

Table 9.8. International standards that are commonly applied to cables

Conductors	Insulation	Screening of conductors and insulation	Inner and outer sheathing	Armouring wires and braids	Fire resistance flame, retardance and smoke emission
BS6360	BS6234	BS6622	BS801 Note b)	BS2627	BS4066 Pts 1, 2, 3
IEC60228	BS6899	IEC60502	BS6724	BS2873	BS6387
VDE0295	BS7655		BS7655	BS4109	BS7622
	IEC60502		BSEN61067	BSEN12166	BSEN61067
			IEC60502	BSEN102571	IEC60331
				IEC60502	IEC60332
					IEC61034

Note a) The table is a summary of standards that relate to particular components of power, control and instrumentation cables.
Note b) Lead alloy.

Copper and aluminium conductors are described in IEC60228 (BS6360), which divides them into a number of classes. Class 1 applies to single stranded conductors, but these are only used in sizes normally less than 1.5 mm^2, and even then finely stranded conductors are preferred. For sizes equal to or greater than 1.5 mm^2 Class 2 is used, and the lowest number of strands used is 7 for sizes up to 16 mm^2 for marine and offshore installations and up to 35 mm^2 for onshore installations. Marine and offshore installations usually require the cable to be more flexible for handling during laying and smaller bending radii during termination. Higher flexibility can be obtained by finer stranding as given by Class 5 of the standard is preferred with a maximum of 400 mm^2 for single core cables due to difficulties in laying larger sizes.

For LV cables having a cross-sectional area above approximately 25 mm^2 the conductors would usually be formed into sector shaped conductors.

In general cable sizes above 400 mm^2 are rarely used in the oil industry.

Note that BS6622 permits the use of sector shaped conductors above certain core sizes for high voltage cables e.g. up to 6600 volts the smallest section is 70 mm^2 and for use up to 11,000 volts the smallest is 95 mm^2.

The stranding of wires in the core can be achieved efficiently in three configurations of the wires at the centre of the core. The first configuration is the simplest, in which one wire is surrounded by the first layer of six wires. Hence the lowest number of strands is seven. The second configuration begins with three wires in a triangle. The third begins with four wires in a square. The first configuration is preferred for Class 2 cores.

The total number of wires (N_c) in a Class 2 stranded core is given by:-

$$N_c = 1 + 3n(1 + n)$$

Where n is the number of layers over the central wire. N_c has the sequence 7, 19, 37, 61, 127, 169, 217 etc.

The outside diameter (d_c) of the core is given by:-

$$d_c = (1 + 2n)d$$

Where d is the diameter of each circular wire.

Table 9.9 shows the calculated cross-sectional area, equivalent core diameter and overall core diameter of a selection of stranded circular conductors. The table applies to cores that are not compacted or tin coated, i.e. before compaction is applied. The preferred sizes are shown in bold type.

Table 9.9. Stranding of circular section cable cores

Dia. of each wire (mm)	No. of wires in core	Nominal CSA (mm^2)	Actual CSA (mm^2)	pu error in CSA	Equivalent dia. of core (mm)	Overall dia. of core mm
0.522	7	**1.50**	1.498		1.381	2.044
0.522	19	4.00	4.066	0.01654	2.275	3.088
0.672	7	**2.50**	2.483		1.778	2.344
0.853	7	**4.00**	4.000		2.257	2.706
0.853	61	35.00	34.859	0.00402	6.662	7.824
0.853	169	95.00	96.577	0.01660	11.089	12.942
1.042	7	**6.00**	5.969		2.757	3.084
1.042	19	16.00	16.202	0.01265	4.542	5.168
1.042	217	185.00	185.048	0.00026	15.350	17.672
1.349	7	**10.00**	10.005		3.569	3.698
1.349	19	**25.0**	27.156	0.08624	5.880	6.396
1.349	127	185.00	181.517	0.01883	15.202	17.188
1.349	169	240.00	241.546	0.00644	17.537	19.886
1.530	19	**35.0**	34.932	0.00194	6.669	7.120
1.695	7	**16.00**	15.795		4.485	4.390
1.695	217	500.00	489.654	0.02069	24.696	28.120
1.830	19	**50.00**	49.974		7.977	8.320
1.830	37	**95.00**	97.318	0.02440	11.131	11.980
1.830	91	240.00	239.350	0.00271	17.457	19.300
2.310	37	**120.00**	119.870		12.354	13.186
2.031	91	300.00	294.816	0.01728	19.375	21.310
2.149	7	25.00	25.390	0.01560	5.686	5.298
2.149	19	**70.00**	68.915		9.367	9.596
2.149	217	800.00	787.086	0.01614	31.657	35.384
2.255	37	**150.00**	147.769		13.717	14.530
2.255	61	**240.00**	243.620		17.612	19.040
2.255	127	500.00	507.209	0.01442	25.413	28.0602
2.527	7	35.00	35.107		6.686	6.054
2.527	19	95.00	95.291		11.015	11.108
2.527	37	**185.00**	185.568		15.371	16.162
2.527	61	**300.00**	305.936		19.736	21.216
2.537	127	**630.00**	636.948		28.478	31.324
2.861	19	120.00	122.146	0.01788	12.471	12.444
2.861	37	240.00	237.863	0.00890	17.403	18.166
2.861	61	**400.00**	392.153		22.345	23.888

Table 9.10. Equivalence between metric and American cable sizes

Actual CSA (mm^2)	Nominal CSA (mm^2)	Circular mils	American wire gauge
0.82	(0.75)	1,624	18
0.97	—	1,910	—
—	1.0	—	—
1.29	—	2,546	—
1.31	(1.5)	2,583	16
—	1.5	—	—
1.94	—	3,820	—
2.08	(2.5)	4,110	14
—	2.5	—	—
2.90	—	5,730	—
3.31	(4.0)	6,530	12
—	4.0	—	—
4.51	—	8,910	—
5.26	(6.0)	10,380	10
—	6.0	—	—
6.45	—	12,730	—
8.37	(10)	16,510	8
9.35	—	18,460	—
—	10	—	—
13.30	(16)	26,250	6
14.51	—	28,650	—
—	16	—	—
19.35	—	38,200	—
21.15	(25)	41,740	4
—	25	—	—
25.80	—	50,930	—
26.67	—	52,630	3
33.63	(35)	66,370	2
—	35	—	—
38.70	—	76,390	—
42.41	—	83,690	1
48.37	—	95,490	—
—	50	—	—
53.48	(50)	105,500	0
64.50	—	127,300	—
67.43	(70)	133,100	00
—	70	—	—
77.40	—	152,800	—
85.03	(95)	167,800	000
—	95	—	—
96.75	—	191,000	—
107.2	—	211,600	0000
—	120	—	—
127.0	(120)	250,000	250 MCM
129.0	—	255,000	—

(*continued overleaf*)

Table 9.10. (*continued*)

Actual CSA (mm^2)	Nominal CSA (mm^2)	Circular mils	American wire gauge
—	150	—	—
152.0	(150)	300,000	300 MCM
161.0	—	318,000	—
177.0	(185)	350,000	350 MCM
—	185	—	—
194.0	—	382,000	—
203.0	—	400,000	400 MCM
—	240	—	—
253.0	(240)	500,000	500 MCM
258.0	—	509,000	—
—	300	—	—
304.0	(300)	600,000	600 MCM

It can be seen that the preferred choices give an accuracy of better than 2.1% in the calculated cross-sectional area if the wire diameter is as shown. Different combinations of the wire diameter and the number of layers can in several cases give almost the same cross-sectional areas. The preferred choices are the most economical in terms of stocking wire sizes in a factory. The largest wire diameter is usually 3.199 mm.

Where the insulation is a rubber-based elastomer it is common practice to tin coat the copper wires, to protect against chemical attack from the elastomer.

9.3.3 Conductor Semiconducting Screen

A semiconducting screen of tape or extruded compound is normally specified for cables that have a rated line voltage of 3000 V and above. IEC60502 applies to solid extrusions of insulation, and requires PE and XLPE compounds to have the screen for 3000 V and above. Likewise the standard requires the screen for 6000 V and above for PVC and EPR compounds. BS6622 calls for screens for all cables for voltages between 6600 and 33,000 volts.

The purpose of the screen is to reduce the voltage gradient (electric stress) at the surface of the conductor where it interfaces with the insulation. Otherwise irregularities in the interface could initiate failure of the insulation in the longer term.

9.3.4 Insulation

The most frequently used insulating compounds are PVC, XLPE and EPR. For most onshore applications PVC and XLPE are preferred because of economic reasons, and XLPE is becoming more popular than PVC. Marine and offshore applications tend to prefer XLPE and EPR. EPR is usually more expensive than XLPE. Both compounds have the advantage that they permit the conductors to operate at higher temperatures (85 to 90°C) than those of PVC (70°C). PVC compounds can be specially manufactured to tolerate conductor temperatures up to 85°C. Silicon rubber can be specified if high conductor temperatures (up to 180°C), and for even higher temperatures (up to 260°C) the compound PTFE can be used. These compounds would tend to be used for special situations such as control circuits and emergency power circuits where overloading could be allowed for a limited period of time, or if exceptionally high surrounding temperatures need to be tolerated e.g. near engines, hot vessels, hot pipes, boilers.

Note that when high voltages are used in marine and offshore installations it is usually necessary to adopt the international standards that apply to onshore oil industry installations.

See sub-section 9.5 for the choice of insulations materials needed for fire survival services.

9.3.5 Insulation Semiconductor Screen

The need for a semiconductor screen is very similar to that for a conductor screen, as described in sub-section 9.3.3. IEC60502 and BS6622 specify the same applicable voltage limits for screens with different compounds.

The insulation screen is important in three-core cables because it prevents the inter-core electric stressing that would occur if the screen were not present. It maintains a radial stress pattern in each core, which is independent of the other cores.

However, the application of the screen itself is slightly different. It is carried out in two parts. The first part is a non-metallic semiconducting tape or polymeric cross-linked compound that is applied over the whole surface of the insulation. This material should be capable of being removed from the insulation without damaging its surface. This requirement is necessary for terminating and jointing the cable during its installation. The second part requires a metallic tape or braid, usually copper or aluminium, to be applied over the non-metallic part to make full contact with it. The metallic part is connected to an external circuit during termination and installation of the cable. The connection is usually only made at one end of the cable so that induced circulating currents do not occur and damage the screen itself.

9.3.6 Inner Sheath

An inner sheath, usually made of extruded polymer, is used to cover the insulation screen, and to fill in the interstices between the cores of a multi-core cable. It is important to fill the interstitial spaces for two reasons. Firstly to ensure good circularity and dimensional accuracy of the finished cable, and secondly to prevent an internal passage within the cable along which flammable gases could travel. The transmission of such gases along a cable must be eliminated by design and construction for cables that are used in hazardous areas.

The sheathing material need not necessarily be the same as the insulation material. It is usually more economical to use a different material such as PE, PVC, CSP, EVA, for general applications and HOFR or ZH for situations where fire resistance and smoke emission must be considered.

The specifications of sheathing materials can be found, for example, in BS7655, BS6724 and IEC60502.

9.3.7 Lead Sheathing

Lead is used as a sheathing material for protecting the cable from chemical attack whilst it is buried directly in hostile ground conditions, e.g. in chemical and refinery plants.

9.3.8 Armouring

Most cables used in oil industry plants are installed for at least part of their length in exposed machinery areas or on trays or ladders. This exposure can permit mechanical damage to occur to the cables e.g. objects falling on to them or impacting into them. Even buried cables are at risk from excavation mistakes, e.g. digging machines.

In order to minimise the possible damage to a cable, and to provide a safe path for electrical earth return currents, it is necessary to specify a metallic armouring. There are several types of metallic armouring used in the oil industry, i.e. galvanised steel wires (GSWA), aluminium wires (AWA), tinned copper wire braid (TCUWB), phosphor bronze wire braid (PBWB).

Various standards specify the diameter, number and design of the wires and braids, e.g. BSEN10257 part 1 and IEC60502 for steel armouring, BS2873 for phosphor bronze and BS4109 for copper braid armouring. GSWA and PBWB are the most commonly used armouring. Armouring in the form of metallic tape is not normally used for oil industry installations.

9.3.9 Outer Sheath

Oil industry cables are usually finished with an extruded heavy-duty polymeric sheath such as PVC, PE or CSP. For situations where resistance to heat, oil and flames is necessary it is the practice to use special elastomerics that are identified as HOFR types. These compounds include EVA, EMA, CPE, and EPR together with suitable fillers that are used during their curing processes. BS7655 details the requirements for HOFR cables, and IEC60332 for their fire retardance.

9.4 CURRENT RATINGS OF POWER CABLES

The choice of cross-sectional area of cable conductors depends upon several factors, the main factors being:-

- Continuous load current.
- Continuous rated current of cable.
- Volt-drop developed across the cable under steady state and transient conditions.
- Dissipation of heat from the conductors during short-circuit conditions.
- Earth loop impedance.

9.4.1 Continuous Load Current

Cables are used to supply power to individual loads such as motors, and to groups of loads as in the case of a feeder to a switchboard. Selecting the load current for the first case is reasonably simple. Most individual loads have a manufacturer's nameplate that gives details such as rated power, voltage, current and power factor. If the current is not given on the plate then it should be calculated from the output power, power factor and efficiency of the load.

Determining the continuous current for a feeder to a switchboard or to its incoming transformer is a little more complicated. All the loads in a group need to be identified into continuous loads, intermittent loads and de-energised standby loads.

The individual loads may be known to have diversity from their nameplate values. If this is the case then the diversity should be included in the estimation of the consumed power. The total load is estimated by adding together the continuous loads, a nominal proportion of the intermittent loads e.g. 30 to 50%, and a small proportion of the standby loads e.g. zero to 10%. The summation should be carried out in two parts, the first part for the active power and the second part for the reactive power. This is necessary because not all the loads in a group have the same power factor. Once these two totals are estimated the total volt-amperes can be found and then the current.

A feeder to a switchboard should be sized on the basis of the known loads at the plant design stage plus a contingency for future expansions. Oil industry plants tend to be upgraded and expanded once or even several times during their lifetime. Hence a contingency of typically 15% to 25% should be added to the feeder current estimated above.

See Chapter 1 for examples of loading and load flow estimation.

9.4.2 Continuous Rated Current of a Cable

A given size of a bare circular section conductor will carry a certain current when it is placed in still air at 25°C and allowed to have a surface temperature of say 85°C. If the same conductor is surrounded by insulating material and also placed in still air at 25°C, it will need to carry less current in order to maintain a surface temperature of 85°C. The electrical insulation will act as thermal insulation. The more layers of thermal insulation that are added e.g. screens, sheathing, armouring, the lower the current will need to be for the same conductor temperature.

The maximum surface temperature of the conductor is determined by the thermal and physical properties of the insulating materials. Some materials melt or deteriorate at lower temperatures than others.

When a cable is placed in a group of cables on a rack, directly buried in the ground, or laid in underground ducts the surroundings provide additional thermal insulation. Each situation adds a different amount. The overall effect is to reduce the rated current of the cable when compared to its performance in still air by itself.

A similar reduction in rated current occurs when several conductors are combined in one cable. Single-core cables can carry more current than three or four core cables. Vertically run cables carry less current than those run horizontally by a factor of approximately 5%, due to the convection of heat given out by the lower part of the cable.

The above thermal insulating effects are taken into account by the manufacturers of cables, before they publish their tables of rating data. International standards such as BS5467, BS6724, BS7671 and IEC60364 also provide tables of rating data. Care should be taken when using or comparing these tables of data because they are not necessarily compiled on the same basic parameters e.g., ambient air temperature, standard ground temperature.

The following tables of current ratings are typical for the cable constructions and service voltages given. There are many tables available in the international standards e.g. BS7671, which is also the IEE Wiring Regulations in its sixteenth form. Such tables cover a wide range of installation configurations and environmental conditions, not all of which are applicable in the oil industry. The following tables were compiled to be on similar bases and for installations commonly used in the oil industry. For example all the reactance data are given for a frequency of 50 Hz. The conductor temperatures are those suitable for the insulation where rated current follows in the cable. The resistance data of the armouring has been given at a temperature of 80°C for wire armouring and 60°C for braided armouring so that the earth loop impedance can be calculated under fault conditions. The depth of burial of cables is taken to the 0.5 m and the ground temperature 15°C. They should be used as guidance in estimating cable sizes. When calculations are being finalised for a project then the data from a particular manufacturer should be used. Most of the data presented were kindly made available by the Anixter Wire and Cable group of companies, see Reference 6. Reference 4 also provides comprehensive data on many types of cables, and was used as a source for PVC insulated cables. Reference 7 although somewhat dated is also a valuable source of data.

Table 9.11. Summary of cable rating and data tables

Table	Cable voltage grade	Brief description
		Land based installations:
9.12	600/1000 V	PVC insulation Current ratings of 1-core cables
9.13	600/1000 V	PVC insulation Impedance data in ohms/km
9.14	600/1000 V	PVC insulation Current ratings of 3 & 4-core cables
9.15	600/1000 V	XLPE insulation Current ratings of 1-core cables
9.16	600/1000 V	XLPE insulation Impedance data in ohms/km
9.17	600/1000 V	XLPE insulation Current ratings of 3 & 4-core cables
9.18	3800/6600 V 6350/11,000 V 8700/15,000 V	XLPE insulation Current ratings of 1-core cables
9.19	3800/6600 V	Impedance data in ohms/km
9.20	6350/11,000 V	Impedance data in ohms/km
9.21	8700/15,000 V	Impedance data in ohms/km
9.22	3800/6600 V 6350/11,000 V 8700/15,000 V	Current ratings of 3-core cables
		Marine installations:
9.23	600/1000 V	EPR insulation Current ratings of 1, 3 & 4-core cables
9.24	600/1000 V	Impedance data in ohms/km

Table 9.12. Land based installations. 600/1000 V. Cu/PVC/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	193	247	193	203	193	202	Thermal resistivity of soil is 1.2°C m/W
70	243	307	229	248	233	243	
95	298	372	269	297	277	288	Ambient air temperature is 30°C
120	347	429	302	337	315	326	
150	395	472	324	376	347	355	Depth of laying cables is 0.5 m
185	452	528	356	423	386	393	
240	532	606	398	485	441	443	Standard ground temperature is 15°C
300	607	672	435	542	490	486	
400	690	719	460	600	533	516	Conductor surface temperature is 70°C

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.02	1.0	0.94	0.87	0.79	0.71	0.61	0.50

Table 9.13. Land based installations. 600/1000 V. Cu/PVC/PVC/AWA/PVC single core Cu/PVC/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Single cores in trefoil		3 and 4 cores		Approximate armouring resistance	
	Resistance at 70°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 70°C (ohm/km)	Reactance at 50 Hz (ohm/km)	AWA at 80°C (ohms/km)	SWA at 80°C (ohms/km)
1.5			14.451	0.104	2.39	11.40
2.5			8.868	0.101	1.99	9.48
4			5.518	0.099	1.16	5.52
6			3.688	0.094	1.03	4.92
10			2.186	0.090	0.857	4.08
16			1.380	0.087	0.554	2.64
25			0.870	0.084	0.529	2.52
35			0.627	0.081	0.479	2.28
50	0.464	0.112	0.464	0.081	0.328	1.56
70	0.321	0.107	0.321	0.079	0.302	1.44
95	0.232	0.103	0.232	0.077	0.247	1.176
120	0.184	0.103	0.184	0.076	0.179	0.852
150	0.150	0.101	0.150	0.076	0.164	0.780
185	0.121	0.099	0.121	0.076	0.149	0.708
240	0.0927	0.096	0.0929	0.075	0.131	0.624
300	0.0751	0.094	0.0752	0.074	0.118	0.564
400	0.0600	0.091	0.0604	0.074	0.0857	0.408

Table 9.14. Land based installations. 600/1000V. Cu/PVC/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
10				
16	87	78	97	
25	116	103	126	
35	142	123	150	
50	175	146	178	Thermal resistivity of soil is 1.2°C m/W
70	218	181	220	
95	268	218	264	Ambient air temperature is 30°C
120	310	247	299	Depth of laying cables is 0.5 m
150	355	279	335	
185	407	314	377	Standard ground temperature is 15°C
240	480	363	435	Conductor surface temperature is 70°C
300	547	407	486	
400	627	466	546	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor for cables laid in air	1.02	1.0	0.94	0.87	0.79	0.71	0.61	0.50

Table 9.15. Land based installations. 600/1000 V. Cu/XLPE/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	231	296	231	231	231	242	Thermal resistivity of
70	295	373	278	284	283	295	soil is 1.2°C m/W
95	362	452	327	340	337	350	Ambient air temperature
120	420	519	366	386	381	395	is 25°C
150	483	577	396	431	424	434	Depth of laying
185	555	649	437	485	474	482	cables is 0.5 m
240	654	745	489	558	542	545	Standard ground
300	745	825	534	623	601	597	temperature is 15°C
400	851	887	567	691	657	637	Conductor surface
							temperature is 90°C

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for Cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

9.4.2.1 Derating factor due to ambient air temperature

Manufacturers quote current ratings of their cables laid in air at a particular ambient temperature e.g., 25°C, 30°C and 45°C. They also provide tables of derating factors (K_{air}) based on the chosen ambient temperature, see the above tables, and Chapter 8 of Reference 4.

Table 9.16. Land based Installations. 600/1000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC 3 and 4 core

Nominal conductor area (mm^2)	Single core in trefoil		3 and 4 cores		Approximate armouring resistance	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	AWA at 80°C (ohm/km) 1-core	SWA at 80°C (ohm/km) 3/4 core
1.5			15.4	0.103		11.40
2.5			9.45	0.101		9.48
4			5.88	0.0929		5.52
6			3.93	0.0885		4.92
10			2.33	0.0835		4.08
16			1.47	0.0815		2.64
25			0.927	0.0818		2.52
35			0.668	0.0771		2.28
50	0.494	0.104	0.494	0.0765	1.018	1.56
70	0.342	0.101	0.342	0.0754	0.919	1.44
95	0.246	0.0969	0.247	0.0727	0.795	1.176
120	0.196	0.0920	0.197	0.0723	0.559	0.852
150	0.160	0.0945	0.160	0.0728	0.509	0.780
185	0.128	0.0932	0.128	0.0730	0.460	0.708
240	0.0985	0.0902	0.0989	0.0722	0.410	0.624
300	0.0799	0.0883	0.0802	0.0717	0.385	0.564
400	0.0639	0.0886	0.0656	0.0715	0.286	0.408

Table 9.17. Land based installations. 600/1000 V. Cu/XLPE/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
1.5	26	26	32	
2.5	35	34	42	
4	47	45	55	
6	59	56	69	
10	82	75	92	
16	107	96	119	Thermal resistivity of soil 1.2°C m/W
25	140	124	152	
35	172	149	182	Ambient air temp. is 25°C
50	209	177	217	Depth of laying cables is 0.5 m
70	263	218	266	
95	324	263	319	Standard ground temp. is 15°C
120	376	300	363	Conductor surface temp. is 90°C
150	430	338	406	
185	495	382	458	
240	584	442	529	
300	666	496	592	
400	766	570	667	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.18. Land based Installations. 3800/6600 V. 6350/11,000 V. 8700/15,000 V. Cu/XLPE/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	250	300	220	220	220	230	Thermal resistivity of soil is 1.2°C m/W
70	310	370	260	270	270	280	
95	375	460	305	320	317	335	Ambient air temp. is 25°C
120	430	530	340	360	355	380	
150	490	600	375	410	403	430	Depth of laying cables is 0.5 m
185	550	690	410	455	445	485	
240	650	820	470	520	505	560	Standard ground temp. is 15°C
300	740	940	500	580	560	640	
400	840	1100	530	650	620	730	Conductor surface temp. is 90°C.

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.19. Land based Installations. 3800/6600 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.137
25			0.927	0.129
35			0.668	0.121
50	0.494	0.134	0.494	0.115
70	0.343	0.125	0.343	0.108
95	0.248	0.119	0.248	0.102
120	0.196	0.114	0.196	0.0988
150	0.159	0.111	0.159	0.0962
185	0.128	0.109	0.128	0.0931
240	0.098	0.105	0.098	0.0900
300	0.080	0.103	0.080	0.0874
400	0.064	0.100	0.064	0.0849

9.4.2.2 Derating factor due to ground temperature

Manufacturers quote current ratings of their cables laid in the ground at a particular ambient temperature e.g., 15°C and 20°C. They also provide tables of derating factors (K_{grd}) based on the chosen ground temperature, see the above tables, and Chapter 8 of Reference 4.

Table 9.20. Land based Installations. 6350/11,000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.137
25			0.927	0.129
35			0.668	0.121
50	0.494	0.138	0.494	0.115
70	0.343	0.130	0.343	0.108
95	0.248	0.123	0.248	0.102
120	0.196	0.118	0.196	0.0988
150	0.159	0.117	0.159	0.0962
185	0.128	0.112	0.128	0.0931
240	0.098	0.109	0.098	0.0900
300	0.080	0.105	0.080	0.0874
400	0.064	0.101	0.064	0.0849

Table 9.21. Land based Installations. 8700/15,000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.147
25			0.927	0.138
35			0.668	0.129
50	0.494	0.144	0.494	0.123
70	0.343	0.135	0.343	0.115
95	0.248	0.129	0.248	0.109
120	0.196	0.124	0.196	0.105
150	0.159	0.121	0.159	0.102
185	0.128	0.117	0.128	0.0986
240	0.098	0.113	0.098	0.0952
300	0.080	0.108	0.080	0.0922
400	0.064	0.107	0.064	0.0893

9.4.2.3 Derating factor due to thermal resistivity of the ground

Cables that are laid in the ground need to dissipate heat into their surroundings. The thermal conductivity of soil varies considerably from 0.7 km/W for wet soil e.g. near lakes, coastal areas, high water tables, to 3.0 km/W for very dry soil such as desert sand, see Reference 7.

The higher the value of thermal resistivity the more difficult it becomes to remove the heat from the cable. A value of 1.2 km/W is frequently used as the base value in data given by a manufacturer.

A typical value of 2.5 km/W is used for dry desert locations, which would cause the cable to be derated to approximately 75% of its nominal rating.

Cables are either laid directly in the ground, in some form of buried ducting system, or in air-filled trenches with lids. The most economical method is direct buried as far as the laying cost is concerned. However, factors such as ground bearing pollution and corrosive substances may require ducts or lined trenches to be used for the full route length. Direct burial will generally provide better heat removal than a ducting system, unless the soil is very dry. Dampness in the soil assists in the process of heat removal. Some installations such as refineries prefer concrete lined trenches with 'shelves' and lids. These will tend to have 'still air' conditions and the concrete enclosure will provide a thermal insulation effect. Hence a concrete trench may have a poorer heat removal property than direct burial in the same soil. See Reference 4 Chapter 8 for tables of derating factors for soil resistivity and grouping of cables that are buried.

9.4.2.4 Derating factor due to grouping cables together

Manufacturers quote current ratings of their cables laid in air or in the ground for a few simple cases of grouping cables together e.g., in trefoil, 3 cables touching horizontally, 3 cables touching vertically, cables spaced apart by a multiple of their outside diameter. The number of combinations of groups of cables, with different spacings and surroundings, becomes far too many to tabulate. This subject has received much attention by cable manufacturers, research establishments and the international standards organisations, see References 8 and 9, BS7672, IEC60287, IEC60364.

For a particular project it is common practice to determine a small number of grouping cases that will apply to most of the cable routes. Special cases such as the trenches entering a large substation or a switch house would require a separate set of factors and derating calculations, because these trenches could be tightly filled with cables. It is common for cables to be laid in horizontal groups e.g., on trays or racks, and vertically e.g., one tray above another. The spacing between the vertical groups will influence the derating factors to apply at each level.

9.4.2.5 The worst-case scenario

A cable may experience various different environments along its route. For example it may start at a switchboard, run through the switch room in a trench with a lid or steel flooring, pass through a duct in a wall and under a roadway, run a long way directly buried and finish on a ladder rack at the consumer. At each of these environments the thermal resistivity and ambient temperature will be different. The environment that causes the most derating of the rated current should be taken and used for the whole cable.

9.4.2.6 Worked example

A 5 MVA 11,000/6900 V ONAF transformer is installed in a desert in the Middle East. Its 11,000 V primary 3-core cable is laid in the ground in a duct at a depth of 1000 mm. Its 6900 V secondary 3-core cable is run above ground in air. The air temperature is 45°C. The primary 3-core cable runs in the same ducted trench as several other cables, less than 6, in horizontal spacing. The trench is back filled with dry sand that has a thermal resistivity of 2.5 km/W. The ground temperature is 35°C.

The secondary cable runs on its own cable rack to a switchboard. Both cable routes are short enough to neglect volt-drop considerations. Find suitable Cu/XLPE/PVC/SWA/PVC cable conductor sizes.

Suitable derating factors:-

a) For air ambient temperature $K_{\text{air}} = 0.84$
b) For ground temperature $K_{\text{grd}} = 0.86$
c) For grouping cables in air $K_{\text{ga}} = 1.00$
d) For grouping cables in the ground $K_{\text{gg}} = 0.65$
e) For ground thermal resistivity $K_{\text{gth}} = 0.75$
f) For depth of burial $K_{\text{bury}} = 0.98$
g) For using ducts in ground $K_{\text{duct}} = 0.875$
h) Overall derating factor for air $K_a = K_{\text{air}} \times K_{\text{ga}} = 0.84$
i) Overall derating factor for ground $K_g = K_{\text{grd}} \times K_{\text{gg}} \times K_{\text{gth}} \times K_{\text{bury}} \times K_{\text{duct}}$
$= 0.86 \times 0.65 \times 0.75 \times 0.98 \times 0.875 = 0.36$

Solution for primary cable:

Calculate the primary current for the ONAF loading of 5 MVA.

$$\text{Primary current } I_p = \frac{5000000}{\sqrt{3} \times 11000} = 262.4 \text{ amps}$$

Overall derating factor $= K_g = 0.36$

$$\text{Cable equivalent current at } 25^\circ\text{C} = I_{c25} = \frac{I_p}{K_g} = \frac{262.4}{0.36} = 728.9 \text{ amps}$$

From Table 9.22 the nearest cable rated current equal to or greater than 728.9 amps for cables run in air is 740 amps for a 400 mm^2 3-core cable. This choice would have a spare capacity in the cable of only 1.5%, which is rather low for a practical design. A 400 mm^2 high voltage cable is also difficult to manipulate during laying. A better choice would be two cables in parallel. The same overall derating factor can be used if the two cables are spaced sufficiently far apart.

$$\text{Cable equivalent current at } 25^\circ\text{C} = \frac{I_{c25}}{2} \text{ per cable} = 364.4 \text{ amps.}$$

From Table 9.22 a suitable cable size to provide at least a 10% margin is 150 mm^2, giving a rated current in air of 430 amps. Hence the appropriate choice for the primary is 2 × 3c × 150 mm^2 cables. The margin will allow for short duration overloading of the transformer.

Solution for the secondary cable:

The corresponding secondary current

$$I_s = 262.4 \times \frac{11000}{6900} = 418.3 \text{ amps}$$

Overall derating factor $= K_a = 0.84$

$$\text{Cable equivalent current at } 25^\circ\text{C} = I_{c25} = \frac{I_s}{K_a} = \frac{418.3}{0.84} = 498.0 \text{ amps}$$

Table 9.22. Land based Installations. 3800/6600 V. 6350/11,000 V. 8700/15,000 V. Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
25	145	125	140	Thermal resistivity of soil is 1.2°C m/W
35	175	150	170	
50	220	180	210	Ambient air temp. is 25°C.
70	270	215	255	Depth of laying cables is 0.5 m
95	330	255	300	
120	375	290	340	Standard ground temp. is 15°C
150	430	330	380	
185	490	370	430	Conductor surface temp. is 90°C.
240	570	425	490	
300	650	470	540	
400	740	530	600	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.23. Marine and offshore 600/1000 V Cu/EPR/CSP/GSWB or PBWB/CSP or PVC installations. Cables run on open trays or enclosed in air. 1 to 6 × single, 3 or 4 cores

Nominal conductor area (mm^2)	Single cores	3 and 4 cores	Notes
1.0	17	12	Ambient air temperature is 45°C
1.5	21	15	
2.5	30	21	
4	40	29	Conductor surface temperature is 90°C.
6	51	36	
10	71	50	
16	95	67	
25	125	89	
35	155	105	
50	190	135	
70	240	170	
95	290	205	
120	340	240	
150	385	270	
185	440	305	
240	520	365	
300	590	415	
400	670	470	

Ambient air temperature °C	35	40	45	50	55	60	65	70	75	80
Rating factor for cables laid in air	1.11	1.05	1.0	0.94	0.88	0.82	0.75	0.69	0.58	0.47

Table 9.24. Marine and offshore 600/1000 V. Cu/EPR/CSP/GSWB or PBWB/CSP or PVC installations. Cables run on open trays or enclosed in air. 1 to 6 × single, 3 or 4 cores

Nominal conductor area (mm^2)	Single cores in trefoil		3 cores		Approximate armouring resistance	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	PBWB at 60°C 1-core (ohm/km)	GSWB at 60°C 3–4 cores (ohm/km)
1.5	15.6	0.185	15.6	0.118		46.2
2.5	9.64	0.173	9.64	0.111		51.3
4	5.99	0.163	5.99	0.108		60.3
6	3.97	0.153	3.97	0.105		30.5
10	2.35	0.148	2.35	0.0983		36.7
16	1.48	0.134	1.48	0.0933		23.1
25	0.936	0.125	0.936	0.0892		28.1
35	0.674	0.121	0.674	0.0867		10.43
50	0.499	0.118	0.499	0.0858		11.81
70	0.344	0.112	0.344	0.0850		13.61
95	0.271	0.108	0.271	0.0825		10.87
120	0.214	0.106	0.214	0.0808		11.92
150	0.175	0.105	0.175	0.0808		7.38
185	0.140	0.105	0.140	0.0808		8.15
240	0.108	0.103	0.108	0.0800		8.94
300	0.087	0.101	0.087	0.0800		10.10
400	0.069	0.0992	0.069	0.0795		10.00

From Table 9.22 the nearest cable size to provide at least 10% margin is 240 mm^2. Hence the appropriate choice for the secondary is 1 × 3c × 240 mm^2 cable.

9.4.3 Volt-drop within a Cable

The actual voltage received by the load at its terminals must be taken into account when selecting a suitable size of cable. An individual consumer is the last item in a series of power system components. Upstream of the load is its own cable, a switchboard, a feeder transformer to switchboard and a cable or overhead line feeding the transformer. All these components will have a volt-drop associated with the current passing through their conductors. When the switchboard is fully loaded, and the tap setting of its feeder transformer is optimally selected, its busbar voltage may not necessarily be the nominal voltage of the system. It could be slightly above or below the nominal value. It is customary to assume a slightly lower busbar voltage when the switchboard is fully loaded under steady state conditions, typically a reduction of 1% can be assumed.

If a switchboard acts as a motor control centre, and it has a predominance of induction motors that are started direct-on-line, then consideration should be given to the voltage deviation at the busbars when groups of motors need to be automatically reaccelerated. Plant processes often require automatic reacceleration of motors shortly after there is a large voltage drop at the busbars, see sub-section 7.7.

Large or complete voltage depressions occur as a result of short circuits at or near the switchboard. The duration of the voltage depression is mainly determined by the response time of the relay or fuse protective devices closest to the point of fault. Individual oil companies tend to have their own philosophy for detecting and responding to the voltage depressions, and to the reacceleration of motors. In order to account for voltage depression and the reacceleration of large groups of motors it may be necessary to allow up to 10% for the drop in busbar voltage during the whole reacceleration period, which may be several seconds. At the same time the voltage received at the terminals of each load should not fall below 80% of its nameplate value. This represents a serious constraint on the sizing of motor feeder cables in particular, due to the high starting currents and their very low power factors. The situation is made worse for long route lengths with low voltage high power motors e.g., 400 volts, 90 to 200 kW motors. Unusually large conductor sizes will result in these situations, which can also make their termination at the load end awkward.

The voltage drop in a cable is due to its series resistance and series inductive reactance. The shunt capacitive reactance is usually too large to be considered for cables installed in a typical plant. However, for long distance high voltage cables, such as submarine cables, the shunt capacitance may need to be included in the calculations of voltage drop.

9.4.3.1 Volt drop in short cables

Let the series resistance be R ohms and the series inductive reactance be X ohms for a cable of length 1 kilometre. Manufacturers usually quote the impedance data in ohms/km or mohms/m. Assume a load current I amperes with a lagging power factor of cos Ø. The sending end phase voltage is V_s and the receiving end phase voltage is V_r. Figure 9.1 shows the phasor diagram of the volt-drop conditions in the cable.

The components of the phasor voltages are:-

$$AB = IR\cos Ø$$

$$BE = IR\sin Ø$$

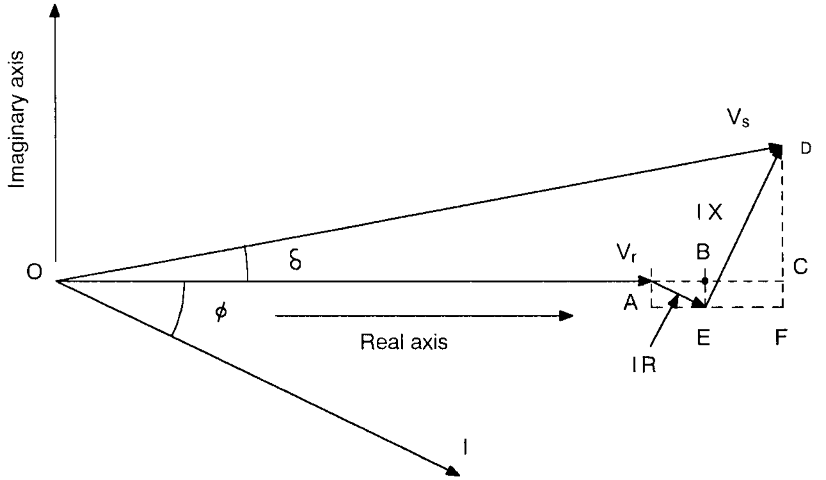

Figure 9.1 Phasor diagram of a loaded cable at a lagging power factor.

$$\begin{aligned}
\mathrm{EF} &= \mathrm{IX}\sin\text{Ø} \\
\mathrm{DF} &= \mathrm{IX}\cos\text{Ø} \\
\mathrm{AC} &= \mathrm{AB} + \mathrm{BC} = \mathrm{AB} + \mathrm{EF} = \mathrm{IR}\cos\text{Ø} + \mathrm{IX}\sin\text{Ø} \qquad (9.1) \\
\mathrm{DC} &= \mathrm{DF} - \mathrm{CF} = \mathrm{DF} - \mathrm{BE} = \mathrm{IX}\cos\text{Ø} - \mathrm{IR}\sin\text{Ø} \\
V_s &= \mathrm{OD} = \sqrt{(\mathrm{OA} + \mathrm{AB} + \mathrm{BC})^2 + (\mathrm{DF} - \mathrm{BE})^2}
\end{aligned}$$

Unless the cable is exceptionally long the bracketed terms can be compared as:-

$$(\mathrm{OA} + \mathrm{AB} + \mathrm{BC})^2 \gg (\mathrm{DF} - \mathrm{BE})^2 \qquad (9.2)$$

Therefore the right-hand bracket can be ignored, and:-

$$\begin{aligned}
V_s &\simeq \mathrm{OA} + \mathrm{AB} + \mathrm{BC} \\
&= V_r + \mathrm{IR}\cos\text{Ø} + \mathrm{IX}\sin\text{Ø} \quad \text{volts/phase}
\end{aligned}$$

The ‘volt-drop’ $\Delta\mathrm{V}$ is normally considered as a per-unit or percentage quantity with respect to the sending end line-to-line voltage V, therefore:-

$$\Delta\mathrm{V} \simeq \frac{\sqrt{3}I\,(\mathrm{R}\cos\text{Ø} + \mathrm{X}\sin\text{Ø})100}{V} \quad \% \qquad (9.3)$$

which is the equation often quoted in cable data publications.

Note $R = rl$ and $X = xl$

Where, r is the specific resistance and x is specific reactance in ohm/km or m ohm/m and l is the route length in km.

9.4.3.1.1 Worked example

A 120 mm^2 3-core XLPE insulated cable 150 m in length feeds a 110 kW induction motor that has a starting current of 6.5 times the full-load current of 180 amps. The starting power factor is 0.35 lagging. The sending end line-to-line voltage is 400 volts. The specific resistance r and reactance x for the cable are 0.197 and 0.072 ohm/km respectively at 90°C and 50 Hz. Find the percentage volt-drop on starting the motor.

The cable.

The series impedance is:-

$$\begin{aligned}
R &= rl = \frac{0.197 \times 150}{1000} = 0.0296 \text{ ohms/phase} \\
X &= xl = \frac{0.072 \times 150}{1000} = 0.0108 \text{ ohms/phase}
\end{aligned}$$

Note that for low voltage cables R is greater than X until the size is in the order of 300 mm^2.

The motor.

The starting current is:-

$$I = 6.5 \times 180.0 = 1170.0 \text{ amps}$$

The power factor is:-

$$\cos Ø = 0.35, \text{ therefore } \sin Ø = 0.9368$$

Solution:

From (9.1), assume the sending voltage is constant at 400 volts.

$$\begin{aligned}
AB &= 1170.0 \times 0.0296 \times 0.3500 = 12.121 \text{ volts/phase}\\
BE &= 1170.0 \times 0.0296 \times 0.9368 = 32.443 \text{ volts/phase}\\
EF &= 1170.0 \times 0.0108 \times 0.9368 = 11.837 \text{ volts/phase}\\
DF &= 1170.0 \times 0.0108 \times 0.3500 = 4.423 \text{ volts/phase}
\end{aligned}$$

From (9.3),

$$\begin{aligned}
\Delta V &\simeq \frac{\sqrt{3} \times 1170.0(0.0296 \times 0.35 + 0.0108 \times 0.9368) \times 100}{400}\\
&= 506.625(0.01036 + 0.01012)\\
&= 10.374\%
\end{aligned}$$

Therefore,

$$\begin{aligned}
V_r &\simeq \frac{400}{\sqrt{3}}(1.0 - 0.10374)\\
&= 206.98 \text{ volts/phase}
\end{aligned}$$

From (9.2),

$$\begin{aligned}
(OA + AB + BC)^2 &= (206.98 + 12.121 + 11.837)^2\\
&= 230.939^2 = 53333.05
\end{aligned}$$

And

$$\begin{aligned}
(DF - BE)^2 &= (4.423 - 32.443)^2\\
&= 28.02^2 = 785.12
\end{aligned}$$

Hence the inequality in (9.2) is valid and the solution is accurate.

Since the volt-drop is less than 20% the motor will accelerate to full speed without difficulty.

9.4.3.2 Volt-drop in long cables

Let the series resistance be R ohms, the series inductive reactance be X_l ohms and the total shunt capacitive reactance X_c ohms for a cable of 1 kilometre. Manufacturers usually quote the shunt capacitance data in microfarads/km.

The method described in sub-section 9.4.3.1 may not always be sufficiently accurate for long cables where the shunt capacitive reactance cannot be neglected. Two more accurate methods can be used in which the cable is treated as an equivalent 'Tee' or an equivalent 'Pye' circuit, see Figures 9.2 and 9.3.

In these methods the complete solution must be found without the simplification made in (9.2). These methods will be shown by an example.

9.4.3.2.1 Worked example

A 240 mm^2 3-core polymeric insulated cable 25 km in length feeds a static load of 20 MVA at a power factor of 0.95 lagging. The nominal system voltage is 33,000 V and the sending end voltage

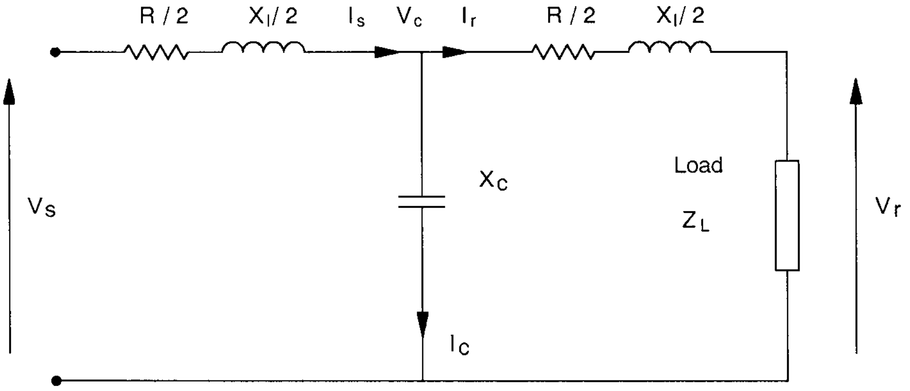

Figure 9.2 Equivalent Tee circuit of a long cable.

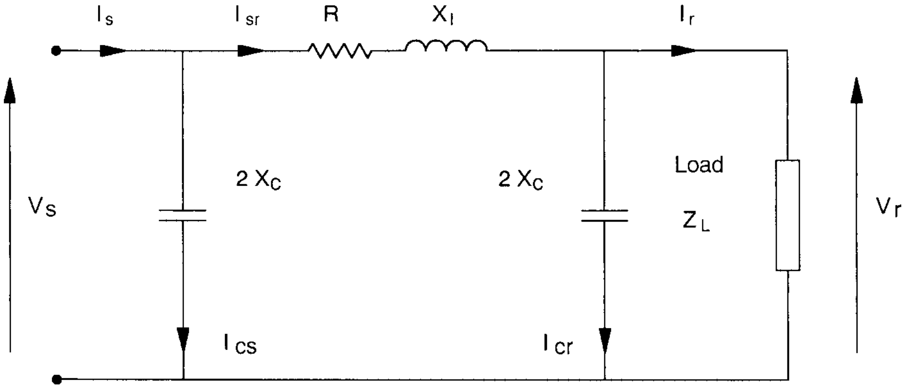

Figure 9.3 Equivalent Pye circuit of a long cable.

is 33,700 V. The specific resistance r, inductive reactance x_l and capacitance c are 0.100 ohm/km, 0.110 ohm/km and 0.24 microfarad/km respectively at 90°C and 50 Hz. Find the percentage volt-drop at the receiving end.

The cable.

The series impedance is:-

$$R = r.l = 0.100 \times 25 = 2.50 \text{ ohms/phase}$$

$$X_l = x_l.l = 0.110 \times 25 = 2.75 \text{ ohms/phase}$$

$$C = c.l = 0.24 \times 25 = 6.00\ \mu\text{F/phase}$$

$$X_c = \frac{10^6}{2\pi f C} = \frac{10^6}{2\pi \times 50 \times 6.0} = 530.52 \text{ ohms/phase}$$

The load.

The system nominal voltage V_n is 33,000 volts.

The line current I_r received at the load is,

$$I_r = \frac{\text{Load MVA} \times 10^6}{\sqrt{3}\text{ line voltage}} = \frac{S_L \times 10^6}{\sqrt{3}\ V_n}$$

$$= \frac{20.0 \times 10^6}{\sqrt{3} \times 33000.0} = 349.91 \text{ amps/phase}$$

The load star connected impedance Z_L is,

$$Z_L = \frac{V_n}{\sqrt{3} I_r} = \frac{33000}{\sqrt{3} \times 349.91} = 54.45 \text{ ohms/phase}$$

The resistive component R_L is,

$$R_L = Z_L \cos \text{Ø} = 54.45 \times 0.95 = 51.728 \text{ ohms/phase}$$

The inductive component X_L is,

$$X_L = Z_L \sin \text{Ø} = 54.45 \times 0.3123 = 17.002 \text{ ohms/phase.}$$

a) The ‘Tee’ equivalent circuit.

The two series elements are,

$$\frac{R}{2} + j\frac{X_1}{2} = 1.25 + j1.375 \text{ ohms/phase}$$

The single shunt element is

$$X_c = -j530.52 \text{ ohms/phase}$$

The solution sequence.

i) Calculate the total impedance seen by the sending end voltage.
ii) Calculate the total sending current.
iii) Calculate the voltage at the centre of the cable, which supplies the shunt capacitance.
iv) Calculate the voltage at the load.

i) The impedance Z_1 to the right-hand side of the shunt reactance is,

$$\begin{aligned} Z_1 &= \frac{R}{2} + j\frac{X_1}{2} + R_L + jX_L \\ &= 1.25 + j1.375 + 51.728 + j17.002 \text{ ohms/phase} \\ &= 52.978 + j18.377 \text{ ohms/phase} \end{aligned}$$

Z_1 is connected in parallel with X_c and so their total impedance is Z_2, which is,

$$\begin{aligned} Z_2 &= \frac{Z_1.X_c}{Z_1 + X_c} = \frac{(52.978 + j18.377)(j530.52)}{52.978 + j18.377 - j530.52} \\ &= 56.246 + j13.218 \text{ ohms/phase} \end{aligned}$$

Z_2 is connected in series with the left-hand side series impedance; hence their total is,

$$\begin{aligned} Z_3 &= Z_2 + \frac{R}{2} + j\frac{X_1}{2} \\ &= 56.246 + j13.218 + 1.25 + j1.375 \\ &= 57.496 + j14.593 \text{ ohms/phase} \end{aligned}$$

ii) This impedance is seen by the sending end phase voltage V_s, hence the sending end current I_s is,

$$\begin{aligned} I_s &= \frac{V_s}{Z_3} = \frac{33700.0}{\sqrt{3}(57.496 + j14.593)} \\ &= \frac{19456.7(57.496 - j14.593)}{3518.75} \\ &= 317.92 - j80.691 \text{ amps} \\ |I_s| &= 328.00 \text{ amps} \end{aligned}$$

The volt-drop in the left-hand side of the cable is V_{sc},

$$\begin{aligned} V_{sc} &= I_s\left(\frac{R}{2} + j\frac{X_1}{2}\right) = (317.92 - j80.691)(1.25 + j1.375) \\ &= 508.35 + j336.28 \text{ volts/phase} \end{aligned}$$

iii) Hence the voltage across the capacitance is,

$$\begin{aligned} V_c &= V_s - V_{\mathrm{sc}} \\ &= 19456.7 + j0.0 - 508.35 - j336.28 \\ &= 18948.35 - j336.28 \text{ volts/phase} \end{aligned}$$

The charging current I_c for the capacitance is,

$$\begin{aligned} I_c &= \frac{V_c}{X_c} = \frac{18949.35 - j336.28}{-j530.52} \\ &= 0.634 + j35.716 \text{ amps} \end{aligned}$$

Deduct I_c from I_s to find I_r,

$$\begin{aligned} I_r &= I_s - I_c = 317.92 - j80.691 - 0.634 - j35.716 \\ &= 317.286 - j116.41 \text{ amps} \end{aligned}$$

The volt-drop in the right-hand side of the cable is V_{cr},

$$\begin{aligned} V_{cr} &= I_r\left(\frac{R}{2} + j\frac{X_1}{2}\right) = (317.286 - j116.41)(1.25 + j1.375) \\ &= 556.671 + j290.756 \text{ volts/phase} \end{aligned}$$

iv) Hence the voltage received at the load is,

$$\begin{aligned} V_r &= V_c - V_{cr} \\ &= 18948.35 - j336.28 - 556.671 - j290.756 \\ &= 18391.68 - j627.04 \text{ volts/phase} \\ |V_r| &= 18402.36 \text{ volts/phase} \end{aligned}$$

The total actual volt-drop

$$\begin{aligned} \Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100 \\ &= \frac{(19456.7 - 18402.36)100}{19456.7} = 5.419\% \end{aligned}$$

The receiving end volt-drop with respect to the nominal system voltage is ΔV_n,

$$\begin{aligned} \Delta V_n &= \frac{|V_n| - |V_r|}{|V_n|} \times 100 \\ &= \frac{(19052.6 - 18402.36)}{19052.6}100 = 3.413\% \end{aligned}$$

b) The ‘Pye’ equivalent circuit.

The single series element is,

$$R + jX_1 = 2.50 + j2.75 \text{ ohms/phase}$$

The two-shunt elements are,

$$2X_c = -j1061.04 \text{ ohms/phase}$$

The solution sequence.

i) Calculate the total impedance seen by the sending end voltage.
ii) Calculate the total sending end current.
iii) Calculate the sending end shunt current.
iv) Calculate the receiving end voltage.

i) The parallel combination of the load impedance and the right-hand side shunt capacitive reactance is,

$$\begin{aligned} Z_4 &= \frac{(R_L + jX_L)2X_c}{R_L + jX_L + 2X_c} \\ &= \frac{(51.728 + j17.002)(-1061.04)}{51.728 + j17.002 - j1061.04} \\ &= 53.296 + j14.638 \text{ ohms/phase} \end{aligned}$$

Z_4 is connected in series with the series impedance of the cable, hence their total is,

$$\begin{aligned} Z_5 &= Z_4 + R + jX_1 \\ &= 53.296 + j14.638 + 2.50 + j2.75 \\ &= 55.795 + j17.388 \text{ ohms/phase} \end{aligned}$$

Z_5 is connected in parallel with the left-hand side shunt capacitive reactance, hence this total Z_6 is,

$$\begin{aligned} Z_6 &= \frac{Z_5 2X_c}{Z_5 + 2X_c} = \frac{(55.795 + j17.388)(-j1061.04)}{55.795 + j17.388 - j1061.04} \\ &= 57.506 + j14.603 \text{ ohms/phase} \end{aligned}$$

This impedance is seen by the sending end phase voltage V_s, hence the sending end current I_s is,

$$\begin{aligned} I_s &= \frac{V_s}{Z_6} = \frac{33700.0}{\sqrt{3}(57.506 + j14.603)} \\ &= \frac{19456.7(57.506 - j14.603)}{3520.19} \\ &= 317.85 - j80.713 \text{ amps} \\ |I_s| &= 327.93 \text{ amps} \end{aligned}$$

The charging current at the sending end I_{cs} is,

$$I_{cs} = \frac{V_s}{2X_c} = \frac{19456.7}{-j1061.04} = +j18.337 \text{ amps}$$

Deduct I_{cs} from I_s to obtain I_{sr},

$$\begin{aligned} I_{sr} &= I_s - I_{cs} = 317.85 - j80.713 - j18.337 \\ &= 317.85 - j99.05 \end{aligned}$$

The volt-drop V_{sr} in the series impedance is,

$$\begin{aligned} V_{sr} = I_{sr}(R + jX_1) &= (317.85 - j99.05)(2.5 + j2.75) \\ &= 794.63 + j874.09 - j247.625 + 272.39 \\ &= 1067.02 + j626.46 \text{ volts/phase} \end{aligned}$$

Hence the voltage received at the load is,

$$\begin{aligned} V_r &= V_s - V_{sr} \\ &= 19456.7 - 1067.02 - j626.46 \\ &= 18389.68 - j626.46 \\ |V_r| &= 18400.35 \text{ volts/phase} \end{aligned}$$

The total actual volt-drop

$$\begin{aligned} \Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100 \\ &= \frac{(19456.7 - 18400.35)100}{19456.7} = 5.429\% \end{aligned}$$

The receiving end volt-drop with respect to the nominal system voltage is ΔV_n,

$$\begin{aligned} \Delta V_n &= \frac{|V_n| - |V_r|}{|V_n|} \times 100 \\ &= \frac{(19052.6 - 18400.35)100}{19052.6} = 3.423\% \end{aligned}$$

c) Neglecting the shunt capacitive reactance.

The method of 9.4.3.1 can be used for a long cable to compare the results and accuracy obtained. The current in the load based on the nominal system voltage is I,

$$I = \frac{S_L \times 10^6}{\sqrt{3}V_n} = 349.91 \text{ amps/phase}$$

And from Figure 9.1,

$$\begin{aligned} AB &= 349.91 \times 2.50 \times 0.9500 = 831.04 \\ BE &= 349.91 \times 2.50 \times 0.3123 = 273.19 \\ EF &= 349.91 \times 2.75 \times 0.3123 = 300.51 \\ DF &= 349.91 \times 2.75 \times 0.9500 = 914.14 \\ \Delta V &\simeq \frac{\sqrt{3}(831.04 + 300.51)\ 100}{33700} = 5.816\% \end{aligned}$$

Alternatively the volt-drop can be calculated by solving the circuit conditions shown in Figure 9.4, as follows:-

By simple proportions V_r can be found from V_s as follows,

$$\begin{aligned} \frac{V_r}{V_s} &= \frac{Z_L}{R + X_l + Z_L} \\ &= \frac{51.728 + j17.002}{2.5 + j2.75 + 51.728 + j17.002} \\ &= 0.94299 + j0.02995 \end{aligned}$$

Therefore,

$$\begin{aligned} V_r &= (0.94299 + j0.02995)(19456.7) \\ &= 18347.47 + j582.73 \end{aligned}$$

And

$$|V_r| = 18356.73 \text{ volts/phase}$$

The total actual volt-drop

$$\begin{aligned} \Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100 \\ &= \frac{(19456.7 - 18356.73) \times 100}{19456.7} = 5.653\% \end{aligned}$$

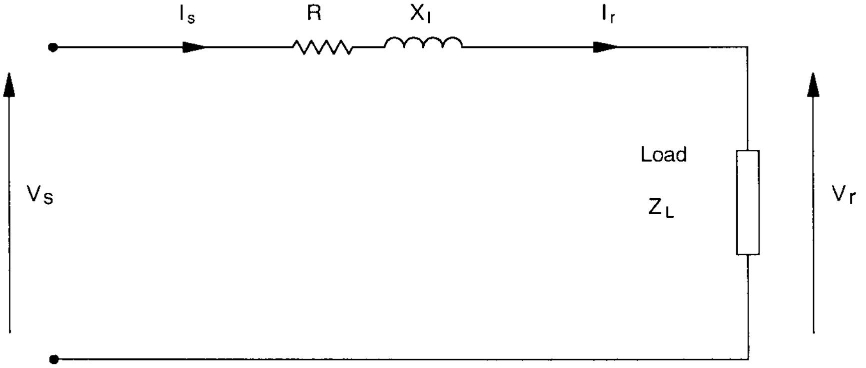

Figure 9.4 Equivalent simple circuit of a long cable. A long cable as a simple series circuit.

By comparing the four methods it can be seen that the results in order of pessimism are:-

Method	Result	Note
Tee equivalent circuit	5.419%	Optimistic
Pye equivalent circuit	5.429%	
Simple series circuit	5.653%	
ΔV formula	5.816%	Pessimistic

In the early stages of a project the pessimistic estimate by the ΔV formula, (9.3), would give a conservative result. Towards the end of a project the 'Tee' or 'Pye' equivalent circuit would give a more appropriate result.

9.4.3.3 Volt-drop in motor feeder cables

When calculating the volt-drop in low voltage motor feeder cables it is necessary to consider three factors in particular:-

a) The full-load running current.

b) The starting current.

c) The maximum route length.

Typical limiting values for the steady state volt-drop at the receiving end of LV and HV cables are:-

Receiving end consumer	Allowable volt-drop% of nominal
HV switchboard (no motors)	1.0
HV motor control centre	1.0
LV main switchboard (no motors)	1.0
LV main motor control centre	1.0
LV auxiliary motor control centre	2.0 to 3.0
HV motor terminals at full-load	1.5 to 3.0
LV motor terminals at full-load	2.5 to 5.0
HV motor terminals at starting	15 to 20
LV motor terminals at starting	20

Equation (9.3) can be used to determine the maximum route length that can be accepted for a) and b) above. Usually two different values of route length will be obtained and the shortest should be taken for selecting the cable size. Equation (9.3) can be transposed to find the route length as follows,

$$\Delta V = \frac{\sqrt{3}I(rl\cos\text{Ø} + xl\sin\text{Ø})}{V}100\%$$

$$l = \frac{V.\Delta V}{100\sqrt{3}I(r\cos\text{Ø} + x\sin\text{Ø})}\ \text{km} \tag{9.5}$$

9.4.3.3.1 Worked example

A 132 kW induction motor is connected to a 415 V 3-phase 50 Hz supply. The motor has the following performance data,

- Running power factor $\cos \O_r = 0.88$
- Running efficiency $\eta = 95.2\%$
- Starting current $= 7.0 \times$ running current
- Starting power factor $\cos \O_s = 0.35$ lagging

Find the smallest cable size and its maximum route length to satisfy a running volt-drop of 5% and a starting volt-drop of 15%. Choose an XLPE insulated 600/1000 V 3-core cable to be routed in air. The ambient air temperature is 25°C.

Solution:

Running conditions:-

The full-load current I_{fl} of the motor is:-

$$I_{\text{fl}} = \frac{\text{Rated power}}{\sqrt{3}\ \text{Line voltage} \times \text{Power factor} \times \text{Efficiency}}$$

$$= \frac{132000}{\sqrt{3} \times 415 \times 0.88 \times 0.952} = 219 \text{ amps}$$

From Table 9.17 the smallest cable size for a running current of 219 amps is 70 mm^2 which from Table 9.16 has a specific resistance r of 0.342 ohm/km and a specific reactance x at 50 Hz of 0.0754 ohm/km.

From (9.5) the route length l_{fl} full-load consideration is,

$$l_{\text{fl}} = \frac{415 \times 5.0}{100\sqrt{3} \times 219 \times (0.342 \times 0.88 + 0.0754 \times 0.4750)}$$

$$= 0.1624 \text{ km} = 162 \text{ metres.}$$

Starting conditions:

The starting current I_{st} of the motor is:-

$$I_{\text{st}} = 7.0 \times I_{\text{fl}} = 7.0 \times 219 = 1533 \text{ amps}$$

From (9.5) the route length l_{st} is,

$$l_{\text{st}} = \frac{415 \times 15.0}{100\sqrt{3} \times 1533 \times (0.342 \times 0.35 + 0.0754 \times 0.9368)}$$

$$= 0.1229 \text{ km} = 123 \text{ metres.}$$

It can be seen that starting current determines the route length to be no greater than 123 metres. If the actual route length is longer than 123 metres then a larger size of cable must be used. If the starting volt-drop is allowed to be 20% then the route length l_{st} would be 164 metres, and the running current would determine the maximum route length to be 162 metres.

9.4.3.4 Cable-sizing tables

It is common practice to prepare cable-sizing tables for low voltage cables that are to be used for a particular project. These tables are usually prepared for,

- Three-phase motors.
- Three-phase static loads.
- Single-phase static loads.
- DC static loads.

Each table should state the operating conditions that apply e.g.,

- Ambient temperature.
- Cable type and construction.
- Cable conductor maximum operating temperature.
- Derating factor for ambient air temperature.
- Derated cable current for each size of cable.
- Motor or static load kW rating.
- Motor or static load running power factor.
- Motor or static load running current.
- Type of protection e.g., fuses, moulded case circuit breakers.

Table 9.25 is a typical example for induction motors and EPR insulated cables.

9.4.3.5 Heat dissipation during short circuits

When a short circuit occurs in a cable the surface temperature of the conductor will rise rapidly. If the short circuit is allowed to persist the temperature will increase to values that will permanently damage the cable insulation. Protective devices such as fuses or circuit breakers will normally operate well before damage can occur. However, the cable manufacturers design cables to withstand a certain level of current for a specified length of time. The level of current will depend mainly on the insulating material used. Table 9.5 shows the maximum temperature that can be allowed to exist for a period of 5 seconds for different insulating materials, see IEC60502, IEC60364, Chapter 9 of Reference 4.

The heat Q developed in the conductor due to its resistance R when current I passes for a time of t seconds is,

$$Q = I^2Rt \text{ joules}$$

This amount of heat is absorbed into the insulation material. If the initial temperature θ_1 of the conductor is its maximum continuous value e.g., 70°C for PVC, 90°C for XLPE and EPR when rated current I_{fl} flows, and the temperature limit θ_2 is the maximum allowed for the insulation e.g., 160°C for PVC, 250°C for XLPE and EPR when a short-circuit current I_{sc} flows, then an equation relating current and time can be given as (see Reference 4 Chapter 9, or Appendix A of IEC60364),

$$(I_{\text{sc}} - I_{\text{fl}})^2 = \frac{A^2k^2}{t} \log_e \left[\frac{\theta_2 + 234.5}{\theta_1 + 234.5}\right] \tag{9.6}$$

Table 9.25. Cable-sizing chart for DOL induction motors

				Cable information EPR cable size in mm^2													
Motor information				2.5	4	5	10	16	25	35	50	70	95	120	150	185	240
Motor rating (kW)	Motor FLC current (A)	Motor FLC power factor	Motor I_s/I_n ratio	Derated cable current in amps													
11	19	0.86	6.5	19	26	33	46	62	83	99	124	159	193	223	253	288	343
15	25	0.87	7.2	Maximum route length in metres (in this case limited by starting current)													
18.5	30	0.89	7.0		105	156	254	389									
22	36	0.88	7.0			99	162	249	375								
30	51	0.86	7.0				123	190	287	377							
37	63	0.85	7.0				106	164	249	328							
45	76	0.85	7.0					110	166	219	278						
55	94	0.84	7.0						187	241	299	379					
75	124	0.86	7.0						155	200	248	314					
90	146	0.87	7.0	Note:						164	204	257	307				
110	178	0.88	7.0	a) Volt-drop on starting 15%.							154	195	233	276			
132	214	0.88	7.0	b) Volt-drop at full-load 5%.								165	198	234	256		
150	243	0.88	7.0	c) Ambient temperature 30°C.									162	192	210	230	
185	297	0.88	7.0	d) System voltage 440 V at 60 Hz.										163	178	194	210
200	317	0.89	7.0	e) Cable derating factor for ambient											156	171	185
				temperature and grouping in air is 0.93.												152	158
																	148

Let

$$K^2 = k^2 \log_e \left[\frac{\theta_2 + 234.5}{\theta_1 + 234.5} \right]$$

For copper conductors

$$k = 226$$

$$K^2 \text{ for PVC} = 226^2 \log_e \left[\frac{160 + 234.5}{70 + 234.5} \right]$$

$$= 226^2 \times 0.25589$$

Therefore

$$K = 226 \times 0.5088 = 115$$

Similarly for XLPE and EPR, $K = 143$.

For bare copper in air with a final temperature of 150°C and an initial temperature of 70°C the value of K is 109. If the initial current is zero and the initial temperature is 30°C then K is 138. See Table 54 B of IEC60364 Part 5, Chapter 54. If the final temperature is allowed to be 250°C then the value of K will be in the order of 170 to 180.

In the calculation of short-circuit current it is usually assumed that this current is much larger than the normal load current even if it is its full-load value. Hence I_{fl} in (9.6) can be ignored, thereby giving the form of equation found in the reference literature,

$$I_{\mathrm{sc}} = \frac{AK}{\sqrt{t}} \text{ amps} \tag{9.7}$$

Or

$$A = \frac{I_{\mathrm{sc}}\sqrt{t}}{K} \text{ mm}^2$$

If the time duration t is taken to be 5 seconds then the lowest acceptable cross-sectional area A for the cable for the various insulating materials is:-

$$\text{PVC, } A = 0.01944 I_{\mathrm{sc}} \text{ mm}^2$$

$$\text{XLPE and EPR, } A = 0.01564 I_{\mathrm{sc}} \text{ mm}^2$$

$$\text{Bare copper, } A = 0.02051 I_{\mathrm{sc}} \text{ mm}^2$$

Equation (9.7) can be used for plotting the time-current characteristic of the cable when this needs to be coordinated with those of the protective relays and fuses in the circuit.

In which case the equation is transposed as,

$$t = \frac{A^2K^2}{I_{\mathrm{sc}}^2}$$

When plotted on log-log paper the equation has the form,

$$\log_{10} t = \log_{10}(A^2K^2) - 2\log_{10} I_{\mathrm{sc}}$$

Or of the form $y = a - bx$

Where $y = \log_{10} t$, $a = \log_{10}(A^2K^2)$

$b = -2$ and $x = \log_{10} I_{\mathrm{sc}}$

which is a straight line having a slope of -2.

The straight line is usually plotted over the time range of 0.1 to 5.0 seconds, to correspond with the operating times of the protective devices.

When cables are to be sized for a particular project with regard to their short-circuit performance it is necessary to consider the let-through current of the protective device in the circuit e.g., fuse, circuit breaker. It is also necessary to determine whether the consumer has ‘fixed’ equipment such as a motor, or ‘temporary’ equipment such as a portable tool plugged into a socket, because this establishes the minimum time duration. This aspect is described in more detail when the earth-loop impedance is being considered, see sub-section 9.4.3.6.

Low voltage three-phase power systems often have their star-points earthed (grounded) by a very low impedance conductor, usually the TT method of IEC60364, sub-section 13.3.3. Therefore all the cables and consumer equipments are subject to a very high prospective short-circuit current when a line-to-ground fault occurs. Low voltage induction motors used in the oil industry are usually started direct-on-line. They have starting currents that can be as high as 7.5 times their full-load currents. The starting, or run-up, time durations for low voltage motors are usually in the order of a few seconds whereas for high voltage motors the duration can be up to 15 seconds when pumps and compressors are being started.

Table 9.26 of maximum starting times can be used as a guide for typical low voltage three-phase induction motors.

It is therefore common practice to use 5 seconds in (9.7) as the disconnection time for motor cables. This choice also corresponds with standardised data given by the manufacturers of fuses and moulded case circuit breakers for their let-through current as calculated from their graphical data.

When a fuse is used in a motor circuit its main purpose is to protect against short circuits in the cable and not against overloading of the motor. A second protective device such as a thermal overload relay should be used. The fuse rating should have a minimum margin above the motor full-load current of 1.3, see sub-section 7.4. The fuse must not 'blow' during the starting period, nor during several successive startings of the motor.

For high voltage cables, and low voltage feeder cables between switchboards, the disconnection time can be reduced from 5 seconds to not less than 0.2 seconds. The time of 0.2 seconds is determined from the total clearance time of a circuit breaker protected by a fast acting overcurrent relay. For high voltage motor circuits in which the short-circuit protection is provided by high-speed fuses, the disconnection time may be determined from the cut-off characteristic of the fuses.

9.4.3.5.1 Worked example

A 440 V 60 Hz emergency switchboard is normally fed by one of two 2.5 MVA transformers. Each 11,000/460 V transformer has a leakage reactance X pu of 6.4% and a resistance R pu of 1.08%. The fault level S_f at the primary winding terminal is 150 MVA, from a circuit that has an X-to-R ratio of 10.0.

A second auxiliary switchboard is fed from the emergency switchboard by a short length of cable which is protected by a set of 200 A fuses. Choose a suitable 3-core XLPE insulated cable and check that the fuses will function in their cut-off mode. Assume a short circuit occurs at the auxiliary switchboard when both transformers are operating in parallel. The 440 V cable is run in air at an ambient temperature of 35°C.

Solution:

The first step is to find the peak asymmetrical prospective fault current seen by the 200A fuses.

Table 9.26. Typical starting ratios and times for LV induction motors

Induction motor rating (kW)	Ratio of starting to running current	Maximum starting time duration (seconds)
Up to 1.0	5	5
1.1 to 75	7	10
Above 75	6.5	15

The base current I_{base} at 11,000 V is,

$$I_{\text{base}} = \frac{S_f \times 10^6}{\sqrt{3} \times V_{\text{base}}} = \frac{150 \times 10^6}{\sqrt{3} \times 11000} = 7872.9 \text{ amps}$$

The base impedance Z_{base} is,

$$Z_{\text{base}} = \frac{V_{\text{base}}}{\sqrt{3} \times I_{\text{base}}} = \frac{11000}{\sqrt{3} \times 7872.9} = 0.8067 \text{ ohms/phase}$$

This impedance has an X/R ratio of 10, its resistance R_{base} and reactance X_{base} are,

$$\begin{aligned} Z_{\text{base}} &= \sqrt{R_{\text{base}}^2 + X_{\text{base}}^2} = \sqrt{\left(\frac{X_{\text{base}}}{10}\right)^2 + X_{\text{base}}^2} \\ &= X_{\text{base}}\sqrt{0.1^2 + 1.0^2} = 1.00499 X_{\text{base}} \\ X_{\text{base}} &= \frac{0.8067}{1.00499} = 0.8027 \text{ ohms/phase} \end{aligned}$$

And

$$R_{\text{base}} = \frac{X_{\text{base}}}{10} = 0.08027 \text{ ohms/phase}$$

Transfer these components to the secondary circuit at 460 volts, and call them Z_{bs}, R_{bs} and X_{bs}.

The transformation ratio u_{ps} of the impedance is,

$$\begin{aligned} u_{\text{ps}} &= \frac{460^2}{11000^2} = 0.001749 \\ Z_{\text{bs}} &= Z_{\text{base}} \times u_{\text{ps}} = 0.8067 \times 0.001749 = 0.001411 \text{ ohms/phase} \end{aligned}$$

Similarly $R_{\text{bs}} = 0.000140$ ohms/phase
And $X_{\text{bs}} = 0.001404$ ohms/phase

The ohmic impedance of the load on the transformer Z_{flt} seen at its secondary winding is found as follows:-

Full-load current I_{flt} of the transformer secondary winding is,

$$I_{\text{flt}} = \frac{S_t \times 10^6}{\sqrt{3} \times V_{\text{os}}}$$

Where, S_t is the MVA rating of the transformer, and V_{os} is the open-circuit line voltage of the secondary winding.

$$I_{\text{flt}} = \frac{2.5 \times 10^6}{\sqrt{3} \times 460} = 3137.8 \text{ amps/phase}$$

The equivalent full-load impedance Z_{flt} is,

$$Z_{\text{flt}} = \frac{V_{\text{os}}}{\sqrt{3}I_{\text{flt}}} = \frac{460}{\sqrt{3} \times 3137.8} = 0.08464 \text{ ohms/phase}$$

This impedance also represents the 100% impedance of the transformer, hence by simple proportion the ohmic resistance R_t and reactance X_t are,

$$R_t = R_{\text{pu}} \times Z_{\text{flt}} = \frac{1.08 \times 0.08464}{10} = 0.000914 \text{ ohms/phase}$$

And

$$X_t = X_{\text{pu}} \times Z_{\text{flt}} = \frac{6.40 \times 0.08464}{100} = 0.005417 \text{ ohms/phase}$$

The total impedance Z_f upstream of the fuses when both transformers are operating is,

$$\begin{aligned} Z_f = Z_{\text{bs}} + \frac{Z_t}{2} &= R_{\text{bs}} + \frac{R_t}{2} + j\left[X_{\text{bs}} + \frac{X_t}{2}\right] \qquad (9.8) \\ &= 0.000597 + j0.004113 \text{ ohms/phase at 460 V.} \end{aligned}$$

The magnitude of which is 0.004156 ohms/phase.

This impedance has an X/R ratio of 6.8894 which will give rise to a current 'doubling factor' D of,

$$\begin{aligned} D = \sqrt{2}\left[1.0 + e^{\frac{-\pi R}{x}}\right] &= \sqrt{2}\left[1.0 + e^{\frac{-\pi}{6.8894}}\right] \\ &= 2.3106, \text{ see sub-section 11.6.1 for an explanation of } D. \end{aligned}$$

The prospective rms fault current at or near to the fuses is I_f,

$$I_f = \frac{V_{\text{os}}}{\sqrt{3}Z_f} = \frac{460}{\sqrt{3} \times 0.004156} = 63903.1 \text{ amps}$$

Hence the peak value of the asymmetrical fault current $I_{\text{fpka}} = 2.3106 \times 63903.1 = 147{,}654$ amps.

To ensure that a good cut-off occurs in the fuses, choose the cut-off current I_{co} to be say 20% of the peak fault current I_{fpka},

$$\begin{aligned} I_{\text{co}} \simeq 0.2 \times I_{\text{fpka}} &= 0.2 \times 147{,}654 \\ &= 29{,}531 \text{ amps} \end{aligned}$$

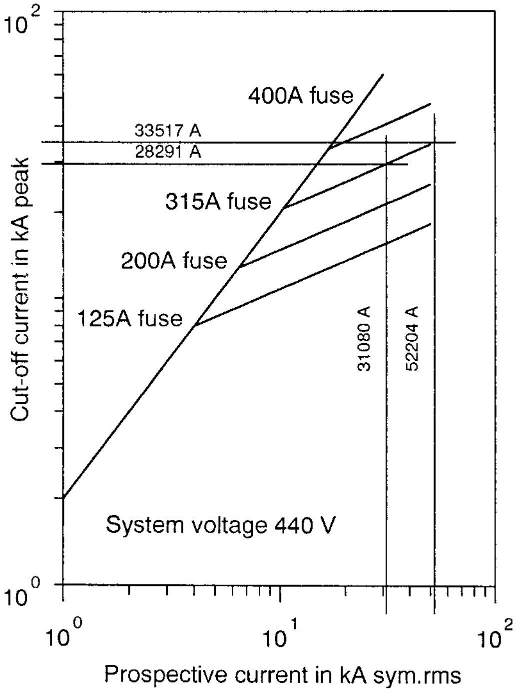

Figure 9.5 Cut-off and prospective current of fuses.

For the selection of fuses the prospective symmetrical rms value of the off-set fault current I_{frms} is calculated as,

$$I_{\text{frms}} = \frac{I_{\text{fpka}}}{2\sqrt{2}} = \frac{147{,}654}{2\sqrt{2}}$$
$$= 52{,}204 \text{ amps}$$

From the graphical characteristics given by the manufacturer the maximum fuse rating can be selected, see Figure 9.5.

The maximum fuse rating is 315 A and so the choice of 200 A is satisfactory.

Select a cable and check that its I-squared-t characteristics are adequate.

From Table 9.17 the derating for ambient temperature K_{air} is 0.92 and assume no derating for the grouping of cables. Hence the nearest cable rating to carry 200 amps at 35°C has a 70 mm^2 cross-sectional area. This cable has a thermal energy constant K of 143. Hence its time-current characteristic is given by two or more points on a straight line on a log-log graph. From the following,

$$\sqrt{t} = \frac{KA}{I} = \frac{143 \times 70}{I} = \frac{10010.0}{I}$$

Several suitable points on the graph are given in Table 9.27.

Table 9.27. Cable and fuse currents and time data

Cable current (kA)	Time (seconds)	Fuse operating current (kA)	
100.1	0.01	4.0	6.5
44.77	0.05	3.0	5.0
31.65	0.10	2.5	4.3
14.16	0.50	1.8	3.1
10.01	1.00	1.5	2.6
4.48	5.00	1.05	1.9

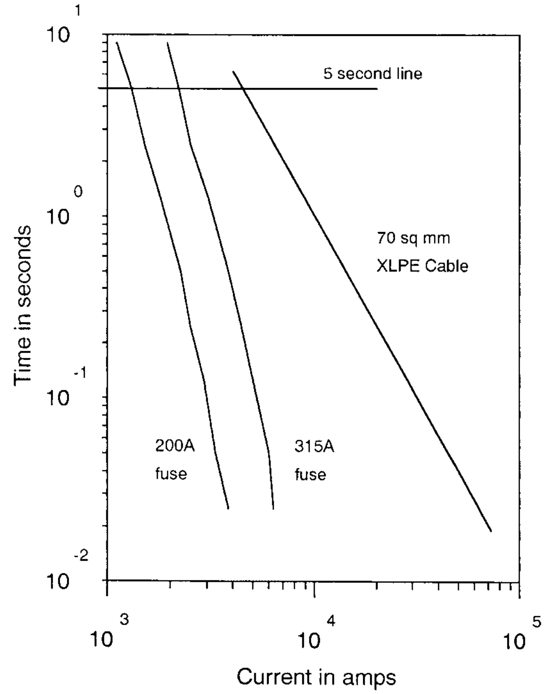

Figure 9.6 Fuse and cable time versus current curves.

A suitable fuse characteristic and the cable I-squared-t characteristic are plotted in Figure 9.6.

It can be seen that the fuse will operate rapidly for a wide range of fault currents and that there is a wide I-squared-t margin between the fuses and the cable.

9.4.3.5.2 Worked example

The emergency switchboard in Example 9.4.3.5.1 also supplies a 440 V 160 kW induction that is started direct-on-line. The motor has an efficiency of 93%, a running power factor of 0.92, a starting to running current ratio of 6.75 and a starting power factor of 0.33. Fuses and a thermal image overload relay protect the motor circuit. The starting time duration is 15 seconds. Each main incoming transformer is protected by an extremely inverse time delay relay in its primary circuit. The current transformer for this relay has a primary current rating of 150 amps. Assume only one of the main transformers is operating. Let the route length of the motor cable be 250 metres and assume that the volt-drop in the cable is 15% during the starting period.

Find a suitable XLPE insulated cable for the motor and ratings for its fuses. Plot the results on a log-log graph.

Solution:

The first step is to find the lowest fuse rating that can be used for the motor.

As a preliminary guide the fuse rating should be not less than approximately 1.3 times the motor full-load current, sub-section 7.4.

The full-load current I_{flm} of the motor is,

$$
\begin{aligned}
I_{\text{flm}} &= \frac{\text{Rated power}}{\sqrt{3}\ \text{Line voltage} \times \text{Power factor} \times \text{Efficiency}} \\
&= \frac{160000}{\sqrt{3}440 \times 0.93 \times 0.92} = 245.4 \text{ amps}
\end{aligned}
$$

Hence the lowest fuse rating would be just above 1.3 × 245.4 amps i.e., 355 amps is a standard rating. However, this may not be adequate to withstand the long starting time.

Since the cable volt-drop is significant it is necessary to revise the starting time duration and current from the data given by the manufacturer of the motor.

The motor receives a reduced terminal voltage of 85% during starting. Consequently the starting current I_{stm} is also reduced to 85% of its design value,

$$I_{\text{stm}} \text{ at reduced voltage} = 0.85 \times 245.4 \times 6.75 = 1408 \text{ amps instead of } 1656.5 \text{ amps.}$$

The torque developed by the motor is proportional to the square of its terminal voltage; hence throughout the starting period the torque applied to the driven machine will be reduced to 0.85 × 0.85 times its design amount. This reduction will apply to nearly the whole of the starting period. As a reasonably accurate approximation the revised starting time t_{str} can be given as,

$$
\begin{aligned}
t_{\text{str}} &= t_{\text{st}} \times (1.0 - \Delta V)^{-2} \\
&= 15.0 \times (1.0 - 0.15)^{-2} \\
&= 20.76 \text{ seconds, round up to 21 seconds.}
\end{aligned}
$$

Where t_{st} is the designed starting time at 100% terminal voltage and ΔV is the known volt-drop at the motor.

Hence the shape of the time-current curve for the motor will be elongated towards the fuse curve. At the end of the starting time the current falls rapidly to its full-load value, hence the curve has a corner point P_m, see Figure 9.7. There needs to be a margin between the corner point P_m of the motor and the fuse operating time point P_f at the value of the reduced starting current, so that the manufacturing tolerances do not interact and cause the fuse to operate. Assume a suitable margin

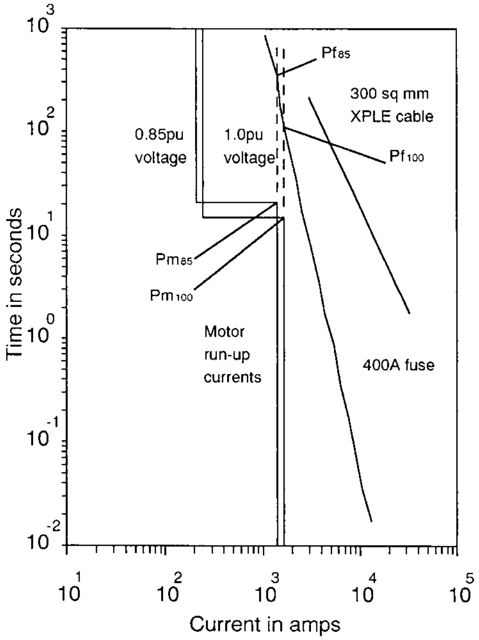

Figure 9.7 Fuse and cable time versus current curves.

to be no less than 3 at the corner point. Hence a fuse must be chosen that has an operating time no less than 63 seconds at a current of 1408 amps. A suitable fuse for motor applications would be rated at 400 amps, see Figure 9.7, the next lower rating of 355 amps may not prove reliable.

Find the cable size to suit the starting current and the route length.

From (9.3) the R and X components can be found in terms of the volt-drop ΔV_{stm} and the current I_{stm} during the starting period,

$$r \cos \varnothing_{\text{stm}} + x \sin \varnothing_{\text{stm}} \leq \frac{V.\Delta V_{\text{stm}}}{l\sqrt{3}I_{\text{stm}} \times 100}$$

Where l is the route length of 250 metres
V is the rated line voltage of 440 volts
$\cos \varnothing_{\text{stm}}$ is the starting power factor of 0.33
and $\sin \varnothing_{\text{stm}} = 0.9440$.

Therefore,

$$0.33r + 0.944x \leq \frac{440 \times 15.0}{0.250 \times \sqrt{3} \times 1408 \times 100}$$

$$\leq 0.10825 \text{ ohm/km for the cable.}$$

Assuming the cable is routed in air which has an ambient temperature of 35°C and that the cable is not grouped with others then its rating at 25°C must be at least 245.4/0.92 i.e., 266.74 amps.

Table 9.28. Cable data for the worked example

Cable conductor area (mm^2)	Resistance at 90°C (ohm/km)	Reactance at 60 Hz (ohm/km)	$0.033r + 0.944x$ (ohm/km)
95	0.247	0.0872	0.16383
120	0.197	0.0868	0.14694
150	0.160	0.0874	0.13531
185	0.128	0.0876	0.12493
240	0.0989	0.0866	0.11439
300	0.0802	0.0860	0.10765

Hence from Tables 9.16 and 9.17 the small size of cable could be 95 mm^2. Table 9.28 can be prepared for cables of 95 mm^2 and above, routed in air.

Hence a 300 mm^2 would be necessary for the starting duty. Check the actual volt-drop for both starting and running currents.

$$\begin{aligned}
\Delta V_{\text{start}} &= \frac{\surd 31408(0.0802 \times 0.33 + 0.086 \times 0.944)0.25 \times 100}{440} \\
&= 14.92 = 14.9\% \\
\Delta V_{\text{run}} &= \frac{\surd 3245.4(0.0802 \times 0.92 + 0.086 \times 0.3919)0.25 \times 100}{440} \\
&= 2.596 = 2.6\%
\end{aligned}$$

The choice of a 300 mm^2 may just be acceptable for a running volt-drop of 2.6%, but satisfies the required starting volt-drop.

Calculate the cut-off capability of the 400 A fuses. The same approach is used as in the previous Example 9.4.3.5.1. The fault impedance Z_f in (9.8) is higher due to operation of only one transformer,

$$Z_f = Z_{\text{bs}} + Z_t = 0.001054 + j0.006821 \text{ ohms/phase}$$

The magnitude of this is 0.006902 ohms/phase, which has an X/R ratio of 6.4715. The doubling factor is,

$$D = \sqrt{2}\left[1.0 + e^{\frac{-\pi}{6.4715}}\right] = 2.2846$$

The prospective RMS fault current at or near to the fuses is I_f,

$$I_f = \frac{V_{\text{os}}}{\sqrt{3}Z_f} = \frac{460}{\sqrt{3} \times 0.006902} = 38478.9 \text{ amps}$$

Hence the peak value of the symmetrical fault current

$$I_{\text{fpka}} = 2.2846 \times 38478.9 = 87908.8 \text{ amps}$$

Again let the cut-off current be 20% of I_{fpka},

$$I_{\text{co}} \simeq 0.2 \times 87909 = 17582 \text{ amps}$$

And

$$I_{\text{frms}} = \frac{I_{\text{fpka}}}{2\sqrt{2}} = \frac{87909}{2\sqrt{2}} = 31080 \text{ amps}$$

From Figure 9.5 it can be seen that a 400 amp fuse will cut-off, with a higher cut-off current than 17,582 amps but still within a good margin at 30,000 amps, i.e. a factor of 34% instead of 20%.

The I-squared-t characteristic of a 300 mm^2 XLPE cable can be found from,

$$\sqrt{t} = \frac{143 \times 300}{I} = \frac{42900}{I}$$

Several points on the graph are given in Table 9.29.

A suitable fuse characteristic and the cable I-squared-t characteristic are plotted in Figure 9.7. It can be seen that the fuse will operate rapidly for a wide range of fault currents, that there is a wide I-squared-t margin between the fuse and the cable, and that the corner point of the motor starting current is well avoided.

9.4.3.6 Earth fault loop impedance

When an earth fault occurs at the far end of a cable it is possible that the armouring, cable gland and the frame of the consumer equipment can be raised to a dangerous potential with respect to electric shock exposure to human operators. This subject has been given considerable attention over the last 20 years, and is well documented in for example IEC60364. The international documentation concentrates on low voltage fixed and portable equipment protected by fuses and miniature circuit breakers. See also Chapter 13.

BS7430 (1998), sub-section 3.13, defines the earth fault loop impedance Z_{loop} in relation to the various types of earthing systems, as follows.

For TN systems:

$$Z_{\text{loop}} = Z_{\text{nez}} + Z_{\text{sec}} + Z_c + Z_a + Z_{\text{bond}} + Z_{\text{mr}} \tag{9.9}$$

Table 9.29. Cable and fuse currents and time data

Cable current (kA)	Time (seconds)	400 A fuse operating current (kA)
429.0	0.01	11.0
191.8	0.05	9.0
135.7	0.10	7.5
60.7	0.50	5.3
42.9	1.00	4.3
19.2	5.00	3.0

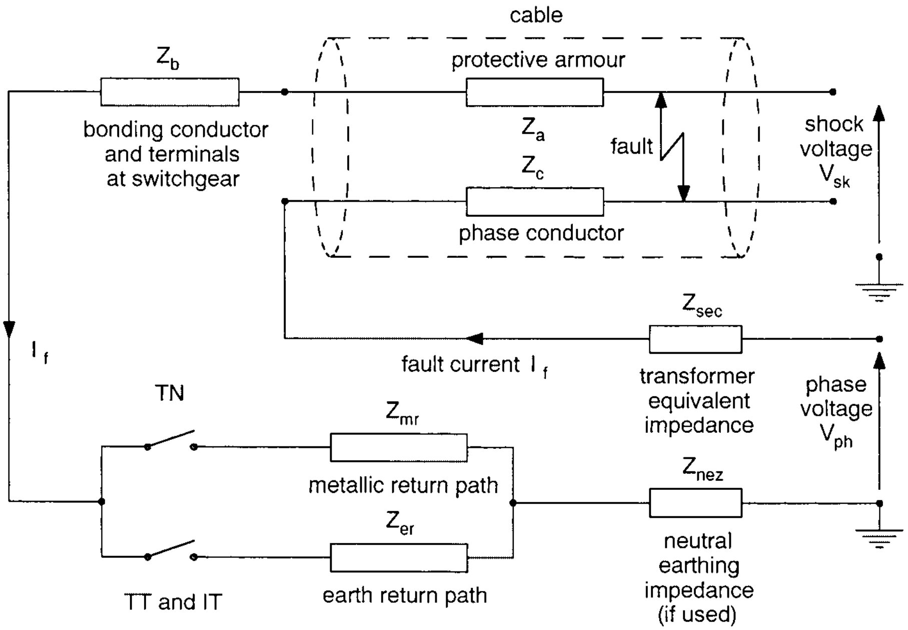

Figure 9.8 Earth loop impedance diagram.

For TT and IT systems:

$$Z_{\text{loop}} = Z_{\text{nez}} + Z_{\text{sec}} + Z_c + Z_a + Z_{\text{bond}} + Z_{\text{er}} \tag{9.10}$$

These components are shown in Figure 9.8.

Where Z_{nez} is the impedance of the neutral earthing device at the source winding.

Z_{sec} is the positive sequence impedance of the source. For a transformer this includes both windings and the upstream impedance. For a generator this will be the sub-transient impedance.

Z_c is the impedance of one phase conductor of the particular cable.

Z_a is the impedance of its armouring of the particular cable. This impedance can be taken as purely resistance (R_a).

Z_{bond} is the impedance of the earthing terminals and bonding conductors at the sending end of the cable.

Z_{mr} is the metallic return path impedance of a TN system. This impedance can be taken as purely resistance, but will usually be low enough to ignore. For offshore installations the multiple series and parallel branches of steel work in three dimensions will render such an impedance as almost zero.

Z_{er} is the impedance of the earth return path of the ground for a TT or IT system. It will be approximately the total impedance of the ground rod or grid at the source and the ground rod or grid at the consumer. The impedance will be almost purely resistance, being typically a fraction of an ohm for damp soil conditions to several ohms for dry sandy and rocky soils. See also the international standard IEEE 80, 1986, section 12.

V_{ph} is the nominal phase-to-neutral voltage of the source.
I_f is the fault current at the far end of the feeder cable where the point of fault occurs.

In this sub-section the main concern is for human safety in low voltage networks, hence some simplifications can be made to (9.9 and 9.10). The majority of low voltage networks are solidly earthed and short large cross-section bonding conductors are used. Hence Z_{nez} and Z_{bond} can be assumed to be zero. The current ratings of most consumer cables are much lower than the current rating of the source transformer or generator. Hence in most situations Z_{sec} can be taken as zero. As a first approximation the return path is Z_{mr} and Z_{er} could be taken as 1.0 ohm (see also IEC60079 Part 14 (1996) subsection 12.2.4 for hazardous areas). The approximate expressions for Z_{loop} is therefore:

For TN systems and for TT and IT systems in high conductivity soils

$$Z_{loop} = Z_c + R_a + 1.0 \tag{9.11}$$

As the cross-sectional area of the cable phase conductors reduces, its impedance increases. Similarly the resistance of the cable armouring also increases. In practice it is usually found that minimising Z_{loop} becomes difficult for small sizes of cables when their route lengths exceed more than about 100 m. The critical length depends upon the type of armouring i.e. wires or braid, and the material used i.e. steel, aluminium, copper, and phosphor bronze. When the critical length is exceeded the circuit should be fitted with an earth leakage current relay, because the overcurrent fuses or circuit breakers will not respond quickly enough to satisfy the recommended international practices.

IEC60364 Part 4 Chapter 41 makes reference to several important definitions regarding the design of the insulation within low voltage equipment, whether the equipment is portable or fixed, and the necessary disconnection time of the source protective device. These are summarised as follows:-

a) Class 1 equipment:

   When the insulation fails in Class 1 equipment the fault current passes from the phase conductors to its conductive frame. The fault current must be interrupted very quickly at the point of supply. This applies to fixed rotating and stationary equipment. It also applies to some forms of hand-held portable equipment. See also BS7430.

b) Class 2 equipment:

   This type of equipment has two levels of insulation. The first level may be considered as being equivalent to that of Class 1 equipment. The first level is then completely surrounded by a second level of insulation so that no contact can be made between the phase conductors and the outer frame. Hence the protective device at the source of supply need not be involved in circuit disconnection when the first level insulation fails. This type of equipment is sometimes referred to as 'double insulation' or 'doubly insulated' equipment e.g. hand-held domestic electric drilling machines. This type of equipment is not considered in the following discussions and calculations. See also BS7430.

c) Portable equipment:

   Portable equipment is not necessarily hand-held equipment, it may be too heavy to carry or lift by one person.

d) Hand-held equipment:

   Hand-held equipments are usually light-weight tools such as drilling machines, sanding machines etc., that are held in one or both hands.

e) Disconnection time:

The standard recommends two nominal disconnection times 0.4 and 5.0 seconds. The time of 0.4 seconds is based on a nominal phase-to-neutral voltage of approximately 240 Vac, where as the time of 5.0 seconds is invariant of voltage.

Where the distribution circuit feeds a stationary item of equipment, not socket outlets and not portable equipment, the disconnection time may be taken as 5.0 seconds. This applies to motors.

The nominal time of 0.4 seconds is intended for circuits supplying socket outlets, regularly moved portable equipment and Class 1 hand-held equipment. For voltages (V_{ph}) different from 240 Vac, the disconnection time (t_{dis}) of 0.4 seconds becomes approximately related as,

$$t_{\text{dis}} \simeq 1.149 \log_{10} \left[\frac{600}{V_{\text{ph}}} \right] \text{ seconds}$$

with a lower limit of 0.1 second.

The maximum value of Z_{loop} can be determined from the following information,

- The network phase-to-neutral voltage V_{ph}.
- The operating current that causes the supply protective device to disconnect the consumer in the specified time t_{dis}. This can be found from the manufacturer's data.

9.4.3.6.1 Worked example

A 37 kW 415 V induction motor is protected by fuses at the motor control centre. The route length of the motor feeder cable is 200 metres. The supply frequency is 50 Hz. The MCC is fed by one 250 kVA, 4.5% impedance, transformer. Assume an X/R ratio of the transformer of 10.0. The motor running efficiency at full-load is 92% and its power factor is 0.85. The starting to running current ratio is 7.0, and the starting power factor is 0.45. The cable is routed in air that has an ambient temperature of 40°C. The conductor maximum temperature is 90°C. The insulation material is EPR and the armouring is galvanised steel wire braid. Assume the cable data in Tables 9.23 and 9.11 for 3-core cables is applicable. The motor fuse data are shown in Figure 8.4 for 100 A, 125 A and 160 A fuses. The permissible volt-drops in the cable for running and starting are 3.0% and 15.0% respectively.

Find the most appropriate cable and fuses for the motor. Determine whether or not an earth leakage current relay should be used at the motor control centre. Assume a TN earthing arrangement.

Replace the steel wire braid armour with round steel wires (GSWA) and reduce the metallic return path impedance Z_{mr} to 0.1 ohm, and compare the effect on the hazardous shock voltage.

Then replace the fuses with moulded case circuit breakers.

Solution:

a) Find the source impedance for a line-to-ground fault of negligible impedance. Refer all calculations to the nominal supply voltage of 415 V. The source impedance is that of the single transformer feeding the MCC.

Full-load current I_{txfl} of the transformer

$$= \frac{S_{\text{tx}}}{\sqrt{3}\ V} = \frac{250000.0}{\sqrt{3} \times 415} = 347.8 \text{ amps}$$

The 100% impedance Z_{Ipu} of the transformer

$$= \frac{V}{\sqrt{3}\ I_{\text{txfl}}} = \frac{45}{\sqrt{3} \times 347.8} = 0.6889 \text{ ohms/phase}$$

Therefore the 4.5% leakage impedance

$$Z_{\text{sec}} = |R_{\text{sec}} + jX_{\text{sec}}| = 0.045 \times 0.6889 = 0.031 \text{ ohms/phase}$$

$$\text{or } 0.00308 + \text{j}0.0308 \text{ ohms/phase}$$

b) Find the motor impedances for the starting and running conditions:

Full-load current I_{flmr} of the motor

$$= \frac{S_m}{\sqrt{3} \times V \text{ Efficiency} \times \text{Power factor}}$$

$$= \frac{37000}{\sqrt{3} \times 415 \times 0.92 \times 0.85} = 65.82 \text{ amps}$$

The 100% impedance Z_{mrn} of the motor

$$= \frac{V}{\sqrt{3}\ I_{\text{flmr}}} = \frac{415}{\sqrt{3} \times 65.82} = 3.64 \text{ ohms/phase at a power factor of 0.85}$$

The starting impedance Z_{ms} of the motor

$$= \frac{Z_{\text{mm}}}{\text{Starting to running current ratio}}$$

$$= \frac{3.64}{7.00} = 0.52 \text{ ohms/phase at a power factor of 0.45}$$

c) Find the conductor and armouring impedances for various cables that may be suitable.

From Tables 9.23 and 9.24 the impedance data for the circuit temperature and power frequency conditions are shown below.

d) Since the motor is fixed equipment of the Class 1 type, the disconnection time t_{dis} is 5.0 seconds.

The fuse operating currents at 5.0 seconds are shown in Table 9.31.

e) Find the I-squared-t parameters for the cable conductors with respect to the fuse operating current (I_s) at 5.0 seconds.

From (9.7)

$$A_{\min} = \frac{I_s\sqrt{5}}{K}$$

$$= I_s \times 0.01564$$

Table 9.30. Cable data for the worked example

Nominal conductor area (mm^2)	Current rating at 40°C (amps)	3-core conductor		GSWB armouring
		Resistance at 90°C ohms R_c	Reactance at 50 Hz (ohms) X_c	resistance (ohms) R_a
16	0.2960	0.0268	4.62	70.35
25	0.1872	0.0250	5.62	93.45
35	0.1348	0.0242	2.086	110.3
50	0.0998	0.0236	2.362	141.8
70	0.0688	0.0224	2.722	178.5

Table 9.31. Fuse data for the worked example

Fuse rating (amps)	Operating current at 5.0 sec (amps)	Maximum earth loop impedance at 240 V/phase Z_{loopf} (ohms)
100	500	0.4792
125	650	0.3686
160	850	0.2819
200	1100	0.2179

Table 9.32. Cable data for the worked example

Fuse rating (amps)	Operating current at 5.0 sec (amps)	Minimum conductor CSA $A_{\min}$ (mm^2)	Nearest practical CSA above $A_{\min}$ (mm^2)
100	500	7.82	10
125	650	10.17	16
160	850	13.29	16
200	1100	17.20	25

Where $K = 143$ for EPR insulation and $A_{\min}$ is the smallest conductor cross-sectional area.

The resulting $A_{\min}$ for the four sizes of fuses are given in Table 9.32:

Hence all the cables 16 mm^2 to 70 mm^2 in c) that suit the motor full-load current will be adequately protected by the fuses in the range given.

f) Calculate the volt-drops for running and starting the motor.

From (9.3) for 'running' conditions,

$$\cos \text{Ø} = 0.85 \text{ and } \sin \text{Ø} = 0.5268$$

Assume the cable conductor area is 16 mm^2,

Therefore,

$$R = 0.2960 \text{ ohms and } X = 0.0268 \text{ ohms}$$

$$\Delta V_{\text{run}} = \frac{\surd 365.82(0.2960 \times 0.85 + 0.0268 \times 0.5268)100}{415}$$
$$= 7.299\%.$$

From (9.3) for 'starting' conditions,

$$\cos \text{Ø} = 0.45 \text{ and } \sin \text{Ø} = 0.8930$$
$$\Delta V_{\text{start}} = \frac{\surd 3460.74(0.2960 \times 0.45 + 0.0268 \times 0.8930)100}{415}$$
$$= 30.216\%.$$

Table 9.33 shows the volt-drop results for all the available cables.

g) Check if the earth loop impedance of the motor circuit is greater than that allowed by the fuses. The motor circuit is shown in Figure 9.9.

Where

$$V_{\text{ph}} = \frac{415}{Z_{\text{loopc}}}$$
$$Z_{\text{sec}} = 0.00308 + j0.0308 \text{ ohms/phase}$$

Table 9.33. Volt-drop in the motor feeder cable for the worked example

Nominal conductor area (mm^2)	Running volt-drop (%)	Starting volt-drop (%)	Accept or reject
16	7.299	30.216	Reject
25	4.733	20.492	Reject
35	3.498	15.820	Reject
50	2.672	12.792	Accept
70	1.9306	9.800	Accept

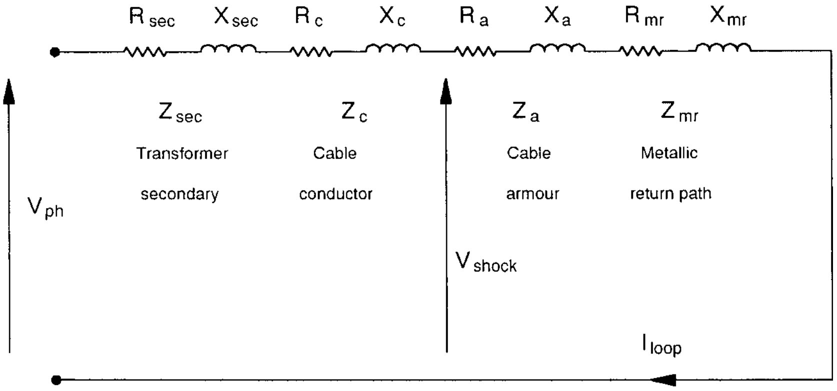

Figure 9.9 Circuit diagram for the earth loop impedance.

Table 9.34. Earth loop impedance results for the worked example with braided armouring

Nominal conductor area (mm^2)	$Z_a + Z_c$	Z_{loopc} magnitude (ohms)	V_{shock}
16	$4.916 + j0.0268$	5.9193	227.49
25	$5.807 + j0.0250$	6.8102	232.91
35	$2.221 + j0.0242$	3.2244	229.31
50	$2.462 + j0.0236$	3.4654	232.45
70	$2.791 + j0.0224$	3.7944	235.03

$$Z_{mr} = 1.0 + j0.0 \text{ ohms}$$

Z_c and Z_a are given in c)

The resulting Z_{loopc} calculated from the circuit for each cable is given in Table 9.34.

Comparing the tabulated results above with those for the fuses in d) shows that all the cables have an earth loop impedance much greater than that permitted by the fuse, by a ratio of approximately 10:1.

Hence an earth leakage circuit breaker should be used in the MCC to protect the circuit against electric shock hazard.

The most appropriate choice of cable cross-sectional area and fuse rating are,

- Cable cross-sectional area should be at least 50 mm^2, to comply with volt-drop.
- Fuse rating should be below the rating of the cable since its primary purpose is to protect the cable. Hence the largest fuse should be 125 A for a 50 mm^2 cable. (If a larger fuse is needed the cable size would need to be increased.)

h) Calculate the electric shock voltage

From Figure 9.9 the shock voltage V_{shock} is,

$$V_{\text{shock}} = \frac{(Z_a + Z_{\text{mr}})V_{\text{ph}}}{Z_{\text{sec}} + Z_c + Z_a + Z_{\text{mr}}}$$

For the 16 mm^2 cable

$$V_{\text{shock}} = \frac{4.62 + 1.0}{5.9193}\left(\frac{415}{\sqrt{3}}\right) = 227.49 \text{ volts}$$

i) Replace the braided armour with round steel wires.

Assume the resistances of the armour wires to be 0.72, 0.50, 0.46, 0.40 and 0.36 ohms for the 200 m route length. Repeat the calculations of g).

For a 16 mm^2 cable,

$$\begin{aligned}
Z_a + Z_c &= 0.2960 + j0.0268 + 0.72 = 1.016 + j0.0268 \\
Z_{\text{loopc}} &= Z_a + Z_c + Z_{\text{sec}} + 0.1 \\
&= 1.016 + j0.0268 + 0.00308 + j0.0308 + 0.1 \\
&= 1.119 + j0.0576 \\
\text{Magnitude of } Z_{\text{loopc}} &= 1.1206 \text{ ohms}
\end{aligned}$$

The resulting Z_{loopc} calculated from the circuit for each cable is given below,

For the 16 mm^2 the shock voltage is,

$$V_{\text{shock}} = \frac{0.72 + 0.1}{1.1206}\left(\frac{415}{\sqrt{3}}\right) = 175.3 \text{ volts}$$

If a 50 mm^2 cable and a fuse rating of 125 amps are chosen as recommended in g) then the circuit earth loop impedance is still too high by a ratio of about 1.65:1. Hence an earth leakage circuit breaker should still be used for this motor circuit. The hazardous shock voltage is still too high.

j) Now replace the fuses with moulded case circuit breakers and show whether or not the situation is improved. From Figure 7.9 it can be seen that a typical MCCB for motor application operates in its inverse region for times equal to 5.0 seconds.

Repeating d) but for MCCBs gives the following limits for Z_{loopf},

Table 9.35. Earth loop impedance results for the worked example with steel wire armouring

Nominal conductor area (mm^2)	$Z_a + Z_c$	Z_{loopc} magnitude (ohms)	V_{shock}
16	$1.016 + j0.0268$	1.1206	175.3
25	$0.6872 + j0.0250$	0.7922	181.5
35	$0.5948 + j0.0242$	0.6999	191.7
50	$0.4998 + j0.0236$	0.6053	197.9
70	$0.4288 + j0.0224$	0.5344	206.2

Table 9.36. Limiting values of earth loop impedance when MCCB is used

MCCB rating (amps)	Lowest operating current at 5.0 sec (amps)	Maximum earth loop impedance at 240 V/phase Z_{loopf} (ohms)
100	370	0.6476
125	470	0.5098
160	720	0.3328
200	900	0.2662

If the 50 mm^2 cable and a MCCB rating of 125 amps are chosen then the circuit earth loop impedance is still too high by a reduced ratio of about 1.19:1. Hence an earth leakage circuit breaker is still required.

Note: In most practical power systems of the TN or TT types it is found that an earth leakage core-balance relay is recommended for all LV motors above approximately 18.5 to 30 kW.

Note: Some oil companies specify a lower disconnection time t_{dis} than 5.0 seconds, e.g., 1.0 second. This significantly increases the disconnection current by a factor of about 3.0 times. This ensures a much lower permissible limit to Z_{loopf}, and thereby making it more necessary to use an earth leakage circuit breaker. Indirectly this reduction in time should be accompanied by ensuring that the earth return impedance Z_{mr} (and Z_{er}) is kept very low i.e. as far below 0.1 ohms as possible. For an offshore platform this should be reasonably easy to achieve, e.g. 0.01 ohms, for a TT system because the general mass of steel is connected in parallel with the neutral conductor if a 4-wire supply is provided. Even for a 3-wire supply the steelwork impedance should be very low.

9.4.4 Protection against Overloading Current

IEC60364 Part 4, section 433, applies to cables and consumer equipment that are protected against overloading current by a fuse or relay device at the source of supply. This requirement should not be confused with protection against short-circuit currents that are disconnected in a short period of time. Overloading currents tend to cause the protective device to disconnect the circuit only after a long period of time has passed e.g. tens of minutes, one hour. The standard defines three particular currents, I_n, I_B and I_2 as follows,

I_n is the nominal current if this is non-adjustable, or the setting current I_{ns} if this is adjustable, of the protective device.

I_2 is the operating current of the protective device.

I_B is the design current of the circuit. This will often be the rated current of the cable under the ambient and grouping conditions of the installation.

I_Z is the rated current of the lowest capacity component in the series circuit, but excluding the load of the consumer.
However, if a cable feeds a motor then the rated current I_Z of the motor should be I_B.

The standard requires the following constraints to be fulfilled,

$$\text{a)} \quad I_B \leq I_n \leq I_z \tag{9.12}$$

and

$$\text{b)} \quad I_z \leq 1.45 I_z \tag{9.13}$$

The circuit diagram showing these currents for a motor consumer is Figure 9.10.

In this situation the main concern is the near-to-asymptotic behaviour of the protective device.

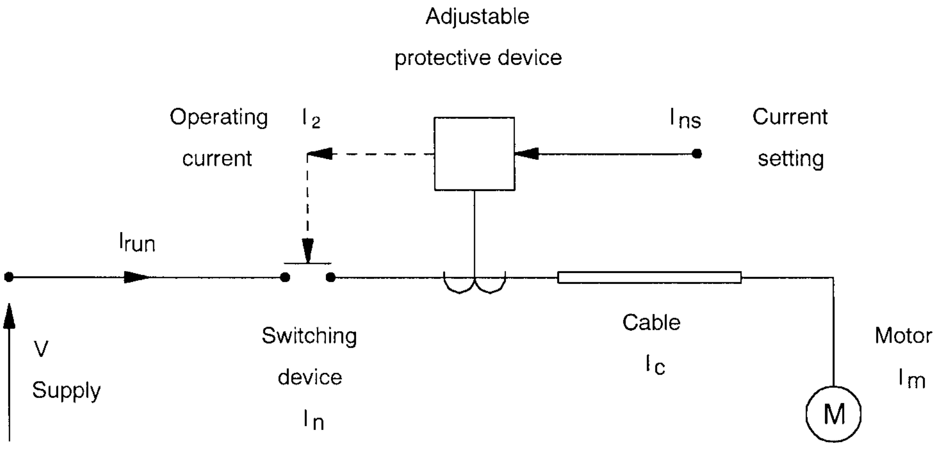

Figure 9.10 Overcurrent protection of a cable and motor.

For the circuit shown the following design conditions should apply,

- Cable 'derated' current I_c should be greater than the rated motor current I_m.
- In practice the motor running current I_{run} would normally be slightly less than I_m, since the motor should have a rating greater than that of its driven machine. The margin in current would depend upon the rating of the motor, see sub-section 1.6.

The following worked example illustrates how (9.12) and (9.13) are applied.

9.4.4.1 Worked example

Consider the worked example in sub-section 9.4.3.5.2 for a 160 kW motor, a 3-core 300 mm^2 XLPE cable, and a 400 amp fuse. Assume the cable is routed in air at an ambient temperature of 35°C.

The motor has a full-load current I_m of 245.4 amps.

The fuse rating is 400 amps and a near-asymptotic current I_2 of between 600 and 800 amps.

The 'derated' current of the cable is $0.92 \times 666 = 613$ amps (see Tables 9.15, 9.16 and 9.17). This is the current I_c.

Now I_B should be the least of I_m and I_c, i.e. $I_B = 245.4$ amps.

I_n should be the rated current of the fuse, i.e. $I_n = 400$ amps

I_z should be the cable 'derated' current I_c i.e., $I_z = 613$ amps.

From (9.12),

$$I_B[245.4] \leq I_n[400] \leq I_z[613]$$

which is satisfactory.

From (9.13):

$$I_2[600 \text{ to } 800] \leq 1.45 I_z[889]$$

which is also satisfactory.

Hence the requirements of IEC60364 are satisfied.

9.5 CABLES WITH ENHANCED PERFORMANCE

Sub-sections 9.1 and 9.2 described the materials and designs for cables that are intended for general use. The oil industry has additional requirements for cables that may be routed in normal hot surroundings, in areas where a fire situation must be tolerated and for the emergency control of critical safety circuits and systems. Examples of these situations are,

a) Normally hot surroundings.

   Cables for ignition and control circuits at the burner face of boilers and furnaces.

   Cables routed close up against hot vessels and pipes.

b) Fire situations

   Cables routed near to wellhead equipment.

   Cables routed in hazardous areas.

   Cables installed in offshore living quarters.

c) Emergency control and power.

   Cables associated with emergency power supplies and control systems.

   Cables that must function as long as possible in safety control systems e.g., fire and gas detection systems, ventilation damper control and power systems, UPS, public address and communication systems, intrinsically safe systems.

There are three important factors regarding the above requirements,

- Fire retardance.
- Fire resistance.
- Emission of toxic gases and smoke.

Fire retardance or reduced flame propagation is described in IEC60331 and fire resistance in IEC60332 (3 parts).

9.5.1 Fire Retardance

The early editions of IEC60332 mainly concerned definitions and testing single lengths of cables. This is useful for making a comparison between one cable and another.

Practical installations more often than not have several or many cables bunched together by cleats on a rack, or in close proximity to each other due to the close spacing of tiered racks. In this respect the IEC60332 Part 3 is more useful and relevant.

The standard describes various testing regimes in which the cable is set in a vertical test rig. A naked flame is applied at the base of the cable. The flame is applied for a given period of time. The extent of burning of the cable is measured from the base. The lower the measured amount of burnt cable, the better is the flame retardant property. IEC60332 Part 3 defines three categories of the volume of combustible non-metallic material present in the test before the flame is applied,

Class A specifies 7 litres of material per metre length.
Class B specifies 3.5 litres of material per metre length.
Class C specifies 1.5 litres of material per metre length.

Good flame retardance can be achieved by PVC, PCP, PTFE and compounds rich in EPR and containing CSP. However, some of these materials may cause the cable to have a poor performance when the emission of toxic gases and smoke are considered.

Reference 10 provides full descriptions of the IEC60331 and IEC60332 tests, together with practical aspects of cable choice and installation.

Reference 11 also describes the testing of cables and the materials that are available.

9.5.2 Fire Resistance

Fire resistance is a much more demanding requirement than fire retardance, and is more difficult to achieve in the manufacturing processes. The fire resistance tests of IEC60331 impose a severe duty on the cable sample. A 1.2 metre sample is mounted horizontally and subjected to a ribbon flame from below for a given period of time at a pre-described temperature. The cable is energised at its rated voltage so that a fault current can be detected. The general requirement is that the cable remains in tact, albeit in a fragile state, throughout the test and that no fault current passes across the insulation material.

In a practical situation a fire could otherwise destroy the cable, but it should still perform as a cable for a period of time sufficient to provide a necessary emergency or shut down service.

Fire resistance is primarily a function of the insulation material. In addition fire resistant mica tapes are often wound round the conductors in the form of a continuous helix. The mica is a good electrical insulator as well as being very resistant to directly applied flames and heat. Fire resistance requires the material to be self-extinguishing after the flame is removed.

It should be noted that fire resistance performance is not normally designed into high voltage cables. This is because the time required to burn down a live high voltage cable, to the point where it fails electrically, is usually much greater than the time required to shut-down and control the emergency. It is also unusual to have high voltage power supplies involved directly in shutdown and emergency services.

9.5.3 Emission of Toxic Gases and Smoke

When some elastomers are burned they evolve what is known as ‘acid gas’ or ‘halogen gas’. These gases are typically composed of hydrochloric or hydrofluoric acid. They are toxic even in relatively small volumes and can cause serious damage to the human respiratory system. Fatal results can occur from bad fire situations.

In addition to injury to health these acid gases can also cause very corrosive damage to equipment, especially if water is employed during the fighting of the fire. Electronic equipment and fine stands of wire are particularly susceptible to damage.

Smoke is usually evolved in the combustion of elastomers, e.g., PVC, PCP and CSP especially if carbon black is present in the compound.

A type of cable known as the ‘low smoke zero halogen’ (LSOH) type has been developed over the past 20 years for use in enclosed environments where good visibility and damage minimisation are of high importance e.g., electronic equipment rooms, corridors, emergency exit routes, medical treatment rooms, living quarters, caissons and basements. The IEC60754 specifies a maximum limit of 0.5% halogen acid shall be emitted in a fire for a cable to be classed as being of the LSOH type.

Non-metallic materials that provide fairly good ‘low-smoke’ characteristics are EVA, silicon rubber, XLPE and EPR.

9.5.4 Application of Fire Retardant and Fire Resistant Cables

The application of fire retardant and fire resistant cables to particular services can be shown in tabular form, see Table 9.37 below.

Table 9.37. Application of fire retardant and fire resistance cables in a typical oil industry plant

Services and systems	Fire retardance	Fire resistance
Deluge systems		√
Drilling system cables	√	
Emergency and escape lighting		√
Emergency power and associated control systems		√
Emergency shutdown systems		√
Emergency telephone systems		√
Emergency UPS cabling systems		√
Escape lighting and signs		√
Fire and gas systems		√
Fire extinguishing systems		√
Fire pump cables		√
Helideck lighting		√
HVAC fire dampers and control systems		√
Instrumentation cables	√	
Internal wiring in switchboard, Panels etc.	√	
Intrinsically safe systems		√
Navigational aides		√
Normal service systems		√
Normal UPS systems	√	
Public address systems		√
Telecommunications		√

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