Chapter G
Sizing and protection of conductors

Contents

1 General

1.1 Methodology and definition

Component parts of an electric circuit and its protection are determined such that all normal and abnormal operating conditions are satisfied

Methodology (see **Fig. G1**)

Following a preliminary analysis of the power requirements of the installation, as described in Chapter B Clause 4, a study of cabling(1) and its electrical protection is undertaken, starting at the origin of the installation, through the intermediate stages to the final circuits.

The cabling and its protection at each level must satisfy several conditions at the same time, in order to ensure a safe and reliable installation, e.g. it must:

- Carry the permanent full load current, and normal short-time overcurrents
- Not cause voltage drops likely to result in an inferior performance of certain loads, for example: an excessively long acceleration period when starting a motor, etc.

Moreover, the protective devices (circuit-breakers or fuses) must:

- Protect the cabling and busbars for all levels of overcurrent, up to and including short-circuit currents
- Ensure protection of persons against indirect contact hazards, particularly in TN- and IT- earthed systems, where the length of circuits may limit the magnitude of short-circuit currents, thereby delaying automatic disconnection (it may be remembered that TT- earthed installations are necessarily protected at the origin by a RCD, generally rated at 300 mA).

The cross-sectional areas of conductors are determined by the general method described in Sub-clause 2 of this Chapter. Apart from this method some national standards may prescribe a minimum cross-sectional area to be observed for reasons of mechanical endurance. Particular loads (as noted in Chapter N) require that the cable supplying them be oversized, and that the protection of the circuit be likewise modified.

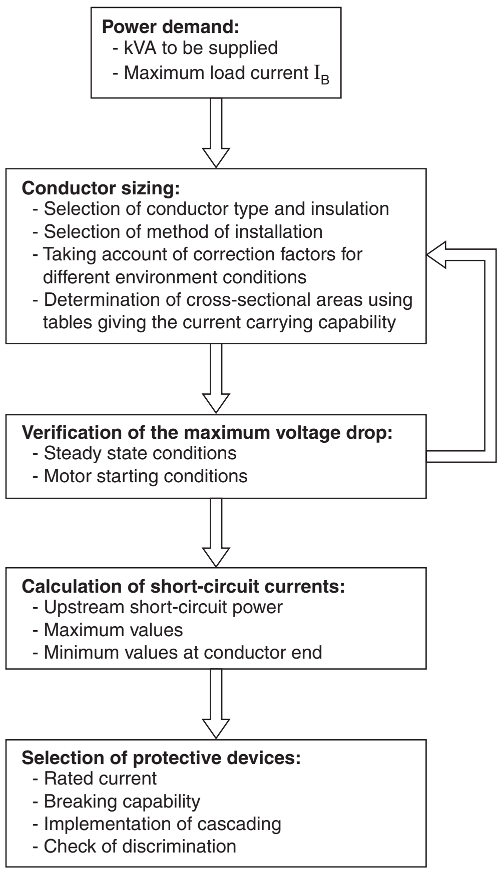


Fig. G1 : Flow-chart for the selection of cable size and protective device rating for a given circuit

(1) The term “cabling” in this chapter, covers all insulated conductors, including multi-core and single-core cables and insulated wires drawn into conduits, etc.

1 General

Definitions

Maximum load current: I_B

■ At the final circuits level, this current corresponds to the rated kVA of the load. In the case of motor-starting, or other loads which take a high in-rush current, particularly where frequent starting is concerned (e.g. lift motors, resistance-type spot welding, and so on) the cumulative thermal effects of the overcurrents must be taken into account. Both cables and thermal type relays are affected.

■ At all upstream circuit levels this current corresponds to the kVA to be supplied, which takes account of the factors of simultaneity (diversity) and utilization, ks and ku respectively, as shown in **Figure G2**.

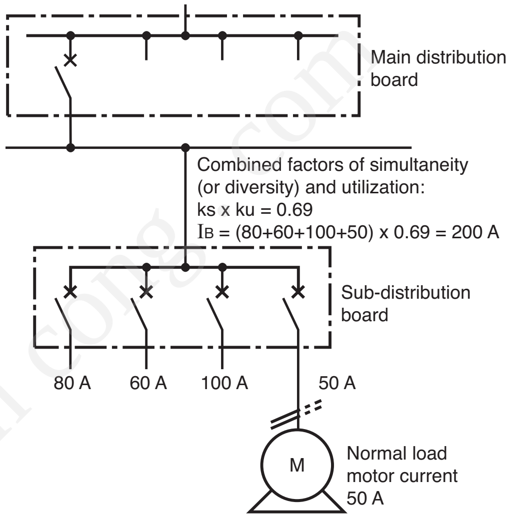


Fig. G2 : Calculation of maximum load current I_B

Maximum permissible current: I_z

This is the maximum value of current that the cabling for the circuit can carry indefinitely, without reducing its normal life expectancy.

The current depends, for a given cross sectional area of conductors, on several parameters:

■ Constitution of the cable and cable-way (Cu or Alu conductors; PVC or EPR etc. insulation; number of active conductors)

■ Ambient temperature

■ Method of installation

■ Influence of neighbouring circuits

Overcurrents

An overcurrent occurs each time the value of current exceeds the maximum load current I_B for the load concerned.

This current must be cut off with a rapidity that depends upon its magnitude, if permanent damage to the cabling (and appliance if the overcurrent is due to a defective load component) is to be avoided.

Overcurrents of relatively short duration can however, occur in normal operation; two types of overcurrent are distinguished:

■ Overloads

These overcurrents can occur in healthy electric circuits, for example, due to a number of small short-duration loads which occasionally occur co-incidentally: motor starting loads, and so on. If either of these conditions persists however beyond a given period (depending on protective-relay settings or fuse ratings) the circuit will be automatically cut off.

■ Short-circuit currents

These currents result from the failure of insulation between live conductors or/and between live conductors and earth (on systems having low-impedance-earthed neutrals) in any combination, viz:

□ 3 phases short-circuited (and to neutral and/or earth, or not)

□ 2 phases short-circuited (and to neutral and/or earth, or not)

□ 1 phase short-circuited to neutral (and/or to earth)

1.2 Overcurrent protection principles

A protective device is provided at the origin of the circuit concerned (see **Fig. G3** and **Fig. G4**).

- Acting to cut-off the current in a time shorter than that given by the I^2t characteristic of the circuit cabling
- But allowing the maximum load current I_B to flow indefinitely

The characteristics of insulated conductors when carrying short-circuit currents can, for periods up to 5 seconds following short-circuit initiation, be determined approximately by the formula:

$I^2t = k^2 S^2$ which shows that the allowable heat generated is proportional to the squared cross-sectional-area of the condutor.

where

t: Duration of short-circuit current (seconds)

S: Cross sectional area of insulated conductor (mm^2)

I: Short-circuit current (A r.m.s.)

k: Insulated conductor constant (values of k^2 are given in Figure G52)

For a given insulated conductor, the maximum permissible current varies according to the environment. For instance, for a high ambient temperature ($\theta a1 > \theta a2$), $Iz1$ is less than $Iz2$ (see **Fig. G5**). θ means "temperature".

Note:

- I_{SC}: 3-phase short-circuit current
- I_{SCB}: rated 3-ph. short-circuit breaking current of the circuit-breaker
- Ir (or Irth)[(1)]: regulated "nominal" current level; e.g. a 50 A nominal circuit-breaker can be regulated to have a protective range, i.e. a conventional overcurrent tripping level (see **Fig. G6** opposite page) similar to that of a 30 A circuit-breaker.

G4

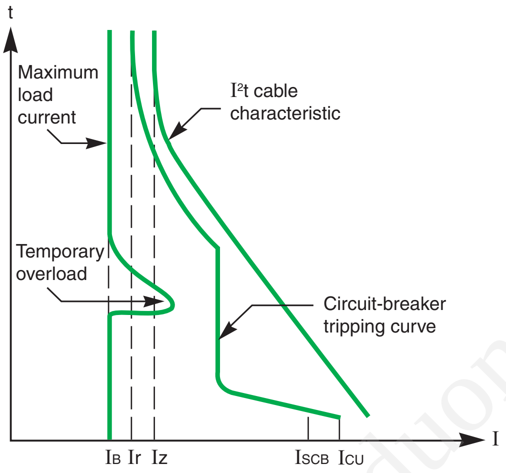


Fig. G3 : Circuit protection by circuit-breaker

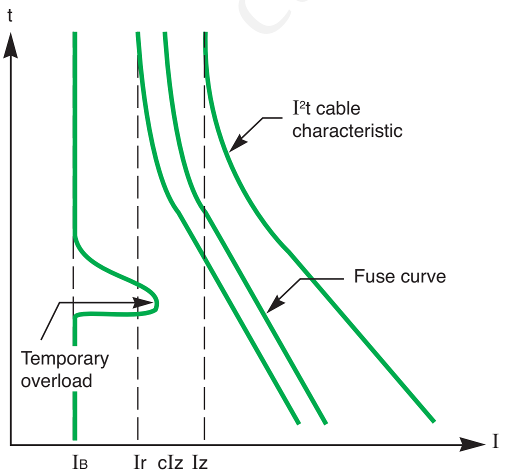


Fig. G4 : Circuit protection by fuses

1.3 Practical values for a protective scheme

The following methods are based on rules laid down in the IEC standards, and are representative of the practices in many countries.

General rules

A protective device (circuit-breaker or fuse) functions correctly if:

- Its nominal current or its setting current In is greater than the maximum load current I_B but less than the maximum permissible current I_z for the circuit, i.e. $I_B \leqslant I_n \leqslant I_z$ corresponding to zone "a" in Figure G6
- Its tripping current I_2 "conventional" setting is less than $1.45\ I_z$ which corresponds to zone "b" in Figure G6

The "conventional" setting tripping time may be 1 hour or 2 hours according to local standards and the actual value selected for I_2. For fuses, I_2 is the current (denoted If) which will operate the fuse in the conventional time.

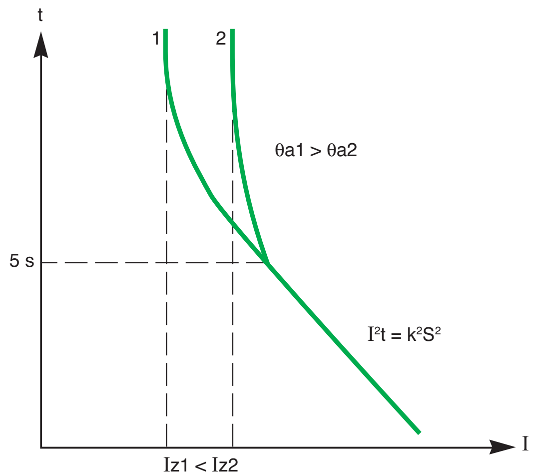


Fig. G5 : I^2t characteristic of an insulated conductor at two different ambient temperatures

(1) Both designations are commonly used in different standards.

1 General

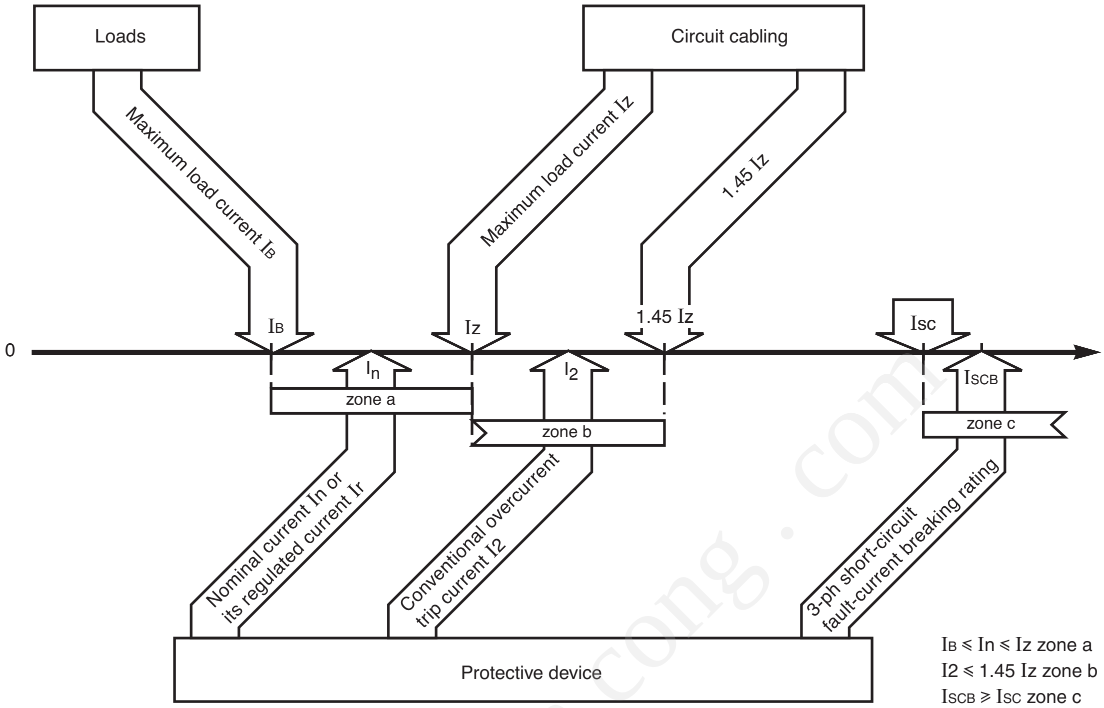


Fig. G6 : Current levels for determining circuir breaker or fuse characteristics

Criteria for circuit-breakers:
$I_B \leqslant I_n \leqslant I_z$ and $I_{SCB} \geqslant I_{SC}$.

Criteria for fuses:
$I_B \leqslant I_n \leqslant I_z/k3$ and $I_{SCF} \geqslant I_{SC}$.

- Its 3-phase short-circuit fault-current breaking rating is greater than the 3-phase short-circuit current existing at its point of installation. This corresponds to zone "c" in Figure G6.

Applications

- Protection by circuit-breaker

By virtue of its high level of precision the current I_2 is always less than 1.45 In (or 1.45 Ir) so that the condition $I_2 \leqslant 1.45\ I_z$ (as noted in the "general rules" above) will always be respected.

- Particular case

If the circuit-breaker itself does not protect against overloads, it is necessary to ensure that, at a time of lowest value of short-circuit current, the overcurrent device protecting the circuit will operate correctly. This particular case is examined in Sub-clause 5.1.

- Protection by fuses

The condition $I_2 \leqslant 1.45\ I_z$ must be taken into account, where I_2 is the fusing (melting level) current, equal to k2 x In (k2 ranges from 1.6 to 1.9) depending on the particular fuse concerned.

A further factor k3 has been introduced ($k3 = \frac{k2}{1.45}$) such that $I_2 \leqslant 1.45\ I_z$ will be valid if $I_n \leqslant I_z/k3$.

For fuses type gG:
In < 16 A → k3 = 1.31
In ⩾ 16 A → k3 = 1.10

Moreover, the short-circuit current breaking capacity of the fuse I_{SCF} must exceed the level of 3-phase short-circuit current at the point of installation of the fuse(s).

- Association of different protective devices

The use of protective devices which have fault-current ratings lower than the fault level existing at their point of installation are permitted by IEC and many national standards in the following conditions:

- There exists upstream, another protective device which has the necessary short-circuit rating, and
- The amount of energy allowed to pass through the upstream device is less than that which can be withstood without damage by the downstream device and all associated cabling and appliances.

In pratice this arrangement is generally exploited in:
□ The association of circuit-breakers/fuses
□ The technique known as “cascading” or “series rating” in which the strong current-limiting performance of certain circuit-breakers effectively reduces the severity of downstream short-circuits

Possible combinations which have been tested in laboratories are indicated in certain manufacturers catalogues.

1.4 Location of protective devices

A protective device is, in general, required at the origin of each circuit

General rule (see **Fig. G7a**)

A protective device is necessary at the origin of each circuit where a reduction of permissible maximum current level occurs.

Possible alternative locations in certain circumstances (see **Fig. G7b**)

The protective device may be placed part way along the circuit:
■ If AB is not in proximity to combustible material, and
■ If no socket-outlets or branch connections are taken from AB

Three cases may be useful in practice:
■ Consider case (1) in the diagram
□ AB ⩽ 3 metres, and
□ AB has been installed to reduce to a practical minimum the risk of a short-circuit (wires in heavy steel conduit for example)
■ Consider case (2)
□ The upstream device P1 protects the length AB against short-circuits in accordance with Sub-clause 5.1
■ Consider case (3)
□ The overload device (S) is located adjacent to the load. This arrangement is convenient for motor circuits. The device (S) constitutes the control (start/stop) and overload protection of the motor while (SC) is: either a circuit-breaker (designed for motor protection) or fuses type aM
□ The short-circuit protection (SC) located at the origin of the circuit conforms with the principles of Sub-clause 5.1

Circuits with no protection (see **Fig. G7c**)

Either
■ The protective device P1 is calibrated to protect the cable S2 against overloads and short-circuits

Or
■ Where the breaking of a circuit constitutes a risk, e.g.
□ Excitation circuits of rotating machines
□ circuits of large lifting electromagnets
□ the secondary circuits of current transformers

No circuit interruption can be tolerated, and the protection of the cabling is of secondary importance.

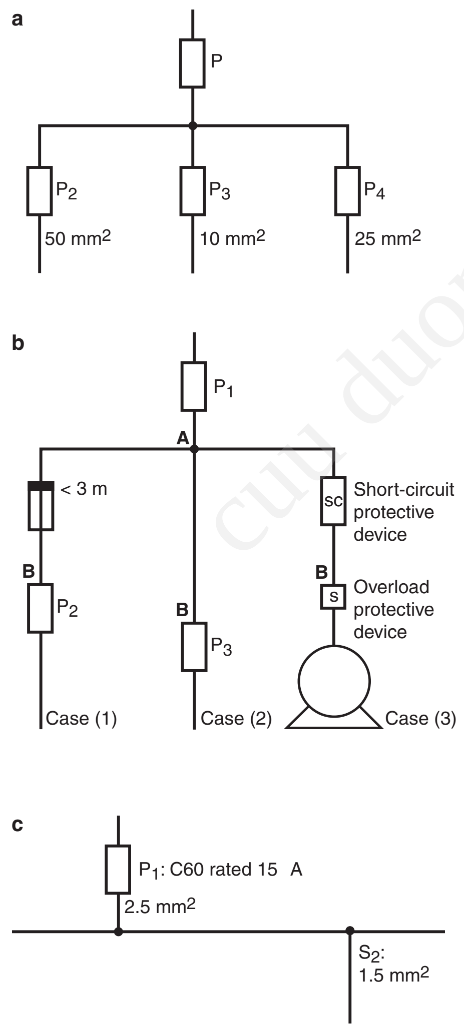


Fig. G7 : Location of protective devices

1.5 Conductors in parallel

Conductors of the same cross-sectional-area, the same length, and of the same material, can be connected in parallel.

The maximum permissible current is the sum of the individual-core maximum currents, taking into account the mutual heating effects, method of installation, etc. Protection against overload and short-circuits is identical to that for a single-cable circuit.

The following precautions should be taken to avoid the risk of short-circuits on the paralleled cables:
■ Additional protection against mechanical damage and against humidity, by the introduction of supplementary protection
■ The cable route should be chosen so as to avoid close proximity to combustible materials

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

2.1 General

The reference international standard for the study of cabling is IEC 60364-5-52: "Electrical installation of buildings - Part 5-52: Selection and erection of electrical equipment - Wiring system".

A summary of this standard is presented here, with examples of the most commonly used methods of installation. The current-carrying capacities of conductors in all different situations are given in annex A of the standard. A simplified method for use of the tables of annex A is proposed in informative annex B of the standard.

2.2 General method for cables

Possible methods of installation for different types of conductors or cables

The different admissible methods of installation are listed in **Figure G8**, in conjonction with the different types of conductors and cables.

Conductors and cables		Method of installation							
		Without fixings	**Clipped direct**	**Conduit**	**Cable trunking (including skirting trunking, flush floor trunking)**	**Cable ducting**	**Cable ladder Cable tray Cable brackets**	**On insulators**	**Support wire**
Bare conductors		–	–	–	–	–	–	+	–
Insulated conductors		–	–	+	+	+	–	+	–
Sheathed cables (including armoured and mineral insulated)	Multi-core	+	+	+	+	+	+	0	+
	Single-core	0	+	+	+	+	+	0	+

+ Permitted.
– Not permitted.
0 Not applicable, or not normally used in practice.

Fig. G8 : Selection of wiring systems (table 52-1 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Possible methods of installation for different situations:

Different methods of installation can be implemented in different situations. The possible combinations are presented in **Figure G9**.

The number given in this table refer to the different wiring systems considered. (see also **Fig. G10**)

Situations	Method of installation							
	Without fixings	With fixings	Conduit	Cable trunking (including skirting trunking, flush floor trunking)	Cable ducting	Cable ladder cable tray, cable brackets	On insulators	Support wire
Building voids	40, 46, 15, 16	0	15, 16, 41, 42	–	43	30, 31, 32, 33, 34	–	–
Cable channel	56	56	54, 55	0	44, 45	30, 31, 32, 33, 34	–	–
Buried in ground	72, 73	0	70, 71	–		70, 71	0	–
Embedded in structure	57, 58	3	1, 2, 59, 60	50, 51, 52, 53	44, 45	0	–	–
Surface mounted	–	20, 21	4, 5	6, 7, 8, 9, 12, 13, 14 22, 23	6, 7, 8, 9	30, 31, 32, 33, 34	36	–
Overhead	–	–	0	10, 11	–	30, 31, 32 33, 34	36	35
Immersed	80	80	0	–	0	0	–	–

– Not permitted.

0 Not applicable, or not normally used in practice.

Fig. G9 : Erection of wiring systems (table 52-2 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Examples of wiring systems and reference methods of installations

An illustration of some of the many different wiring systems and methods of installation is provided in Figure G10.

Several reference methods are defined (with code letters A to G), grouping installation methods having the same characteristics relative to the current-carrying capacities of the wiring systems.

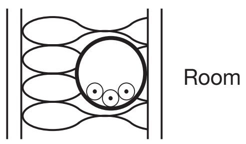
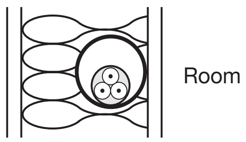
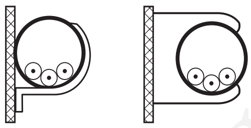
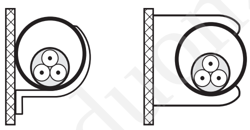
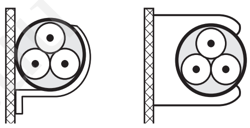
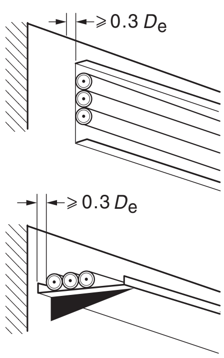
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
1		Insulated conductors or single-core cables in conduit in a thermally insulated wall	A1
2		Multi-core cables in conduit in a thermally insulated wall	A2
4		Insulated conductors or single-core cables in conduit on a wooden, or masonry wall or spaced less than 0,3 x conduit diameter from it	B1
5		Multi-core cable in conduit on a wooden, or mansonry wall or spaced less than 0,3 x conduit diameter from it	B2
20		Single-core or multi-core cables: - fixed on, or sapced less than 0.3 x cable diameter from a wooden wall	C
30		On unperforated tray	C

Fig. G10 : Examples of methods of installation (part of table 52-3 of IEC 60364-5-52) (continued on next page)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

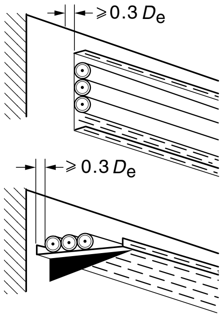
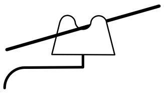
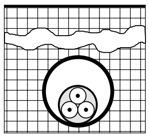
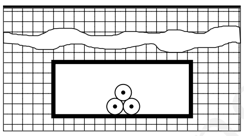
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
31		On perforated tray	E or F
36		Bare or insulated conductors on insulators	G
70		Multi-core cables in conduit or in cable ducting in the ground	D
71		Single-core cable in conduit or in cable ducting in the ground	D

Fig. G10 : Examples of methods of installation (part of table 52-3 of IEC 60364-5-52)

Maximum operating temperature:

The current-carrying capacities given in the subsequent tables have been determined so that the maximum insulation temperature is not exceeded for sustained periods of time.

For different type of insulation material, the maximum admissible temperature is given in **Figure G11**.

Type of insulation	Temperature limit °C
Polyvinyl-chloride (PVC)	70 at the conductor
Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR)	90 at the conductor
Mineral (PVC covered or bare exposed to touch)	70 at the sheath
Mineral (bare not exposed to touch and not in contact with combustible material)	105 at the seath

Fig. G11 : Maximum operating temperatures for types of insulation (table 52-4 of IEC 60364-5-52)

Correction factors:

In order to take environnement or special conditions of installation into account, correction factors have been introduced.
The cross sectional area of cables is determined using the rated load current I_B divided by different correction factors, k_1, k_2, ...:

$$I'_B = \frac{I_B}{k_1 \cdot k_2 ...}$$

I'_B is the corrected load current, to be compared to the current-carrying capacity of the considered cable.

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

■ Ambient temperature

The current-carrying capacities of cables in the air are based on an average air temperature equal to 30 °C. For other temperatures, the correction factor is given in **Figure G12** for PVC, EPR and XLPE insulation material.

The related correction factor is here noted k_1.

Ambient temperature °C	Insulation	
	PVC	XLPE and EPR
10	1.22	1.15
15	1.17	1.12
20	1.12	1.08
25	1.06	1.04
35	0.94	0.96
40	0.87	0.91
45	0.79	0.87
50	0.71	0.82
55	0.61	0.76
60	0.50	0.71
65	-	0.65
70	-	0.58
75	-	0.50
80	-	0.41

Fig. G12 : Correction factors for ambient air temperatures other than 30 °C to be applied to the current-carrying capacities for cables in the air (from table A.52-14 of IEC 60364-5-52)

The current-carrying capacities of cables in the ground are based on an average ground temperature equal to 20 °C. For other temperatures, the correction factor is given in **Figure G13** for PVC, EPR and XLPE insulation material.

The related correction factor is here noted k_2.

Ground temperature °C	Insulation	
	PVC	XLPE and EPR
10	1.10	1.07
15	1.05	1.04
25	0.95	0.96
30	0.89	0.93
35	0.84	0.89
40	0.77	0.85
45	0.71	0.80
50	0.63	0.76
55	0.55	0.71
60	0.45	0.65
65	-	0.60
70	-	0.53
75	-	0.46
80	-	0.38

Fig. G13 : Correction factors for ambient ground temperatures other than 20 °C to be applied to the current-carrying capacities for cables in ducts in the ground (from table A.52-15 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

■ Soil thermal resistivity

The current-carrying capacities of cables in the ground are based on a ground resistivity equal to 2.5 K.m/W. For other values, the correction factor is given in **Figure G14**.

The related correction factor is here noted k3.

Thermal resistivity, K.m/W	1	1.5	2	2.5	3
Correction factor	1.18	1.1	1.05	1	0.96

Fig. G14 : Correction factors for cables in buried ducts for soil thermal resistivities other than 2.5 K.m/W to be applied to the current-carrying capacities for reference method D (table A52.16 of IEC 60364-5-52)

Based on experience, a relationship exist between the soil nature and resistivity. Then, empiric values of correction factors k3 are proposed in **Figure G15**, depending on the nature of soil.

Nature of soil	k3
Very wet soil (saturated)	1.21
Wet soil	1.13
Damp soil	1.05
Dry soil	1.00
Very dry soil (sunbaked)	0.86

Fig. G15 : Correction factor k3 depending on the nature of soil

■ Grouping of conductors or cables

The current-carrying capacities given in the subsequent tables relate to single circuits consisting of the following numbers of loaded conductors:

□ Two insulated conductors or two single-core cables, or one twin-core cable (applicable to single-phase circuits);

□ Three insulated conductors or three single-core cables, or one three-core cable (applicable to three-phase circuits).

Where more insulated conductors or cables are installed in the same group, a group reduction factor (here noted k4) shall be applied.

Examples are given in **Figures G16** to **G18** for different configurations (installation methods, in free air or in the ground).

Figure G16 gives the values of correction factor k4 for different configurations of unburied cables or conductors, grouping of more than one circuit or multi-core cables.

Arrangement (cables touching)	Number of circuits or multi-core cables												Reference methods
	1	2	3	4	5	6	7	8	9	12	16	20	
Bunched in air, on a surface, embedded or enclosed	1.00	0.80	0.70	0.65	0.60	0.57	0.54	0.52	0.50	0.45	0.41	0.38	Methods A to F
Single layer on wall, floor or unperforated tray	1.00	0.85	0.79	0.75	0.73	0.72	0.72	0.71	0.70	No further reduction factor for more than nine circuits or multi-core cables			Method C
Single layer fixed directly under a wooden ceiling	0.95	0.81	0.72	0.68	0.66	0.64	0.63	0.62	0.61				
Single layer on a perforated horizontal or vertical tray	1.00	0.88	0.82	0.77	0.75	0.73	0.73	0.72	0.72				Methods E and F
Single layer on ladder support or cleats etc.	1.00	0.87	0.82	0.80	0.80	0.79	0.79	0.78	0.78				

Fig. G16 : Reduction factors for groups of more than one circuit or of more than one multi-core cable (table A.52-17 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Figure G17 gives the values of correction factor k_4 for different configurations of unburied cables or conductors, for groups of more than one circuit of single-core cables in free air.

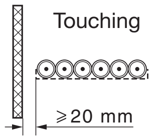
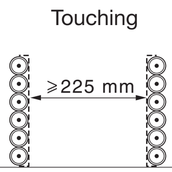
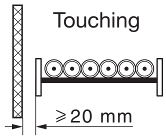
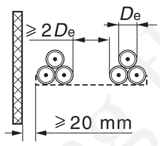
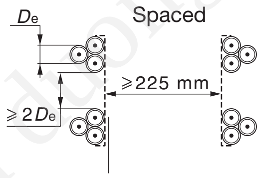
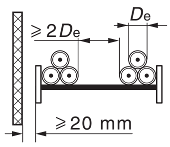
Method of installation			Number of tray	Number of three-phase circuits			Use as a multiplier to rating for
				1	2	3	
Perforated trays	31		1	0.98	0.91	0.87	Three cables in horizontal formation
			2	0.96	0.87	0.81	
			3	0.95	0.85	0.78	
Vertical perforated trays	31		1	0.96	0.86		Three cables in vertical formation
			2	0.95	0.84		
Ladder supports, cleats, etc...	32		1	1.00	0.97	0.96	Three cables in horizontal formation
	33		2	0.98	0.93	0.89	
	34		3	0.97	0.90	0.86	
Perforated trays	31		1	1.00	0.98	0.96	Three cables in trefoil formation
			2	0.97	0.93	0.89	
			3	0.96	0.92	0.86	
Vertical perforated trays	31		1	1.00	0.91	0.89	
			2	1.00	0.90	0.86	
Ladder supports, cleats, etc...	32		1	1.00	1.00	1.00	
	33		2	0.97	0.95	0.93	
	34		3	0.96	0.94	0.90	

Fig. G17 : Reduction factors for groups of more than one circuit of single-core cables to be applied to reference rating for one circuit of single-core cables in free air - Method of installation F. (table A.52.21 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Figure G18 gives the values of correction factor k4 for different configurations of cables or conductors laid directly in the ground.

Number of circuits	Cable to cable clearance (*a*)[a]				
	Nil (cables touching)	**One cable diameter**	**0.125 m**	**0.25 m**	**0.5 m**
2	0.75	0.80	0.85	0.90	0.90
3	0.65	0.70	0.75	0.80	0.85
4	0.60	0.60	0.70	0.75	0.80
5	0.55	0.55	0.65	0.70	0.80
6	0.50	0.55	0.60	0.70	0.80

[a] Multi-core cables

[a] Single-core cables

Fig. G18 : Reduction factors for more than one circuit, single-core or multi-core cables laid directly in the ground. Installation method D. (table 52-18 of IEC 60364-5-52)

■ Harmonic current

The current-carrying capacity of three-phase, 4-core or 5-core cables is based on the assumption that only 3 conductors are fully loaded.

However, when harmonic currents are circulating, the neutral current can be significant, and even higher than the phase currents. This is due to the fact that the 3rd harmonic currents of the three phases do not cancel each other, and sum up in the neutral conductor.

This of course affects the current-carrying capacity of the cable, and a correction factor noted here k5 shall be applied.

In addition, if the 3rd harmonic percentage h_3 is greater than 33%, the neutral current is greater than the phase current and the cable size selection is based on the neutral current. The heating effect of harmonic currents in the phase conductors has also to be taken into account.

The values of k5 depending on the 3rd harmonic content are given in **Figure G19**.

Third harmonic content of phase current %	Correction factor	
	Size selection is based on phase current	**Size selection is based on neutral current**
0 - 15	1.0	
15 - 33	0.86	
33 - 45		0.86
> 45		1.0

Fig. G19 : Correction factors for harmonic currents in four-core and five-core cables (table D.52.1 of IEC 60364-5-52)

Admissible current as a function of nominal cross-sectional area of conductors

IEC standard 60364-5-52 proposes extensive information in the form of tables giving the admissible currents as a function of cross-sectional area of cables. Many parameters are taken into account, such as the method of installation, type of insulation material, type of conductor material, number of loaded conductors.

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

As an example, **Figure G20** gives the current-carrying capacities for different methods of installation of PVC insulation, three loaded copper or aluminium conductors, free air or in ground.

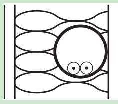
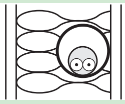
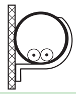
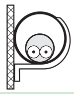
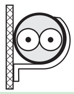
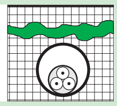
Nominal cross-sectional area of conductors (mm^2)	Installation methods					
	A1	A2	B1	B2	C	D
						
1	2	3	4	5	6	7
Copper						
1.5	13.5	13	15.5	15	17.5	18
2.5	18	17.5	21	20	24	24
4	24	23	28	27	32	31
6	31	29	36	34	41	39
10	42	39	50	46	57	52
16	56	52	68	62	76	67
25	73	68	89	80	96	86
35	89	83	110	99	119	103
50	108	99	134	118	144	122
70	136	125	171	149	184	151
95	164	150	207	179	223	179
120	188	172	239	206	259	203
150	216	196	-	-	299	230
185	245	223	-	-	341	258
240	286	261	-	-	403	297
300	328	298	-	-	464	336
Aluminium						
2.5	14	13.5	16.5	15.5	18.5	18.5
4	18.5	17.5	22	21	25	24
6	24	23	28	27	32	30
10	32	31	39	36	44	40
16	43	41	53	48	59	52
25	57	53	70	62	73	66
35	70	65	86	77	90	80
50	84	78	104	92	110	94
70	107	98	133	116	140	117
95	129	118	161	139	170	138
120	149	135	186	160	197	157
150	170	155	-	-	227	178
185	194	176	-	-	259	200
240	227	207	-	-	305	230
300	261	237	-	-	351	260

Fig. G20 : Current-carrying capacities in amperes for different methods of installation, PVC insulation, three loaded conductors, copper or aluminium, conductor temperature: 70 °C, ambient temperature: 30 °C in air, 20 °C in ground (table A.52.4 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

2.3 Recommended simplified approach for cables

In order to facilitate the selection of cables, 2 simplified tables are proposed, for unburied and buried cables.
These tables summarize the most commonly used configurations and give easier access to the information.

- Unburied cables:

Reference methods	Number of loaded conductors and type of insulation											
A1		2 PVC	3 PVC		3 XLPE	2 XLPE						
A2	3 PVC	2 PVC		3 XLPE	2 XLPE							
B1				3 PVC	2 PVC		3 XLPE		2 XLPE			
B2			3 PVC	2 PVC		3 XLPE	2 XLPE					
C					3 PVC		2 PVC	3 XLPE		2 XLPE		
E						3 PVC		2 PVC	3 XLPE		2 XLPE	
F							3 PVC		2 PVC	3 XLPE		2 XLPE
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Size (mm²) Copper												
1.5	13	13.5	14.5	15.5	17	18.5	19.5	22	23	24	26	-
2.5	17.5	18	19.5	21	23	25	27	30	31	33	36	-
4	23	24	26	28	31	34	36	40	42	45	49	-
6	29	31	34	36	40	43	46	51	54	58	63	-
10	39	42	46	50	54	60	63	70	75	80	86	-
16	52	56	61	68	73	80	85	94	100	107	115	-
25	68	73	80	89	95	101	110	119	127	135	149	161
35	-	-	-	110	117	126	137	147	158	169	185	200
50	-	-	-	134	141	153	167	179	192	207	225	242
70	-	-	-	171	179	196	213	229	246	268	289	310
95	-	-	-	207	216	238	258	278	298	328	352	377
120	-	-	-	239	249	276	299	322	346	382	410	437
150	-	-	-	-	285	318	344	371	395	441	473	504
185	-	-	-	-	324	362	392	424	450	506	542	575
240	-	-	-	-	380	424	461	500	538	599	641	679
Aluminium												
2.5	13.5	14	15	16.5	18.5	19.5	21	23	24	26	28	-
4	17.5	18.5	20	22	25	26	28	31	32	35	38	-
6	23	24	26	28	32	33	36	39	42	45	49	-
10	31	32	36	39	44	46	49	54	58	62	67	-
16	41	43	48	53	58	61	66	73	77	84	91	-
25	53	57	63	70	73	78	83	90	97	101	108	121
35	-	-	-	86	90	96	103	112	120	126	135	150
50	-	-	-	104	110	117	125	136	146	154	164	184
70	-	-	-	133	140	150	160	174	187	198	211	237
95	-	-	-	161	170	183	195	211	227	241	257	289
120	-	-	-	186	197	212	226	245	263	280	300	337
150	-	-	-	-	226	245	261	283	304	324	346	389
185	-	-	-	-	256	280	298	323	347	371	397	447
240	-	-	-	-	300	330	352	382	409	439	470	530

***Fig. G21a** : Current-carrying capacity in amperes (table B.52-1 of IEC 60364-5-52)*

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Correction factors are given in **Figure G21b** for groups of several circuits or multi-core cables:

Arrangement	Number of circuits or multi-core cables								
	1	2	3	4	6	9	12	16	20
Embedded or enclosed	1.00	0.80	0.70	0.70	0.55	0.50	0.45	0.40	0.40
Single layer on walls, floors or on unperforatedtrays	1.00	0.85	0.80	0.75	0.70	0.70	-	-	-
Single layer fixed directly under a ceiling	0.95	0.80	0.70	0.70	0.65	0.60	-	-	-
Single layer on perforated horizontal trays or on vertical trays	1.00	0.90	0.80	0.75	0.75	0.70	-	-	-
Single layer on cable ladder supports or cleats, etc...	1.00	0.85	0.80	0.80	0.80	0.80	-	-	-

Fig. G21b : Reduction factors for groups of several circuits or of several multi-core cables (table B.52-3 of IEC 60364-5-52)

- Buried cables:

Installation method	Size mm²	Number of loaded conductors and type of insulation			
		Two PVC	Three PVC	Two XLPE	Three XLPE
D	Copper				
	1.5	22	18	26	22
	2.5	29	24	34	29
	4	38	31	44	37
	6	47	39	56	46
	10	63	52	73	61
	16	81	67	95	79
	25	104	86	121	101
	35	125	103	146	122
	50	148	122	173	144
	70	183	151	213	178
	95	216	179	252	211
	120	246	203	287	240
	150	278	230	324	271
	185	312	258	363	304
	240	361	297	419	351
	300	408	336	474	396
D	Aluminium				
	2.5	22	18.5	26	22
	4	29	24	34	29
	6	36	30	42	36
	10	48	40	56	47
	16	62	52	73	61
	25	80	66	93	78
	35	96	80	112	94
	50	113	94	132	112
	70	140	117	163	138
	95	166	138	193	164
	120	189	157	220	186
	150	213	178	249	210
	185	240	200	279	236
	240	277	230	322	272
	300	313	260	364	308

Fig. G22 : Current-carrying capacity in amperes (table B.52-1 of IEC 60364-5-52)

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

2.4 Busbar trunking systems

The selection of busbar trunking systems is very straightforward, using the data provided by the manufacturer. Methods of installation, insulation materials, correction factors for grouping are not relevant parameters for this technology.

The cross section area of any given model has been determined by the manufacturer based on:
- The rated current,
- An ambient air temperature equal to 35 °C,
- 3 loaded conductors.

Rated current

The rated current can be calculated taking account of:
- The layout,
- The current absorbed by the different loads connected along the trunking system.

Ambient temperature

A correction factor has to be applied for temperature higher than 35 °C. The correction factor applicable to medium and high power range (up to 4,000 A) is given in **Figure G23a**.

°C	35	40	45	50	55
Correction factor	1	0.97	0.93	0.90	0.86

Fig. G23a : Correction factor for air temperature higher than 35 °C

Neutral current

Where 3rd harmonic currents are circulating, the neutral conductor may be carrying a significant current and the corresponding additional power losses must be taken into account.
Figure G23b represents the maximum admissible phase and neutral currents (per unit) in a high power busbar trunking system as functions of 3rd harmonic level.

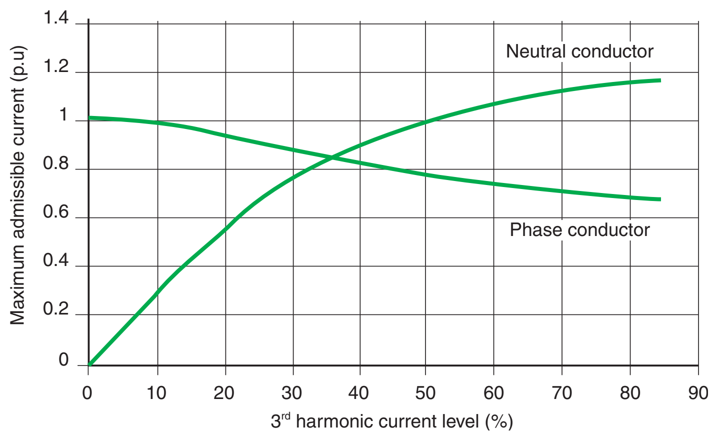


Fig. G23b : Maximum admissible currents (p.u.) in a busbar trunking system as functions of the 3rd harmonic level.

2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

The layout of the trunking system depends on the position of the current consumers, the location of the power source and the possibilities for fixing the system.

- One single distribution line serves a 4 to 6 meter area
- Protection devices for current consumers are placed in tap-off units, connected directly to usage points.
- One single feeder supplies all current consumers of different powers.

Once the trunking system layout is established, it is possible to calculate the absorbed current I_n on the distribution line.

I_n is equal to the sum of absorbed currents by the current I_n consumers: $I_n = \Sigma I_B$.
The current consumers do not all work at the same time and are not permanently on full load, so we have to use a clustering coefficient k_S : $I_n = \Sigma (I_B . k_S)$.

Application	Number of current consumers	Ks Coefficient
Lighting, Heating		1
Distribution (engineering workshop)	2...3	0.9
	4...5	0.8
	6...9	0.7
	10...40	0.6
	40 and over	0.5

Note : for industrial installations, remember to take account of upgrading of the machine equipment base. As for a switchboard, a 20 % margin is recommended:
$I_n \leq I_B \times k_s \times 1.2$.

Fig G24 : *Clustering coefficient according to the number of current consumers*

3 Determination of voltage drop

The impedance of circuit conductors is low but not negligible: when carrying load current there is a voltage drop between the origin of the circuit and the load terminals. The correct operation of a load (a motor, lighting circuit, etc.) depends on the voltage at its terminals being maintained at a value close to its rated value. It is necessary therefore to determine the circuit conductors such that at full-load current, the load terminal voltage is maintained within the limits required for correct performance.

This section deals with methods of determining voltage drops, in order to check that:

- They comply with the particular standards and regulations in force
- They can be tolerated by the load
- They satisfy the essential operational requirements

3.1 Maximum voltage drop

Maximum allowable voltage-drop vary from one country to another. Typical values for LV installations are given below in **Figure G25**.

Type of installations	Lighting circuits	Other uses (heating and power)
A low-voltage service connection from a LV public power distribution network	3%	5%
Consumers MV/LV substation supplied from a public distribution MV system	6%	8%

Fig. G25 : Maximum voltage-drop between the service-connection point and the point of utilization

These voltage-drop limits refer to normal steady-state operating conditions and do not apply at times of motor starting, simultaneous switching (by chance) of several loads, etc. as mentioned in Chapter A Sub-clause 4.3 (factor of simultaneity, etc.).

When voltage drops exceed the values shown in Figure G25, larger cables (wires) must be used to correct the condition.

The value of 8%, while permitted, can lead to problems for motor loads; for example:

- In general, satisfactory motor performance requires a voltage within ± 5% of its rated nominal value in steady-state operation,
- Starting current of a motor can be 5 to 7 times its full-load value (or even higher). If an 8% voltage drop occurs at full-load current, then a drop of 40% or more will occur during start-up. In such conditions the motor will either:
  - Stall (i.e. remain stationary due to insufficient torque to overcome the load torque) with consequent over-heating and eventual trip-out
  - Or accelerate very slowly, so that the heavy current loading (with possibly undesirable low-voltage effects on other equipment) will continue beyond the normal start-up period
- Finally an 8% voltage drop represents a continuous power loss, which, for continuous loads will be a significant waste of (metered) energy. For these reasons it is recommended that the maximum value of 8% in steady operating conditions should not be reached on circuits which are sensitive to under-voltage problems (see **Fig. G26**).

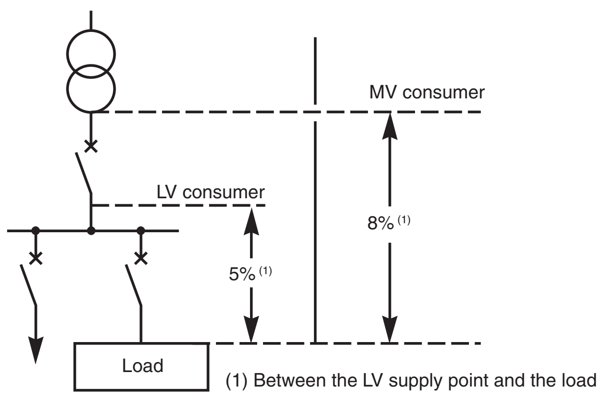


Fig. G26 : Maximum voltage drop

3 Determination of voltage drop

3.2 Calculation of voltage drop in steady load conditions

Use of formulae

Figure G27 below gives formulae commonly used to calculate voltage drop in a given circuit per kilometre of length.

If:

- I_B: The full load current in amps
- L: Length of the cable in kilometres
- R: Resistance of the cable conductor in Ω/km

$$R = \frac{22.5\ \Omega\ mm^2/km}{S(c.s.a.\ in\ mm^2)} \text{ for copper}$$

$$R = \frac{36\ \Omega\ mm^2/km}{S(c.s.a.\ in\ mm^2)} \text{ for aluminium}$$

Note: R is negligible above a c.s.a. of 500 mm^2

- X: inductive reactance of a conductor in Ω/km

Note: X is negligible for conductors of c.s.a. less than 50 mm^2. In the absence of any other information, take X as being equal to 0.08 Ω/km.

- φ: phase angle between voltage and current in the circuit considered, generally:
  - Incandescent lighting: cos φ = 1
  - Motor power:
    - At start-up: cos φ = 0.35
    - In normal service: cos φ = 0.8
- Un: phase-to-phase voltage
- Vn: phase-to-neutral voltage

For prefabricated pre-wired ducts and bustrunking, resistance and inductive reactance values are given by the manufacturer.

Circuit	Voltage drop (ΔU) in volts	in %
Single phase: phase/phase	$\Delta U = 2 I_B (R \cos\varphi + X \sin\varphi) L$	$\frac{100\ \Delta U}{Un}$
Single phase: phase/neutral	$\Delta U = 2 I_B (R \cos\varphi + X \sin\varphi) L$	$\frac{100\ \Delta U}{Vn}$
Balanced 3-phase: 3 phases (with or without neutral)	$\Delta U = \sqrt{3}\, I_B (R \cos\varphi + X \sin\varphi) L$	$\frac{100\ \Delta U}{Un}$

Fig. G27 : Voltage-drop formulae

Simplified table

Calculations may be avoided by using **Figure G28** next page, which gives, with an adequate approximation, the phase-to-phase voltage drop per km of cable per ampere, in terms of:

- Kinds of circuit use: motor circuits with cos φ close to 0.8, or lighting with a cos φ close to 1.
- Type of cable; single-phase or 3-phase

Voltage drop in a cable is then given by:

K x I_B x L

K is given by the table,

I_B is the full-load current in amps,

L is the length of cable in km.

The column motor power "cos φ = 0.35" of Figure G28 may be used to compute the voltage drop occurring during the start-up period of a motor (see example no. 1 after the Figure G28).

3 Determination of voltage drop

c.s.a. in mm²		Single-phase circuit			Balanced three-phase circuit		
		Motor power		Lighting	Motor power		Lighting
		Normal service	Start-up		Normal service	Start-up	
Cu	Al	cos φ = 0.8	cos φ = 0.35	cos φ = 1	cos φ = 0.8	cos φ = 0.35	cos φ = 1
1.5		24	10.6	30	20	9.4	25
2.5		14.4	6.4	18	12	5.7	15
4		9.1	4.1	11.2	8	3.6	9.5
6	10	6.1	2.9	7.5	5.3	2.5	6.2
10	16	3.7	1.7	4.5	3.2	1.5	3.6
16	25	2.36	1.15	2.8	2.05	1	2.4
25	35	1.5	0.75	1.8	1.3	0.65	1.5
35	50	1.15	0.6	1.29	1	0.52	1.1
50	70	0.86	0.47	0.95	0.75	0.41	0.77
70	120	0.64	0.37	0.64	0.56	0.32	0.55
95	150	0.48	0.30	0.47	0.42	0.26	0.4
120	185	0.39	0.26	0.37	0.34	0.23	0.31
150	240	0.33	0.24	0.30	0.29	0.21	0.27
185	300	0.29	0.22	0.24	0.25	0.19	0.2
240	400	0.24	0.2	0.19	0.21	0.17	0.16
300	500	0.21	0.19	0.15	0.18	0.16	0.13

Fig. G28 : Phase-to-phase voltage drop ΔU for a circuit, in volts per ampere per km

Examples

Example 1 (see **Fig. G29**)

A three-phase 35 mm² copper cable 50 metres long supplies a 400 V motor taking:

- 100 A at a cos φ = 0.8 on normal permanent load
- 500 A (5 In) at a cos φ = 0.35 during start-up

The voltage drop at the origin of the motor cable in normal circumstances (i.e. with the distribution board of Figure G29 distributing a total of 1,000 A) is 10 V phase-to-phase.

What is the voltage drop at the motor terminals:

- In normal service?
- During start-up?

Solution:

- Voltage drop in normal service conditions:

$$\Delta U\% = 100\frac{\Delta U}{Un}$$

Table G28 shows 1 V/A/km so that:

ΔU for the cable = 1 x 100 x 0.05 = 5 V

ΔU total = 10 + 5 = 15 V = i.e.

$$\frac{15}{400} \times 100 = 3.75\%$$

This value is less than that authorized (8%) and is satisfactory.

- Voltage drop during motor start-up:

ΔUcable = 0.52 x 500 x 0.05 = 13 V

Owing to the additional current taken by the motor when starting, the voltage drop at the distribution board will exceed 10 Volts.

Supposing that the infeed to the distribution board during motor starting is 900 + 500 = 1,400 A then the voltage drop at the distribution board will increase approximately pro rata, i.e.

$$\frac{10 \times 1,400}{1,000} = 14 \text{ V}$$

ΔU distribution board = 14 V

ΔU for the motor cable = 13 V

ΔU total = 13 + 14 = 27 V i.e.

$$\frac{27}{400} \times 100 = 6.75\%$$

a value which is satisfactory during motor starting.

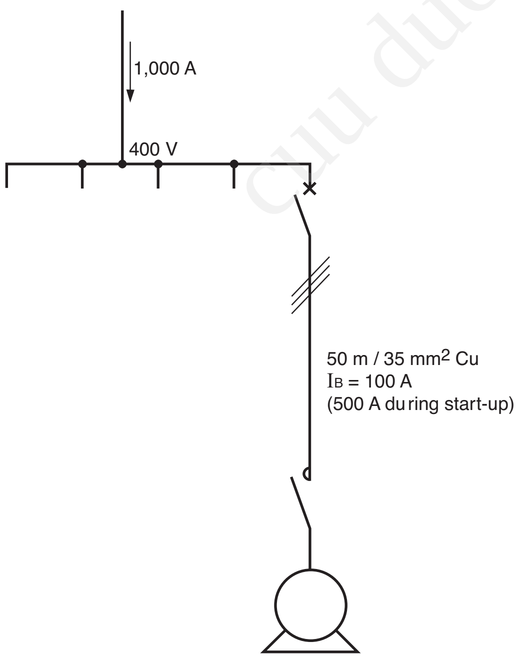


Fig. G29 : Example 1

3 Determination of voltage drop

Example 2 (see **Fig. G30**)
A 3-phase 4-wire copper line of 70 mm^2 c.s.a. and a length of 50 m passes a current of 150 A. The line supplies, among other loads, 3 single-phase lighting circuits, each of 2.5 mm^2 c.s.a. copper 20 m long, and each passing 20 A.
It is assumed that the currents in the 70 mm^2 line are balanced and that the three lighting circuits are all connected to it at the same point.

What is the voltage drop at the end of the lighting circuits?

Solution:

- Voltage drop in the 4-wire line:

$$\Delta U\% = 100\frac{\Delta U}{Un}$$

Figure G28 shows 0.55 V/A/km

ΔU line = 0.55 x 150 x 0.05 = 4.125 V phase-to-phase

which gives: $\frac{4.125}{\sqrt{3}} = 2.38\text{ V}$ phase to neutral.

- Voltage drop in any one of the lighting single-phase circuits:

ΔU for a single-phase circuit = 18 x 20 x 0.02 = 7.2 V

The total voltage drop is therefore

7.2 + 2.38 = 9.6 V

$$\frac{9.6\text{ V}}{230\text{ V}} \text{ x } 100 = 4.2\%$$

This value is satisfactory, being less than the maximum permitted voltage drop of 6%.

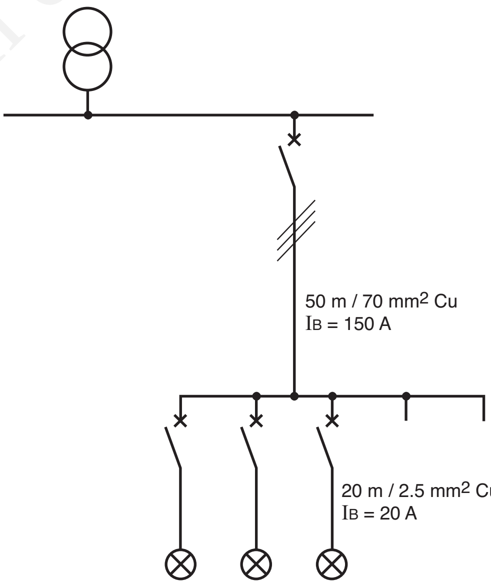


Fig. G30 : Example 2

4 Short-circuit current

Knowing the levels of 3-phase symmetrical short-circuit currents (Isc) at different points in an installation is an essential feature of its design

A knowledge of 3-phase symmetrical short-circuit current values (Isc) at strategic points of an installation is necessary in order to determine switchgear (fault current rating), cables (thermal withstand rating), protective devices (discriminative trip settings) and so on...

In the following notes a 3-phase short-circuit of zero impedance (the so-called bolted short-circuit) fed through a typical MV/LV distribution transformer will be examined. Except in very unusual circumstances, this type of fault is the most severe, and is certainly the simplest to calculate.

Short-circuit currents occurring in a network supplied from a generator and also in DC systems are dealt with in Chapter N.

The simplified calculations and practical rules which follow give conservative results of sufficient accuracy, in the large majority of cases, for installation design purposes.

4.1 Short-circuit current at the secondary terminals of a MV/LV distribution transformer

The case of one transformer

■ In a simplified approach, the impedance of the MV system is assumed to be negligibly small, so that: $Isc = \frac{In \times 100}{Usc}$ where $In = \frac{P \times 10^3}{U_{20}\sqrt{3}}$ and:

P = kVA rating of the transformer
U_{20} = phase-to-phase secondary volts on open circuit
In = nominal current in amps
Isc = short-circuit fault current in amps
Usc = short-circuit impedance voltage of the transformer in %.

Typical values of Usc for distribution transformers are given in **Figure G31**.

Transformer rating (kVA)	Usc in %	
	Oil-immersed	Cast-resin dry type
50 to 750	4	6
800 to 3,200	6	6

Fig. G31 : Typical values of Usc for different kVA ratings of transformers with MV windings ⩽ 20 kV

■ **Example**

400 kVA transformer, 420 V at no load
Usc = 4%

$In = \frac{400 \times 10^3}{420 \times \sqrt{3}} = 550$ A $\quad Isc = \frac{550 \times 100}{4} = 13.7$ kA

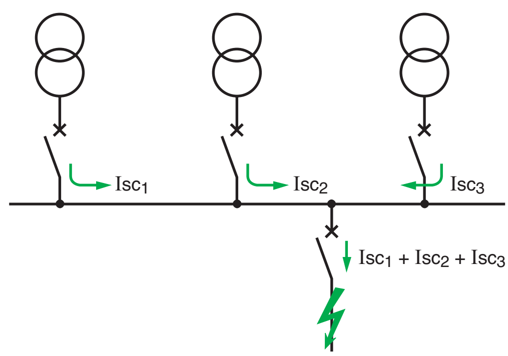


Fig. G32 : Case of several transformers in parallel

The case of several transformers in parallel feeding a busbar

The value of fault current on an outgoing circuit immediately downstream of the busbars (see **Fig. G32**) can be estimated as the sum of the Isc from each transformer calculated separately.

It is assumed that all transformers are supplied from the same MV network, in which case the values obtained from Figure G31 when added together will give a slightly higher fault-level value than would actually occur.

Other factors which have not been taken into account are the impedance of the busbars and of the circuit-breakers.

The conservative fault-current value obtained however, is sufficiently accurate for basic installation design purposes. The choice of circuit-breakers and incorporated protective devices against short-circuit fault currents is described in Chapter H Sub-clause 4.4.

4.2 3-phase short-circuit current (Isc) at any point within a LV installation

In a 3-phase installation Isc at any point is given by:

$$Isc = \frac{U_{20}}{\sqrt{3}\,Z_T} \quad \text{where}$$

U_{20} = phase-to-phase voltage of the open circuited secondary windings of the power supply transformer(s).

Z_T = total impedance per phase of the installation upstream of the fault location (in Ω)

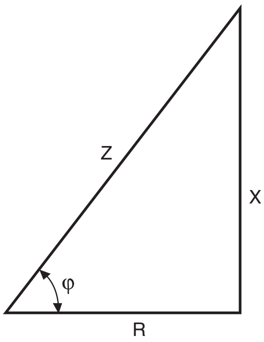


Fig. G33 : Impedance diagram

Method of calculating Z_T

Each component of an installation (MV network, transformer, cable, circuit-breaker, busbar, and so on...) is characterized by its impedance Z, comprising an element of resistance (R) and an inductive reactance (X). It may be noted that capacitive reactances are not important in short-circuit current calculations.

The parameters R, X and Z are expressed in ohms, and are related by the sides of a right angled triangle, as shown in the impedance diagram of **Figure G33**.

The method consists in dividing the network into convenient sections, and to calculate the R and X values for each.

Where sections are connected in series in the network, all the resistive elements in the section are added arithmetically; likewise for the reactances, to give R_T and X_T. The impedance (Z_T) for the combined sections concerned is then calculated from

$$Z_T = \sqrt{{R_T}^2 + {X_T}^2}$$

Any two sections of the network which are connected in parallel, can, if predominantly both resistive (or both inductive) be combined to give a single equivalent resistance (or reactance) as follows:

Let R1 and R2 be the two resistances connected in parallel, then the equivalent resistance R3 will be given by:

$$R3 = \frac{R1 \times R2}{R1 + R2} \quad \text{or for reactances} \quad X3 = \frac{X1 \times X2}{X1 + X2}$$

It should be noted that the calculation of X3 concerns only separated circuit without mutual inductance. If the circuits in parallel are close togother the value of X3 will be notably higher.

Determination of the impedance of each component

■ **Network upstream of the MV/LV transformer** (see **Fig. G34**)

The 3-phase short-circuit fault level P_{SC}, in kA or in MVA(1) is given by the power supply authority concerned, from which an equivalent impedance can be deduced.

Psc	Uo (V)	Ra (mΩ)	Xa (mΩ)
250 MVA	420	0.07	0.7
500 MVA	420	0.035	0.351

Fig. G34 : The impedance of the MV network referred to the LV side of the MV/LV transformer

A formula which makes this deduction and at the same time converts the impedance to an equivalent value at LV is given, as follows:

$$Zs = \frac{{U_0}^2}{Psc}$$

where

Zs = impedance of the MV voltage network, expressed in milli-ohms

Uo = phase-to-phase no-load LV voltage, expressed in volts

Psc = MV 3-phase short-circuit fault level, expressed in kVA

The upstream (MV) resistance Ra is generally found to be negligible compared with the corresponding Xa, the latter then being taken as the ohmic value for Za. If more accurate calculations are necessary, Xa may be taken to be equal to 0.995 Za and Ra equal to 0.1 Xa.

Figure G36 gives values for Ra and Xa corresponding to the most common MV(2) short-circuit levels in utility power-supply networks, namely, 250 MVA and 500 MVA.

(1) Short-circuit MVA: $\sqrt{3}\ E_L\ Isc$ where:
■ E_L = phase-to-phase nominal system voltage expressed in kV (r.m.s.)
■ Isc = 3-phase short-circuit current expressed in kA (r.m.s.)
(2) up to 36 kV

■ **Transformers** (see **Fig. G35**)

The impedance Ztr of a transformer, viewed from the LV terminals, is given by the formula:

$$Ztr = \frac{U_{20}^2}{Pn} \times \frac{Usc}{100}$$

where:

U_{20} = open-circuit secondary phase-to-phase voltage expressed in volts

Pn = rating of the transformer (in kVA)

Usc = the short-circuit impedance voltage of the transformer expressed in %

The transformer windings resistance Rtr can be derived from the total losses as follows:

$$Pcu = 3In^2 \times Rtr \text{ so that } Rtr = \frac{Pcu \times 10^3}{3In^2} \text{ in milli-ohms}$$

where

Pcu = total losses in watts

In = nominal full-load current in amps

Rtr = resistance of one phase of the transformer in milli-ohms (the LV and corresponding MV winding for one LV phase are included in this resistance value).

$$Xtr = \sqrt{Ztr^2 - Rtr^2}$$

For an approximate calculation Rtr may be ignored since X ≈ Z in standard distribution type transformers.

Rated Power (kVA)	Oil-immersed				Cast-resin			
	Usc (%)	Rtr (mΩ)	Xtr (mΩ)	Ztr (mΩ)	Usc (%)	Rtr (mΩ)	Xtr (mΩ)	Ztr (mΩ)
100	4	37.9	59.5	70.6	6	37.0	99.1	105.8
160	4	16.2	41.0	44.1	6	18.6	63.5	66.2
200	4	11.9	33.2	35.3	6	14.1	51.0	52.9
250	4	9.2	26.7	28.2	6	10.7	41.0	42.3
315	4	6.2	21.5	22.4	6	8.0	32.6	33.6
400	4	5.1	16.9	17.6	6	6.1	25.8	26.5
500	4	3.8	13.6	14.1	6	4.6	20.7	21.2
630	4	2.9	10.8	11.2	6	3.5	16.4	16.8
800	6	2.9	12.9	13.2	6	2.6	13.0	13.2
1,000	6	2.3	10.3	10.6	6	1.9	10.4	10.6
1,250	6	1.8	8.3	8.5	6	1.5	8.3	8.5
1,600	6	1.4	6.5	6.6	6	1.1	6.5	6.6
2,000	6	1.1	5.2	5.3	6	0.9	5.2	5.3

Fig. G35 : Resistance, reactance and impedance values for typical distribution 400 V transformers with MV windings ⩽ 20 kV

■ **Circuit-breakers**

In LV circuits, the impedance of circuit-breakers upstream of the fault location must be taken into account. The reactance value conventionally assumed is 0.15 mΩ per CB, while the resistance is neglected.

■ **Busbars**

The resistance of busbars is generally negligible, so that the impedance is practically all reactive, and amounts to approximately 0.15 mΩ/metre(1) length for LV busbars (doubling the spacing between the bars increases the reactance by about 10% only).

■ **Circuit conductors**

The resistance of a conductor is given by the formula: $Rc = \rho \frac{L}{S}$

where

ρ = the resistivity constant of the conductor material at the normal operating temperature being:

□ 22.5 mΩ.mm²/m for copper

□ 36 mΩ.mm²/m for aluminium

L = length of the conductor in m

S = c.s.a. of conductor in mm²

(1) For 50 Hz systems, but 0.18 mΩ/m length at 60 Hz

Cable reactance values can be obtained from the manufacturers. For c.s.a. of less than 50 mm² reactance may be ignored. In the absence of other information, a value of 0.08 mΩ/metre may be used (for 50 Hz systems) or 0.096 mΩ/metre (for 60 Hz systems). For prefabricated bus-trunking and similar pre-wired ducting systems, the manufacturer should be consulted.

■ **Motors**

At the instant of short-circuit, a running motor will act (for a brief period) as a generator, and feed current into the fault.

In general, this fault-current contribution may be ignored. However, if the total power of motors running simultaneously is higher than 25% of the total power of transformers, the influence of motors must be taken into account. Their total contribution can be estimated from the formula:

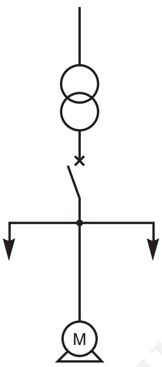
Iscm = 3.5 In from each motor i.e. 3.5*m*In for *m* similar motors operating concurrently.

The motors concerned will be the 3-phase motors only; single-phase-motor contribution being insignificant.

■ **Fault-arc resistance**

Short-circuit faults generally form an arc which has the properties of a resistance. The resistance is not stable and its average value is low, but at low voltage this resistance is sufficient to reduce the fault-current to some extent. Experience has shown that a reduction of the order of 20% may be expected. This phenomenon will effectively ease the current-breaking duty of a CB, but affords no relief for its fault-current making duty.

■ Recapitulation table (see **Fig. G36**)



Parts of power-supply system	R (mΩ)	X (mΩ)
Supply network Figure G34	$\frac{Ra}{Xa} = 0.1$	$Xa = 0.995\ Za;\ Za = \frac{U_{20}^2}{Psc}$
Transformer Figure G35	$Rtr = \frac{Pcu \times 10^3}{3 In^2}$ Rtr is often negligible compared to Xtr for transformers > 100 kVA	$\sqrt{Ztr^2 - Rtr^2}$ with $Ztr = \frac{U_{20}^2}{Pn} \times \frac{Usc}{100}$
Circuit-breaker	Negligible	XD = 0.15 mΩ/pole
Busbars	Negligible for S > 200 mm² in the formula: $R = \rho \frac{L}{S}$ (1)	XB = 0.15 mΩ/m
Circuit conductors(2)	$R = \rho \frac{L}{S}$ (1)	Cables: Xc = 0.08 mΩ/m
Motors	See Sub-clause 4.2 Motors (often negligible at LV)	
Three-phase short circuit current in kA	$Isc = \frac{U_{20}}{\sqrt{3}\sqrt{R_T^2 + X_T^2}}$	

U_{20}: Phase-to-phase no-load secondary voltage of MV/LV transformer (in volts).

Psc: 3-phase short-circuit power at MV terminals of the MV/LV transformers (in kVA).

Pcu: 3-phase total losses of the MV/LV transformer (in watts).

Pn: Rating of the MV/LV transformer (in kVA).

Usc: Short-circuit impedance voltage of the MV/LV transfomer (in %).

R_T : Total resistance. X_T: Total reactance

(1) ρ = resistivity at normal temperature of conductors in service

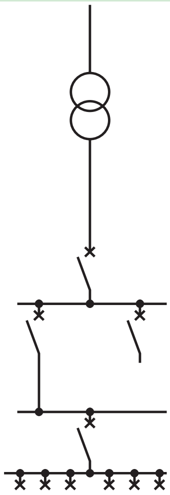
■ ρ = 22.5 mΩ x mm²/m for copper

■ ρ = 36 mΩ x mm²/m for aluminium

(2) If there are several conductors in parallel per phase, then divide the resistance of one conductor by the number of conductors. The reactance remains practically unchanged.

Fig. G36 : Recapitulation table of impedances for different parts of a power-supply system

■ Example of short-circuit calculations (see **Fig. G37**)



LV installation	R (mΩ)	X (mΩ)	RT (mΩ)	XT (mΩ)	$I_{sc} = \frac{420}{\sqrt{3}\sqrt{R_T^2 + X_T^2}}$
MV network Psc = 500 MVA	0.035	0.351			
Transformer 20 kV/420 V Pn = 1000 kVA Usc = 5% Pcu = 13.3 x 10^3 watts	2.24	8.10			
Single-core cables 5 m copper 4 x 240 mm²/phase	$R_C = \frac{22.5}{4} \times \frac{5}{240} = 0.12$	X_C = 0.08 x 5 = 0.40	2.41	8.85	I_{sc1} = 26 kA
Main circuit-breaker	R_D = 0	X_D = 0.15			
Busbars 10 m	R_B = 0	X_B = 1.5	2.41	10.5	I_{sc2} = 22 kA
Three-core cable 100 m 95 mm² copper	$R_C = 22.5 \times \frac{100}{95} = 23.68$	X_C = 100 x 0.08 = 8	26.1	18.5	I_{sc3} = 7.4 kA
Three-core cable 20 m 10 mm² copper final circuits	$R_C = 22.5 \times \frac{20}{10} = 45$	X_C = 20 x 0.08 = 1.6	71.1	20.1	I_{sc4} = 3.2 kA

Fig. G37 : Example of short-circuit current calculations for a LV installation supplied at 400 V (nominal) from a 1,000 kVA MV/LV transformer

4.3 Isc at the receiving end of a feeder as a function of the Isc at its sending end

The network shown in **Figure G38** typifies a case for the application of **Figure G39** next page, derived by the «method of composition» (mentioned in Chapter F Sub-clause 6.2). These tables give a rapid and sufficiently accurate value of short-circuit current at a point in a network, knowing:

■ The value of short-circuit current upstream of the point considered

■ The length and composition of the circuit between the point at which the short-circuit current level is known, and the point at which the level is to be determined

It is then sufficient to select a circuit-breaker with an appropriate short-circuit fault rating immediately above that indicated in the tables.

If more precise values are required, it is possible to make a detailled calculation (see Sub-Clause 4.2) or to use a software package, such as Ecodial. In such a case, moreover, the possibility of using the cascading technique should be considered, in which the use of a current limiting circuit-breaker at the upstream position would allow all circuit-breakers downstream of the limiter to have a short-circuit current rating much lower than would otherwise be necessary (See chapter H Sub-Clause 4.5).

Method

Select the c.s.a. of the conductor in the column for copper conductors (in this example the c.s.a. is 47.5 mm²).

Search along the row corresponding to 47.5 mm² for the length of conductor equal to that of the circuit concerned (or the nearest possible on the low side). Descend vertically the column in which the length is located, and stop at a row in the middle section (of the 3 sections of the Figure) corresponding to the known fault-current level (or the nearest to it on the high side).

In this case 30 kA is the nearest to 28 kA on the high side. The value of short-circuit current at the downstream end of the 20 metre circuit is given at the intersection of the vertical column in which the length is located, and the horizontal row corresponding to the upstream Isc (or nearest to it on the high side).

This value in the example is seen to be 14.7 kA.

The procedure for aluminium conductors is similar, but the vertical column must be ascended into the middle section of the table.

In consequence, a DIN-rail-mounted circuit-breaker rated at 63 A and Isc of 25 kA (such as a NG 125N unit) can be used for the 55 A circuit in Figure G38.

A Compact rated at 160 A with an Isc capacity of 25 kA (such as a NS160 unit) can be used to protect the 160 A circuit.

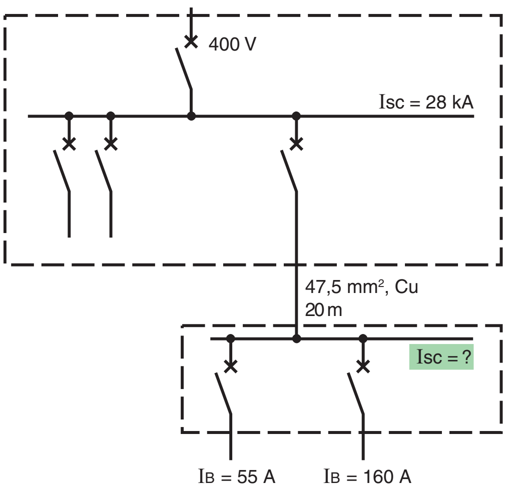


Fig. G38 : Determination of downstream short-circuit current level Isc using Figure G39

Copper 230 V / 400 V																						
c.s.a. of phase conductors (mm²)	Length of circuit (in metres)																					
1.5														1.3	1.8	2.6	3.6	5.2	7.3	10.3	14.6	21
2.5												1.1	1.5	2.1	3.0	4.3	6.1	8.6	12.1	17.2	24	34
4											1.2	1.7	2.4	3.4	4.9	6.9	9.7	13.7	19.4	27	39	55
6											1.8	2.6	3.6	5.2	7.3	10.3	14.6	21	29	41	58	82
10										2.2	3.0	4.3	6.1	8.6	12.2	17.2	24	34	49	69	97	137
16								1.7	2.4	3.4	4.9	6.9	9.7	13.8	19.4	27	39	55	78	110	155	220
25						1.3	1.9	2.7	3.8	5.4	7.6	10.8	15.2	21	30	43	61	86	121	172	243	343
35						1.9	2.7	3.8	5.3	7.5	10.6	15.1	21	30	43	60	85	120	170	240	340	480
47.5					1.8	2.6	3.6	5.1	7.2	10.2	14.4	20	29	41	58	82	115	163	231	326	461	
70					2.7	3.8	5.3	7.5	10.7	15.1	21	30	43	60	85	120	170	240	340			
95				2.6	3.6	5.1	7.2	10.2	14.5	20	29	41	58	82	115	163	231	326	461			
120		1.6	2.3	3.2	4.6	6.5	9.1	12.9	18.3	26	37	52	73	103	146	206	291	412				
150	1.2	1.8	2.5	3.5	5.0	7.0	9.9	14.0	19.8	28	40	56	79	112	159	224	317	448				
185	1.5	2.1	2.9	4.2	5.9	8.3	11.7	16.6	23	33	47	66	94	133	187	265	374	529				
240	1.8	2.6	3.7	5.2	7.3	10.3	14.6	21	29	41	58	83	117	165	233	330	466	659				
300	2.2	3.1	4.4	6.2	8.8	12.4	17.6	25	35	50	70	99	140	198	280	396	561					
2x120	2.3	3.2	4.6	6.5	9.1	12.9	18.3	26	37	52	73	103	146	206	292	412	583					
2x150	2.5	3.5	5.0	7.0	9.9	14.0	20	28	40	56	79	112	159	224	317	448	634					
2x185	2.9	4.2	5.9	8.3	11.7	16.6	23	33	47	66	94	133	187	265	375	530	749					
553x120	3.4	4.9	6.9	9.7	13.7	19.4	27	39	55	77	110	155	219	309	438	619						
3x150	3.7	5.3	7.5	10.5	14.9	21	30	42	60	84	119	168	238	336	476	672						
3x185	4.4	6.2	8.8	12.5	17.6	25	35	50	70	100	141	199	281	398	562							
Isc upstream (in kA)	Isc downstream (in kA)																					
100	93	90	87	82	77	70	62	54	45	37	29	22	17.0	12.6	9.3	6.7	4.9	3.5	2.5	1.8	1.3	0.9
90	84	82	79	75	71	65	58	51	43	35	28	22	16.7	12.5	9.2	6.7	4.8	3.5	2.5	1.8	1.3	0.9
80	75	74	71	68	64	59	54	47	40	34	27	21	16.3	12.2	9.1	6.6	4.8	3.5	2.5	1.8	1.3	0.9
70	66	65	63	61	58	54	49	44	38	32	26	20	15.8	12.0	8.9	6.6	4.8	3.4	2.5	1.8	1.3	0.9
60	57	56	55	53	51	48	44	39	35	29	24	20	15.2	11.6	8.7	6.5	4.7	3.4	2.5	1.8	1.3	0.9
50	48	47	46	45	43	41	38	35	31	27	22	18.3	14.5	11.2	8.5	6.3	4.6	3.4	2.4	1.7	1.2	0.9
40	39	38	38	37	36	34	32	30	27	24	20	16.8	13.5	10.6	8.1	6.1	4.5	3.3	2.4	1.7	1.2	0.9
35	34	34	33	33	32	30	29	27	24	22	18.8	15.8	12.9	10.2	7.9	6.0	4.5	3.3	2.4	1.7	1.2	0.9
30	29	29	29	28	27	27	25	24	22	20	17.3	14.7	12.2	9.8	7.6	5.8	4.4	3.2	2.4	1.7	1.2	0.9
25	25	24	24	24	23	23	22	21	19.1	17.4	15.5	13.4	11.2	9.2	7.3	5.6	4.2	3.2	2.3	1.7	1.2	0.9
20	20	20	19.4	19.2	18.8	18.4	17.8	17.0	16.1	14.9	13.4	11.8	10.1	8.4	6.8	5.3	4.1	3.1	2.3	1.7	1.2	0.9
15	14.8	14.8	14.7	14.5	14.3	14.1	13.7	13.3	12.7	11.9	11.0	9.9	8.7	7.4	6.1	4.9	3.8	2.9	2.2	1.6	1.2	0.9
10	9.9	9.9	9.8	9.8	9.7	9.6	9.4	9.2	8.9	8.5	8.0	7.4	6.7	5.9	5.1	4.2	3.4	2.7	2.0	1.5	1.1	0.8
7	7.0	6.9	6.9	6.9	6.9	6.8	6.7	6.6	6.4	6.2	6.0	5.6	5.2	4.7	4.2	3.6	3.0	2.4	1.9	1.4	1.1	0.8
5	5.0	5.0	5.0	4.9	4.9	4.9	4.9	4.8	4.7	4.6	4.5	4.3	4.0	3.7	3.4	3.0	2.5	2.1	1.7	1.3	1.0	0.8
4	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.9	3.8	3.7	3.6	3.5	3.3	3.1	2.9	2.6	2.2	1.9	1.6	1.2	1.0	0.7
3	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.8	2.7	2.6	2.5	2.3	2.1	1.9	1.6	1.4	1.1	0.9	0.7
2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.7	1.6	1.4	1.3	1.1	1.0	0.8	0.6
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.7	0.6	0.6	0.5
Aluminium 230 V / 400 V																						
c.s.a. of phase conductors (mm²)	Length of circuit (in metres)																					
2.5														1.4	1.9	2.7	3.8	5.4	7.6	10.8	15.3	22
4												1.1	1.5	2.2	3.1	4.3	6.1	8.6	12.2	17.3	24	35
6												1.6	2.3	3.2	4.6	6.5	9.2	13.0	18.3	26	37	52
10											1.9	2.7	3.8	5.4	7.7	10.8	15.3	22	31	43	61	86
16										2.2	3.1	4.3	6.1	8.7	12.2	17.3	24	35	49	69	98	138
25								1.7	2.4	3.4	4.8	6.8	9.6	13.5	19.1	27	38	54	76	108	153	216
35							1.7	2.4	3.4	4.7	6.7	9.5	13.4	18.9	27	38	54	76	107	151	214	302
47.5						1.6	2.3	3.2	4.6	6.4	9.1	12.9	18.2	26	36	51	73	103	145	205	290	410
70						2.4	3.4	4.7	6.7	9.5	13.4	19.0	27	38	54	76	107	151	214	303	428	
95					2.3	3.2	4.6	6.4	9.1	12.9	18.2	26	36	51	73	103	145	205	290	411		
120					2.9	4.1	5.8	8.1	11.5	16.3	23	32	46	65	92	130	184	259	367			
150					3.1	4.4	6.3	8.8	12.5	17.7	25	35	50	71	100	141	199	282	399			
185				2.6	3.7	5.2	7.4	10.4	14.8	21	30	42	59	83	118	167	236	333	471			
240	1.2	1.6	2.3	3.3	4.6	6.5	9.2	13.0	18.4	26	37	52	73	104	147	208	294	415				
300	1.4	2.0	2.8	3.9	5.5	7.8	11.1	15.6	22	31	44	62	88	125	177	250	353	499				
2x120	1.4	2.0	2.9	4.1	5.8	8.1	11.5	16.3	23	33	46	65	92	130	184	260	367	519				
2x150	1.6	2.2	3.1	4.4	6.3	8.8	12.5	17.7	25	35	50	71	100	141	200	282	399					
2x185	1.9	2.6	3.7	5.2	7.4	10.5	14.8	21	30	42	59	83	118	167	236	334	472					
2x240	2.3	3.3	4.6	6.5	9.2	13.0	18.4	26	37	52	74	104	147	208	294	415	587					
3x120	2.2	3.1	4.3	6.1	8.6	12.2	17.3	24	34	49	69	97	138	195	275	389	551					
3x150	2.3	3.3	4.7	6.6	9.4	13.3	18.8	27	37	53	75	106	150	212	299	423	598					
3x185	2.8	3.9	5.5	7.8	11.1	15.7	22	31	44	63	89	125	177	250	354	500	707					
3x240	3.5	4.9	6.9	9.8	13.8	19.5	28	39	55	78	110	156	220	312	441	623						

Note: for a 3-phase system having 230 V between phases, divide the above lengths by $\sqrt{3}$

Fig. G39 : Isc at a point downstream, as a function of a known upstream fault-current value and the length and c.s.a. of the intervening conductors, in a 230/400 V 3-phase system

4.4 Short-circuit current supplied by a generator or an inverter: Please refer to Chapter N

5 Particular cases of short-circuit current

5.1 Calculation of minimum levels of short-circuit current

If a protective device in a circuit is intended only to protect against short-circuit faults, it is essential that it will operate with certainty at the lowest possible level of short-circuit current that can occur on the circuit

In general, on LV circuits, a single protective device protects against all levels of current, from the overload threshold through the maximum rated short-circuit current-breaking capability of the device.

In certain cases, however, overload protective devices and separate short-circuit protective devices are used.

Examples of such arrangements

Figures G40 to **G42** show some common arrangements where overload and short-circuit protections are achieved by separate devices.

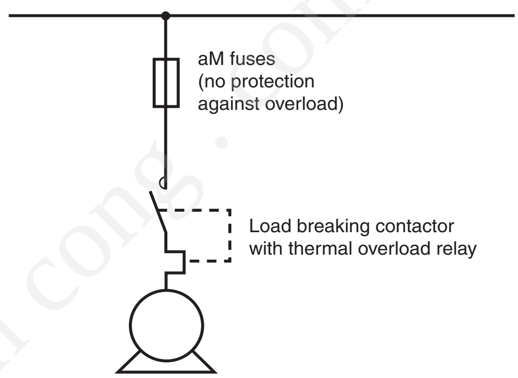


Fig. G40 : Circuit protected by aM fuses

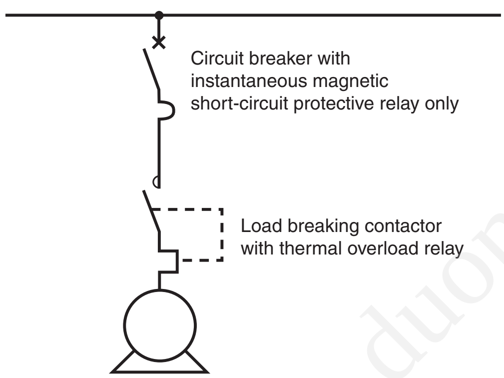


Fig. G41 : Circuit protected by circuit-breaker without thermal overload relay

As shown in Figures G40 and G41, the most common circuits using separate devices control and protect motors.

Figure G42a constitutes a derogation in the basic protection rules, and is generally used on circuits of prefabricated bustrunking, lighting rails, etc.

Variable speed drive

Figure G42b shows the functions provided by the variable speed drive, and if necessary some additional functions provided by devices such as circuit-breaker, thermal relay, RCD.

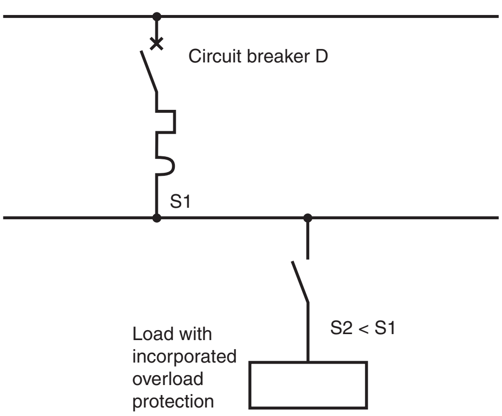


Fig. G42a : Circuit-breaker D provides protection against short-circuit faults as far as and including the load

Protection to be provided	Protection generally provided by the variable speed drive	Additional protection
Cable overload	Yes = (1)	Not necessary if (1)
Motor overload	Yes = (2)	Not necessary if (2)
Downstream short-circuit	Yes	
Variable speed drive overload	Yes	
Overvoltage	Yes	
Undervoltage	Yes	
Loss of phase	Yes	
Upstream short-circuit		Circuit-breaker (short-circuit tripping)
Internal fault		Circuit-breaker (short-circuit and overload tripping)
Downstream earth fault (indirect contact)	(self protection)	RCD ⩾ 300 mA
Direct contact fault		RCD ⩽ 30 mA

Figure G42b : Protection to be provided for variable speeed drive applications

5 Particular cases of short-circuit current

The protective device must fulfill:
- *instantaneous trip setting Im < Isc_{min} for a circuit-breaker*
- *fusion current Ia < Isc_{min} for a fuse*

Conditions to be fulfilled

The protective device must therefore satisfy the two following conditions:
- Its fault-current breaking rating must be greater than Isc, the 3-phase short-circuit current at its point of installation
- Elimination of the minimum short-circuit current possible in the circuit, in a time tc compatible with the thermal constraints of the circuit conductors, where:

$$tc \leqslant \frac{K^2S^2}{Isc_{min}^{\ 2}}$$ (valid for tc < 5 seconds)

Comparison of the tripping or fusing performance curve of protective devices, with the limit curves of thermal constraint for a conductor shows that this condition is satisfied if:
- Isc (min) > Im (instantaneous or short timedelay circuit-breaker trip setting current level), (see **Fig. G45**)
- Isc (min) > Ia for protection by fuses. The value of the current Ia corresponds to the crossing point of the fuse curve and the cable thermal withstand curve (see **Fig. G44** and **G45**)

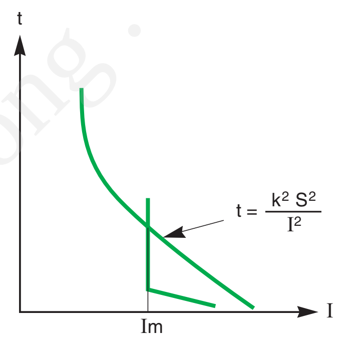


Fig. G45 : Protection by circuit-breaker

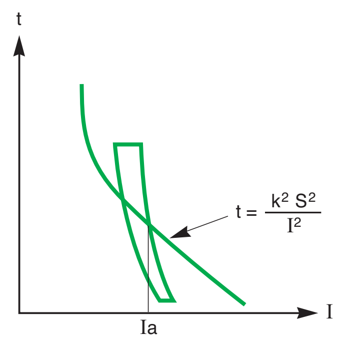


Fig. G46 : Protection by aM-type fuses

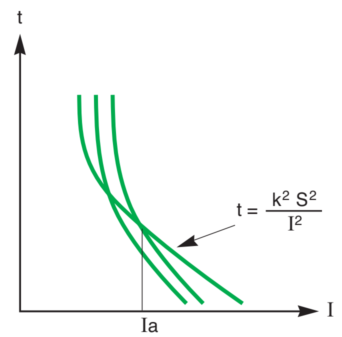


Fig. G47 : Protection by gl-type fuses

5 Particular cases of short-circuit current

In practice this means that the length of circuit downstream of the protective device must not exceed a calculated maximum length:

$$L_{max} = \frac{0.8\ U\ Sph}{2 \rho Im}$$

Practical method of calculating Lmax

The limiting effect of the impedance of long circuit conductors on the value of short-circuit currents must be checked and the length of a circuit must be restricted accordingly.

The method of calculating the maximum permitted length has already been demonstrated in TN- and IT- earthed schemes for single and double earth faults, respectively (see Chapter F Sub-clauses 6.2 and 7.2). Two cases are considered below:

1 - Calculation of L_{max} for a 3-phase 3-wire circuit

The minimum short-circuit current will occur when two phase wires are short-circuited at the remote end of the circuit (see **Fig. G46**).

Fig G46 : Definition of L for a 3-phase 3-wire circuit

Using the "conventional method", the voltage at the point of protection P is assumed to be 80% of the nominal voltage during a short-circuit fault, so that 0.8 U = Isc Zd, where:

Zd = impedance of the fault loop

Isc = short-circuit current (ph/ph)

U = phase-to-phase nominal voltage

For cables ⩽ 120 mm², reactance may be neglected, so that

$$Zd = \rho \frac{2L}{Sph} \ (1)$$

where:

ρ = resistivity of conductor material at the average temperature during a short-circuit,

Sph = c.s.a. of a phase conductor in mm²

L = length in metres

The condition for the cable protection is Im ⩽ Isc with Im = magnetic trip current setting of the CB.

This leads to $Im \leqslant \frac{0.8\ U}{Zd}$ which gives $L \leqslant \frac{0.8\ U\ Sph}{2 \rho Im}$

with U = 400 V

ρ = 1.25 x 0.018 = 0.023 Ω.mm²/m(2) (Cu)

Lmax = maximum circuit length in metres

$$L_{max} = \frac{k\ Sph}{Im}$$

2 - Calculation of Lmax for a 3-phase 4-wire 230/400 V circuit

The minimum Isc will occur when the short-circuit is between a phase conductor and the neutral.

A calculation similar to that of example 1 above is required, but using the following formulae (for cable ⩽ 120 mm² (1)).

- Where Sn for the neutral conductor = Sph for the phase conductor

$$L_{max} = \frac{3{,}333\ Sph}{Im}$$

- If Sn for the neutral conductor < Sph, then

$$L_{max} = 6{,}666 \frac{Sph}{Im} \frac{1}{1+m} \quad \text{where } m = \frac{Sph}{Sn}$$

For larger c.s.a.'s than those listed, reactance values must be combined with those of resistance to give an impedance. Reactance may be taken as 0.08 mΩ/m for cables (at 50 Hz). At 60 Hz the value is 0.096 mΩ/m.

(1) For larger c.s.a.'s, the resistance calculated for the conductors must be increased to account for the non-uniform current density in the conductor (due to "skin" and "proximity" effects)

Suitable values are as follows:

150 mm²: R + 15%

185 mm²: R + 20%

240 mm²: R + 25%

300 mm²: R + 30%

(2) The high value for resistivity is due to the elevated temperature of the conductor when passing short-circuit current

Tabulated values for Lmax

Figure G47 below gives maximum circuit lengths (Lmax) in metres, for:

- 3-phase 4-wire 400 V circuits (i.e. with neutral) and
- 1-phase 2-wire 230 V circuits

protected by general-purpose circuit-breakers.

In other cases, apply correction factors (given in Figure G53) to the lengths obtained. The calculations are based on the above methods, and a short-circuit trip level within ± 20% of the adjusted value Im.

For the 50 mm² c.s.a., calculation are based on a 47.5 mm² real c.s.a.

Operating current level Im of the instantaneous magnetic tripping element (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm²)														
	1.5	2.5	4	6	10	16	25	35	50	70	95	120	150	185	240
50	100	167	267	400											
63	79	133	212	317											
80	63	104	167	250	417										
100	50	83	133	200	333										
125	40	67	107	160	267	427									
160	31	52	83	125	208	333									
200	25	42	67	100	167	267	417								
250	20	33	53	80	133	213	333	467							
320	16	26	42	63	104	167	260	365	495						
400	13	21	33	50	83	133	208	292	396						
500	10	17	27	40	67	107	167	233	317						
560	9	15	24	36	60	95	149	208	283	417					
630	8	13	21	32	63	85	132	185	251	370					
700	7	12	19	29	48	76	119	167	226	333	452				
800	6	10	17	25	42	67	104	146	198	292	396				
875	6	10	15	23	38	61	95	133	181	267	362	457			
1000	5	8	13	20	33	53	83	117	158	233	317	400	435		
1120	4	7	12	18	30	48	74	104	141	208	283	357	388	459	
1250	4	7	11	16	27	43	67	93	127	187	253	320	348	411	
1600		5	8	13	21	33	52	73	99	146	198	250	272	321	400
2000		4	7	10	17	27	42	58	79	117	158	200	217	257	320
2500			5	8	13	21	33	47	63	93	127	160	174	206	256
3200			4	6	10	17	26	36	49	73	99	125	136	161	200
4000				5	8	13	21	29	40	58	79	100	109	128	160
5000				4	7	11	17	23	32	47	63	80	87	103	128
6300					5	8	13	19	25	37	50	63	69	82	102
8000					4	7	10	15	20	29	40	50	54	64	80
10000						5	8	12	16	23	32	40	43	51	64
12500						4	7	9	13	19	25	32	35	41	51

Fig. G47 : Maximum circuit lengths in metres for copper conductors (for aluminium, the lengths must be multiplied by 0.62)

Figures G48 to **G50** next page give maximum circuit length (Lmax) in metres for:

- 3-phase 4-wire 400 V circuits (i.e. with neutral) and
- 1-phase 2-wire 230 V circuits

protected in both cases by domestic-type circuit-breakers or with circuit-breakers having similar tripping/current characteristics.

In other cases, apply correction factors to the lengths indicated. These factors are given in **Figure G51** next page.

5 Particular cases of short-circuit current

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm^2)								
	1.5	2.5	4	6	10	16	25	35	50
6	200	333	533	800					
10	120	200	320	480	800				
16	75	125	200	300	500	800			
20	60	100	160	240	400	640			
25	48	80	128	192	320	512	800		
32	37	62	100	150	250	400	625	875	
40	30	50	80	120	200	320	500	700	
50	24	40	64	96	160	256	400	560	760
63	19	32	51	76	127	203	317	444	603
80	15	25	40	60	100	160	250	350	475
100	12	20	32	48	80	128	200	280	380
125	10	16	26	38	64	102	160	224	304

Fig. G48 : Maximum length of copper-conductor circuits in metres protected by B-type circuit-breakers

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm2)								
	1.5	2.5	4	6	10	16	25	35	50
6	100	167	267	400	667				
10	60	100	160	240	400	640			
16	37	62	100	150	250	400	625	875	
20	30	50	80	120	200	320	500	700	
25	24	40	64	96	160	256	400	560	760
32	18.0	31	50	75	125	200	313	438	594
40	15.0	25	40	60	100	160	250	350	475
50	12.0	20	32	48	80	128	200	280	380
63	9.5	16.0	26	38	64	102	159	222	302
80	7.5	12.5	20	30	50	80	125	175	238
100	6.0	10.0	16.0	24	40	64	100	140	190
125	5.0	8.0	13.0	19.0	32	51	80	112	152

Fig. G49 : Maximum length of copper-conductor circuits in metres protected by C-type circuit-breakers

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm2)								
	1.5	2.5	4	6	10	16	25	35	50
1	429	714							
2	214	357	571	857					
3	143	238	381	571	952				
4	107	179	286	429	714				
6	71	119	190	286	476	762			
10	43	71	114	171	286	457	714		
16	27	45	71	107	179	286	446	625	848
20	21	36	57	86	143	229	357	500	679
25	17.0	29	46	69	114	183	286	400	543
32	13.0	22	36	54	89	143	223	313	424
40	11.0	18.0	29	43	71	114	179	250	339
50	9.0	14.0	23	34	57	91	143	200	271
63	7.0	11.0	18.0	27	45	73	113	159	215
80	5.0	9.0	14.0	21	36	57	89	125	170
100	4.0	7.0	11.0	17.0	29	46	71	100	136
125	3.0	6.0	9.0	14.0	23	37	57	80	109

Fig. G50 : Maximum length of copper-conductor circuits in metres protected by D-type circuit-breakers

Circuit detail		
3-phase 3-wire 400 V circuit or 1-phase 2-wire 400 V circuit (no neutral)		1.73
1-phase 2-wire (phase and neutral) 230 V circuit		1
3-phase 4-wire 230/400 V circuit or 2-phase 3-wire 230/400 V circuit (i.e with neutral)	Sph / S neutral = 1	1
	Sph / S neutral = 2	0.67

Fig. G51 : Correction factor to apply to lengths obtained from Figures G47 to G50

Note: IEC 60898 accepts an upper short-circuit-current tripping range of 10-50 In for type D circuit-breakers. European standards, and Figure G50 however, are based on a range of 10-20 In, a range which covers the vast majority of domestic and similar installations.

5 Particular cases of short-circuit current

Examples

Example 1

In a 1-phase 2-wire installation the protection is provided by a 50 A circuit-breaker type NSX80HMA, the instantaneous short-circuit current trip, is set at 500 A (accuracy of ± 20%), i.e. in the worst case would require 500 x 1,2 = 600 A to trip. The cable c.s.a. = 10 mm^2 and the conductor material is copper.

In Figure G47, the row I_m = 500 A crosses the column c.s.a. = 10 mm^2 at the value for Lmax of 67 m. The circuit-breaker protects the cable against short-circuit faults, therefore, provided that its length does not exceed 67 metres.

Example 2

In a 3-phase 3-wire 400 V circuit (without neutral), the protection is provided by a 220 A circuit-breaker type NSX250N with an instantaneous short-circuit current trip unit type MA set at 2,000 A (± 20%), i.e. a worst case of 2,400 A to be certain of tripping. The cable c.s.a. = 120 mm^2 and the conductor material is copper.

In Figure G47 the row I_m = 2,000 A crosses the column c.s.a. = 120 mm^2 at the value for Lmax of 200 m. Being a 3-phase 3-wire 400 V circuit (without neutral), a correction factor from Figure G51 must be applied. This factor is seen to be 1.73. The circuit-breaker will therefore protect the cable against short-circuit current, provided that its length does not exceed 200 x 1.73= 346 metres.

5.2 Verification of the withstand capabilities of cables under short-circuit conditions

In general, verification of the thermal-withstand capability of a cable is not necessary, except in cases where cables of small c.s.a. are installed close to, or feeding directly from, the main general distribution board

Thermal constraints

When the duration of short-circuit current is brief (several tenths of a second up to five seconds maximum) all of the heat produced is assumed to remain in the conductor, causing its temperature to rise. The heating process is said to be adiabatic, an assumption that simplifies the calculation and gives a pessimistic result, i.e. a higher conductor temperature than that which would actually occur, since in practice, some heat would leave the conductor and pass into the insulation.

For a period of 5 seconds or less, the relationship $I^2t = k^2S^2$ characterizes the time in seconds during which a conductor of c.s.a. S (in mm^2) can be allowed to carry a current I, before its temperature reaches a level which would damage the surrounding insulation.

The factor k^2 is given in **Figure G52** below.

Insulation	Conductor copper (Cu)	Conductor aluminium (Al)
PVC	13,225	5,776
XLPE	20,449	8,836

Fig. G52 : Value of the constant k^2

The method of verification consists in checking that the thermal energy I^2t per ohm of conductor material, allowed to pass by the protecting circuit-breaker (from manufacturers catalogues) is less than that permitted for the particular conductor (as given in **Figure G53** below).

S (mm^2)	PVC		XLPE	
	Copper	Aluminium	Copper	Aluminium
1.5	0.0297	0.0130	0.0460	0.0199
2.5	0.0826	0.0361	0.1278	0.0552
4	0.2116	0.0924	0.3272	0.1414
6	0.4761	0.2079	0.7362	0.3181
10	1.3225	0.5776	2.0450	0.8836
16	3.3856	1.4786	5.2350	2.2620
25	8.2656	3.6100	12.7806	5.5225
35	16.2006	7.0756	25.0500	10.8241
50	29.839	13.032	46.133	19.936

Fig. G53 : Maximum allowable thermal stress for cables I^2t (expressed in ampere^2 x second x 10^6)

5 Particular cases of short-circuit current

Example

Is a copper-cored XLPE cable of 4 mm^2 c.s.a. adequately protected by a C60N circuit-breaker?

Figure G53 shows that the I^2t value for the cable is 0.3272 x 10^6, while the maximum "let-through" value by the circuit-breaker, as given in the manufacturer's catalogue, is considerably less (< 0.1.10^6 A^2s).

The cable is therefore adequately protected by the circuit-breaker up to its full rated breaking capability.

Electrodynamic constraints

For all type of circuit (conductors or bus-trunking), it is necessary to take electrodynamic effects into account.

To withstand the electrodynamic constraints, the conductors must be solidly fixed and the connection must be strongly tightened.

For bus-trunking, rails, etc. it is also necessary to verify that the electrodynamic withstand performance is satisfactory when carrying short-circuit currents. The peak value of current, limited by the circuit-breaker or fuse, must be less than the busbar system rating. Tables of coordination ensuring adequate protection of their products are generally published by the manufacturers and provide a major advantage of such systems.

6 Protective earthing conductor (PE)

6.1 Connection and choice

Protective (PE) conductors provide the bonding connection between all exposed and extraneous conductive parts of an installation, to create the main equipotential bonding system. These conductors conduct fault current due to insulation failure (between a phase conductor and an exposed conductive part) to the earthed neutral of the source. PE conductors are connected to the main earthing terminal of the installation.

The main earthing terminal is connected to the earthing electrode (see Chapter E) by the earthing conductor (grounding electrode conductor in the USA).

PE conductors must be:

- Insulated and coloured yellow and green (stripes)
- Protected against mechanical and chemical damage

In IT and TN-earthed schemes it is strongly recommended that PE conductors should be installed in close proximity (i.e. in the same conduits, on the same cable tray, etc.) as the live cables of the related circuit. This arrangement ensures the minimum possible inductive reactance in the earth-fault current carrying circuits.

It should be noted that this arrangement is originally provided by bus-trunking.

Connection

PE conductors must:

- Not include any means of breaking the continuity of the circuit (such as a switch, removable links, etc.)
- Connect exposed conductive parts individually to the main PE conductor, i.e. in parallel, not in series, as shown in **Figure G54**
- Have an individual terminal on common earthing bars in distribution boards.

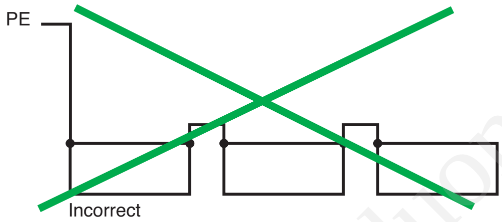


Fig. G54 : A poor connection in a series arrangement will leave all downstream appliances unprotected

TT scheme

The PE conductor need not necessarily be installed in close proximity to the live conductors of the corresponding circuit, since high values of earth-fault current are not needed to operate the RCD-type of protection used in TT installations.

IT and TN schemes

The PE or PEN conductor, as previously noted, must be installed as close as possible to the corresponding live conductors of the circuit and no ferro-magnetic material must be interposed between them. A PEN conductor must always be connected directly to the earth terminal of an appliance, with a looped connection from the earth terminal to the neutral terminal of the appliance (see **Fig. G55**).

- TN-C scheme (the neutral and PE conductor are one and the same, referred to as a PEN conductor)

The protective function of a PEN conductor has priority, so that all rules governing PE conductors apply strictly to PEN conductors

- TN-C to TN-S transition

The PE conductor for the installation is connected to the PEN terminal or bar (see **Fig. G56**) generally at the origin of the installation. Downstream of the point of separation, no PE conductor can be connected to the neutral conductor.

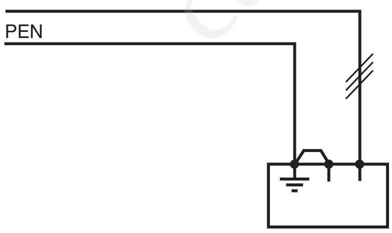


Fig. G55 : Direct connection of the PEN conductor to the earth terminal of an appliance

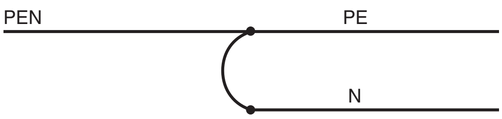


Fig. G56 : The TN-C-S scheme

6 Protective earthing conductor (PE)

Types of materials

Materials of the kinds mentioned below in **Figure G57** can be used for PE conductors, provided that the conditions mentioned in the last column are satisfied.

Type of protective earthing conductor (PE)		IT scheme	TN scheme	TT scheme	Conditions to be respected
Supplementary conductor	In the same cable as the phases, or in the same cable run	Strongly recommended	Strongly recommended	Correct	The PE conductor must be insulated to the same level as the phases
	Independent of the phase conductors	Possible (1)	Possible (1) (2)	Correct	■ The PE conductor may be bare or insulated (2)
Metallic housing of bus-trunking or of other prefabricated prewired ducting (5)		Possible (3)	PE possible (3) PEN possible (8)	Correct	■ The electrical continuity must be assured by protection against deterioration by mechanical, chemical and electrochemical hazards
External sheath of extruded, mineral- insulated conductors (e.g. «pyrotenax» type systems)		Possible (3)	PE possible (3) PEN not recommended (2)(3)	Possible	
Certain extraneous conductive elements (6) such as: ■ Steel building structures ■ Machine frames ■ Water pipes (7)		Possible (4)	PE possible (4) PEN forbidden	Possible	■ Their conductance must be adequate
Metallic cable ways, such as, conduits (9), ducts, trunking, trays, ladders, and so on…		Possible (4)	PE possible (4) PEN not recommended (2)(4)	Possible	
Forbidden for use as PE conductors, are: metal conduits (9), gas pipes, hot-water pipes, cable-armouring tapes (9) or wires (9)					

(1) In TN and IT schemes, fault clearance is generally achieved by overcurrent devices (fuses or circuit-breakers) so that the impedance of the fault-current loop must be sufficiently low to assure positive protective device operation. The surest means of achieving a low loop impedance is to use a supplementary core in the same cable as the circuit conductors (or taking the same route as the circuit conductors). This solution minimizes the inductive reactance and therefore the impedance of the loop.

(2) The PEN conductor is a neutral conductor that is also used as a protective earth conductor. This means that a current may be flowing through it at any time (in the absence of an earth fault). For this reason an insulated conductor is recommended for PEN operation.

(3) The manufacturer provides the necessary values of R and X components of the impedances (phase/PE, phase/PEN) to include in the calculation of the earth-fault loop impedance.

(4) Possible, but not recomended, since the impedance of the earth-fault loop cannot be known at the design stage. Measurements on the completed installation are the only practical means of assuring adequate protection for persons.

(5) It must allow the connection of other PE conductors. **Note**: these elements must carry an indivual green/yellow striped visual indication, 15 to 100 mm long (or the letters PE at less than 15 cm from each extremity).

(6) These elements must be demountable only if other means have been provided to ensure uninterrupted continuity of protection.

(7) With the agreement of the appropriate water authorities.

(8) In the prefabricated pre-wired trunking and similar elements, the metallic housing may be used as a PEN conductor, in parallel with the corresponding bar, or other PE conductor in the housing.

(9) Forbidden in some countries only. Universally allowed to be used for supplementary equipotential conductors.

Fig. G57 : Choice of protective conductors (PE)

6.2 Conductor sizing

Figure G58 below is based on IEC 60364-5-54. This table provides two methods of determining the appropriate c.s.a. for both PE or PEN conductors.

	c.s.a. of phase conductors Sph (mm²)	Minimum c.s.a. of PE conductor (mm²)	Minimum c.s.a. of PEN conductor (mm²)	
			Cu	Al
Simplified method (1)	$S_{ph} \leqslant 16$	S_{ph} (2)	S_{ph} (3)	S_{ph} (3)
	$16 < S_{ph} \leqslant 25$	16	16	
	$25 < S_{ph} \leqslant 35$			25
	$35 < S_{ph} \leqslant 50$	$S_{ph}/2$	$S_{ph}/2$	
	$S_{ph} > 50$			$S_{ph}/2$
Adiabatic method	Any size	$S_{PE/PEN} = \frac{\sqrt{I^2 \cdot t}}{k}$ (3) (4)		

(1) Data valid if the prospective conductor is of the same material as the line conductor. Otherwise, a correction factor must be applied.

(2) When the PE conductor is separated from the circuit phase conductors, the following minimum values must be respected:
■ 2.5 mm² if the PE is mechanically protected
■ 4 mm² if the PE is not mechanically protected

(3) For mechanical reasons, a PEN conductor, shall have a cross-sectional area not less than 10 mm² in copper or 16 mm² in aluminium.

(4) Refer to table G53 for the application of this formula.

Fig. G58 : Minimum cross section area of protective conductors

6 Protective earthing conductor (PE)

The two methods are:

■ Adiabatic (which corresponds with that described in IEC 60724)

This method, while being economical and assuring protection of the conductor against overheating, leads to small c.s.a.'s compared to those of the corresponding circuit phase conductors. The result is sometimes incompatible with the necessity in IT and TN schemes to minimize the impedance of the circuit earth-fault loop, to ensure positive operation by instantaneous overcurrent tripping devices. This method is used in practice, therefore, for TT installations, and for dimensioning an earthing conductor (1).

■ Simplified

This method is based on PE conductor sizes being related to those of the corresponding circuit phase conductors, assuming that the same conductor material is used in each case.

Thus, in Figure G58 for:

$Sph \leqslant 16\ mm^2 \quad S_{PE} = Sph$

$16 < Sph \leqslant 35\ mm^2 \quad S_{PE} = 16\ mm^2$

$Sph > 35\ mm^2 \quad S_{PE} = \frac{Sph}{2}$

Note: when, in a TT scheme, the installation earth electrode is beyond the zone of influence of the source earthing electrode, the c.s.a. of the PE conductor can be limited to 25 mm² (for copper) or 35 mm² (for aluminium).

The neutral cannot be used as a PEN conductor unless its c.s.a. is equal to or larger than 10 mm² (copper) or 16 mm² (aluminium).

Moreover, a PEN conductor is not allowed in a flexible cable. Since a PEN conductor functions also as a neutral conductor, its c.s.a. cannot, in any case, be less than that necessary for the neutral, as discussed in Subclause 7.1 of this Chapter.

This c.s.a. cannot be less than that of the phase conductors unless:

■ The kVA rating of single-phase loads is less than 10% of the total kVA load, and

■ Imax likely to pass through the neutral in normal circumstances, is less than the current permitted for the selected cable size.

Furthermore, protection of the neutral conductor must be assured by the protective devices provided for phase-conductor protection (described in Sub-clause 7.2 of this Chapter).

Values of factor k to be used in the formulae

These values are identical in several national standards, and the temperature rise ranges, together with factor k values and the upper temperature limits for the different classes of insulation, correspond with those published in IEC 60724 (1984).

The data presented in **Figure G59** are those most commonly needed for LV installation design.

k values		**Nature of insulation**	
		Polyvinylchloride (PVC)	**Cross-linked-polyethylene (XLPE) Ethylene-propylene-rubber (EPR)**
Final temperature (°C)		160	250
Initial temperature (°C)		30	30
Insulated conductors not incoporated in cables or bare conductors in contact with cable jackets	Copper	143	176
	Aluminium	95	116
	Steel	52	64
Conductors of a multi-core-cable	Copper	115	143
	Aluminium	76	94

Fig. G59 : k factor values for LV PE conductors, commonly used in national standards and complying with IEC 60724

(1) Grounding electrode conductor

6 Protective earthing conductor (PE)

6.3 Protective conductor between MV/LV transformer and the main general distribution board (MGDB)

These conductors must be sized according to national practices

All phase and neutral conductors upstream of the main incoming circuit-breaker controlling and protecting the MGDB are protected by devices at the MV side of the transformer. The conductors in question, together with the PE conductor, must be dimensioned accordingly. Dimensioning of the phase and neutral conductors from the transformer is exemplified in Sub-clause 7.5 of this chapter (for circuit C1 of the system illustrated in Fig. G65).

Recommended conductor sizes for bare and insulated PE conductors from the transformer neutral point, shown in **Figure G60**, are indicated below in **Figure G61**. The kVA rating to consider is the sum of all (if more than one) transformers connected to the MGDB.

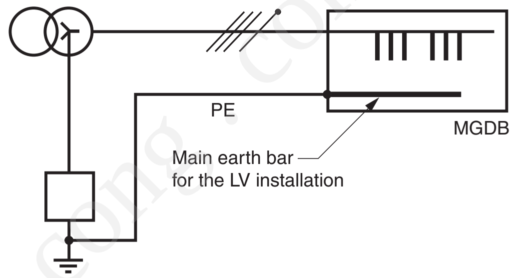


Fig. G60 : PE conductor to the main earth bar in the MGDB

The table indicates the c.s.a. of the conductors in mm² according to:

- The nominal rating of the MV/LV transformer(s) in kVA
- The fault-current clearance time by the MV protective devices, in seconds
- The kinds of insulation and conductor materials

If the MV protection is by fuses, then use the 0.2 seconds columns.

In IT schemes, if an overvoltage protection device is installed (between the transformer neutral point and earth) the conductors for connection of the device should also be dimensioned in the same way as that described above for PE conductors.

Transformer rating in kVA (230/400 V output)	Conductor material	Bare conductors			PVC-insulated conductors			XLPE-insulated conductors		
	Copper t(s)	0.2	0.5	-	0.2	0.5	-	0.2	0.5	-
	Aluminium t(s)	-	0.2	0.5	-	0.2	0.5	-	0.2	0.5
≤100	c.s.a. of PE conductors SPE (mm²)	25	25	25	25	25	25	25	25	25
160		25	25	35	25	25	50	25	25	35
200		25	35	50	25	35	50	25	25	50
250		25	35	70	35	50	70	25	35	50
315		35	50	70	35	50	95	35	50	70
400		50	70	95	50	70	95	35	50	95
500		50	70	120	70	95	120	50	70	95
630		70	95	150	70	95	150	70	95	120
800		70	120	150	95	120	185	70	95	150
1,000		95	120	185	95	120	185	70	120	150
1,250		95	150	185	120	150	240	95	120	185

Fig. G61 : Recommended c.s.a. of PE conductor between the MV/LV transformer and the MGDB, as a function of transformer ratings and fault-clearance times.

6 Protective earthing conductor (PE)

6.4 Equipotential conductor

The main equipotential conductor

This conductor must, in general, have a c.s.a. at least equal to half of that of the largest PE conductor, but in no case need exceed 25 mm² (copper) or 35 mm² (aluminium) while its minimum c.s.a. is 6 mm² (copper) or 10 mm² (aluminium).

Supplementary equipotential conductor

This conductor allows an exposed conductive part which is remote from the nearest main equipotential conductor (PE conductor) to be connected to a local protective conductor. Its c.s.a. must be at least half of that of the protective conductor to which it is connected.

If it connects two exposed conductive parts (M1 and M2 in **Figure G62**) its c.s.a. must be at least equal to that of the smaller of the two PE conductors (for M1 and M2). Equipotential conductors which are not incorporated in a cable, should be protected mechanically by conduits, ducting, etc. wherever possible.

Other important uses for supplementary equipotential conductors concern the reduction of the earth-fault loop impedance, particulary for indirect-contact protection schemes in TN- or IT-earthed installations, and in special locations with increased electrical risk (refer to IEC 60364-4-41).

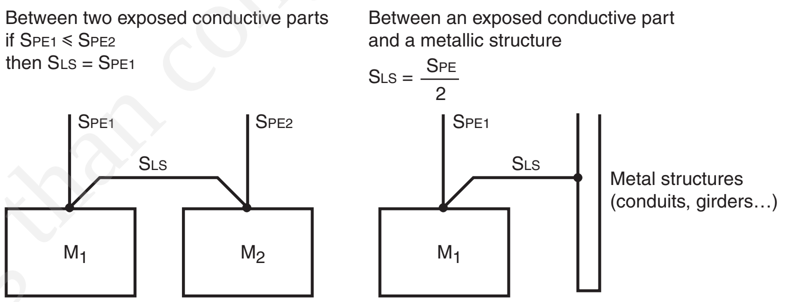


Fig. G62 : Supplementary equipotential conductors

7 The neutral conductor

The c.s.a. and the protection of the neutral conductor, apart from its current-carrying requirement, depend on several factors, namely:

- The type of earthing system, TT, TN, etc.
- The harmonic currents
- The method of protection against indirect contact hazards according to the methods described below

The color of the neutral conductor is statutorily blue. PEN conductor, when insulated, shall be marked by one of the following methods :

- Green-and-yellow throughout its length with, in addition, light blue markings at the terminations, or
- Light blue throughout its length with, in addition, green-and-yellow markings at the terminations

7.1 Sizing the neutral conductor

Influence of the type of earthing system

TT and TN-S schemes

- Single-phase circuits or those of c.s.a. ≤ 16 mm² (copper) 25 mm² (aluminium): the c.s.a. of the neutral conductor must be equal to that of the phases
- Three-phase circuits of c.s.a. > 16 mm² copper or 25 mm² aluminium: the c.s.a. of the neutral may be chosen to be:
  - □ Equal to that of the phase conductors, or
  - □ Smaller, on condition that:

- The current likely to flow through the neutral in normal conditions is less than the permitted value Iz. The influence of triplen(1) harmonics must be given particular consideration or
- The neutral conductor is protected against short-circuit, in accordance with the following Sub-clause G-7.2
- The size of the neutral conductor is at least equal to 16 mm² in copper or 25 mm² in aluminium

TN-C scheme

The same conditions apply in theory as those mentioned above, but in practice, the neutral conductor must not be open-circuited under any circumstances since it constitutes a PE as well as a neutral conductor (see Figure G58 "c.s.a. of PEN conductor" column).

IT scheme

In general, it is not recommended to distribute the neutral conductor, i.e. a 3-phase 3-wire scheme is preferred. When a 3-phase 4-wire installation is necessary, however, the conditions described above for TT and TN-S schemes are applicable.

Influence of harmonic currents

Effects of triplen harmonics

Harmonics are generated by the non-linear loads of the installation (computers, fluorescent lighting, rectifiers, power electronic choppers) and can produce high currents in the Neutral. In particular triplen harmonics of the three Phases have a tendency to cumulate in the Neutral as:

- Fundamental currents are out-of-phase by $2\pi/3$ so that their sum is zero
- On the other hand, triplen harmonics of the three Phases are always positioned in the same manner with respect to their own fundamental, and are in phase with each other (see **Fig. G63a**).

(1) Harmonics of order 3 and multiple of 3

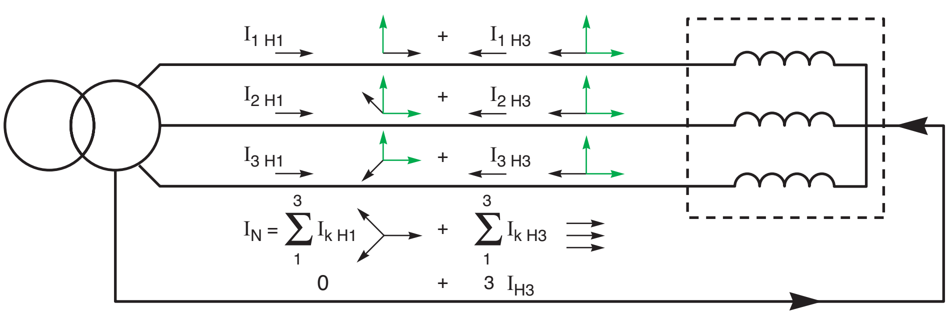


Fig. G63a : Triplen harmonics are in phase and cumulate in the Neutral

7 The neutral conductor

Figure G63b shows the load factor of the neutral conductor as a function of the percentage of 3rd harmonic.

In practice, this maximum load factor cannot exceed $\sqrt{3}$.

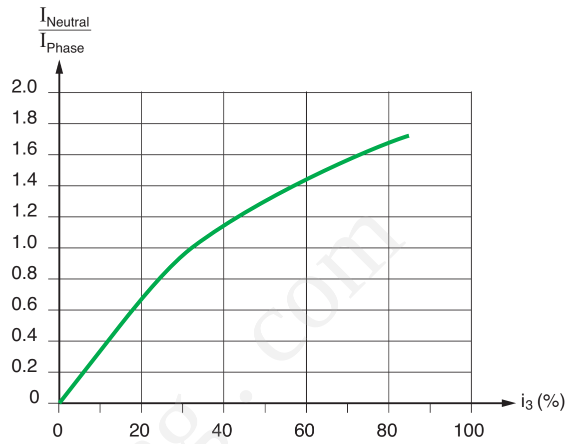


Fig. G63b : Load factor of the neutral conductor vs the percentage of 3rd harmonic

Reduction factors for harmonic currents in four-core and five-core cables with four cores carrying current

The basic calculation of a cable concerns only cables with three loaded conductors i.e there is no current in the neutral conductor. Because of the third harmonic current, there is a current in the neutral. As a result, this neutral current creates an hot environment for the 3 phase conductors and for this reason, a reduction factor for phase conductors is necessary (see **Fig. G63**).

Reduction factors, applied to the current-carrying capacity of a cable with three loaded conductors, give the current-carrying capacity of a cable with four loaded conductors, where the current in the fourth conductor is due to harmonics. The reduction factors also take the heating effect of the harmonic current in the phase conductors into account.

- Where the neutral current is expected to be higher than the phase current, then the cable size should be selected on the basis of the neutral current
- Where the cable size selection is based on a neutral current which is not significantly higher than the phase current, it is necessary to reduce the tabulated current carrying capacity for three loaded conductors
- If the neutral current is more than 135% of the phase current and the cable size is selected on the basis of the neutral current then the three phase conductors will not be fully loaded. The reduction in heat generated by the phase conductors offsets the heat generated by the neutral conductor to the extent that it is not necessary to apply any reduction factor to the current carrying capacity for three loaded conductors.
- In order to protect cables, the fuse or circuit-breaker has to be sized taking into account the greatest of the values of the line currents (phase or neutral). However, there are special devices (for example the Compact NSX circuit breaker equipped with the OSN tripping unit), that allow the use of a c.s.a. of the phase conductors smaller than the c.s.a. of the neutral conductor. A big economic gain can thus be made.

Compact NSX100 circuit breaker

Third harmonic content of phase current (%)	Reduction factor	
	Size selection is based on phase current	Size selection is based on neutral current
0 - 15	1.0	-
15 - 33	0.86	-
33 - 45	-	0.86
> 45	-	1.0

Fig. G63 : Reduction factors for harmonic currents in four-core and five-core cables (according to IEC 60364-5-52)

7 The neutral conductor

Examples

Consider a three-phase circuit with a design load of 37 A to be installed using four-core PVC insulated cable clipped to a wall, installation method C. From Figure G24, a 6 mm^2 cable with copper conductors has a current-carrying capacity of 40 A and hence is suitable if harmonics are not present in the circuit.

- If 20 % third harmonic is present, then a reduction factor of 0,86 is applied and the design load becomes: 37/0.86 = 43 A.

For this load a 10 mm^2 cable is necessary.

In this case, the use of a special protective device (Compact NSX equipped with the OSN trip unit for instance) would allow the use of a 6 mm^2 cable for the phases and of 10 mm^2 for the neutral.

- If 40 % third harmonic is present, the cable size selection is based on the neutral current which is: 37 x 0,4 x 3 = 44,4 A and a reduction factor of 0,86 is applied, leading to a design load of: 44.4/0.86 = 51.6 A.

For this load a 10 mm^2 cable is suitable.

- If 50 % third harmonic is present, the cable size is again selected on the basis of the neutral current, which is: 37 x 0,5 x 3 = 55,5 A .In this case the rating factor is 1 and a 16 mm^2 cable is required.

In this case, the use of a special protective device (Compact NSX equipped with the OSN trip for instance) would allow the use of a 6 mm^2 cable for the phases and of 10 mm^2 for the neutral.

7.2 Protection of the neutral conductor

(see **Fig. G64** next page)

Protection against overload

If the neutral conductor is correctly sized (including harmonics), no specific protection of the neutral conductor is required because it is protected by the phase protection.

However, in practice, if the c.s.a. of the neutral conductor is lower than the phase c.s.a, a neutral overload protection must be installed.

Protection against short-circuit

If the c.s.a. of the neutral conductor is lower than the c.s.a. of the phase conductor, the neutral conductor must be protected against short-circuit.

If the c.s.a. of the neutral conductor is equal or greater than the c.s.a. of the phase conductor, no specific protection of the neutral conductor is required because it is protected by the phase protection.

7.3 Breaking of the neutral conductor

(see Fig. G64 next page)

The need to break or not the neutral conductor is related to the protection against indirect contact.

In TN-C scheme

The neutral conductor must not be open-circuited under any circumstances since it constitutes a PE as well as a neutral conductor.

In TT, TN-S and IT schemes

In the event of a fault, the circuit-breaker will open all poles, including the neutral pole, i.e. the circuit-breaker is omnipolar.

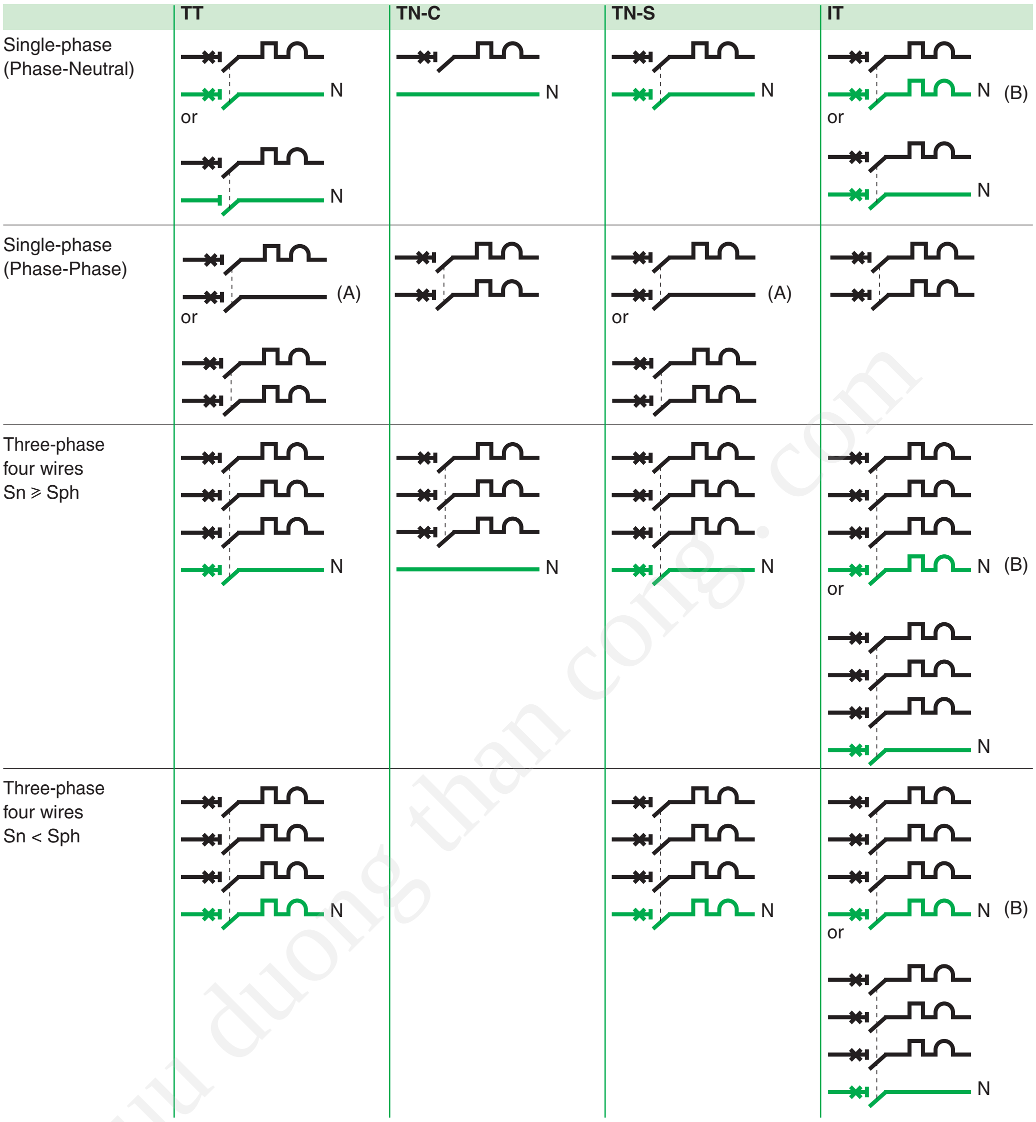
The action can only be achieved with fuses in an indirect way, in which the operation of one or more fuses triggers a mechanical trip-out of all poles of an associated series-connected load-break switch.

7.4 Isolation of the neutral conductor

(see **Fig. G64** next page)

It is considered to be the good practice that every circuit be provided with the means for its isolation.

7 The neutral conductor



(A) Authorized for TT or TN-S systems if a RCD is installed at the origin of the circuit or upstream of it, and if no artificial neutral is distributed downstream of its location

(B) The neutral overcurrent protection is not necessary:

- If the neutral conductor is protected against short-circuits by a device placed upstream, or,
- If the circuit is protected by a RCD which sensitivity is less than 15% of the neutral admissible current.

Fig. G64 : The various situations in which the neutral conductor may appear

8 Worked example of cable calculation

Worked example of cable calculation (see **Fig. G65**)

The installation is supplied through a 1,000 kVA transformer. The process requires a high degree of supply continuity and this is provided by the installation of a 500 kVA 400 V standby generator and the adoption of a 3-phase 3-wire IT system at the main general distribution board. The remainder of the installation is isolated by a 400 kVA 400/400 V transformer. The downstream network is a TT-earthed 3-phase 4-wire system. Following the single-line diagram shown in Figure G65 below, a reproduction of the results of a computer study for the circuit C1, the circuit-breaker Q1, the circuit C6 and the circuit-breaker Q6. These studies were carried out with ECODIAL 3.3 software (a Merlin Gerin product).

This is followed by the same calculations carried out by the method described in this guide.

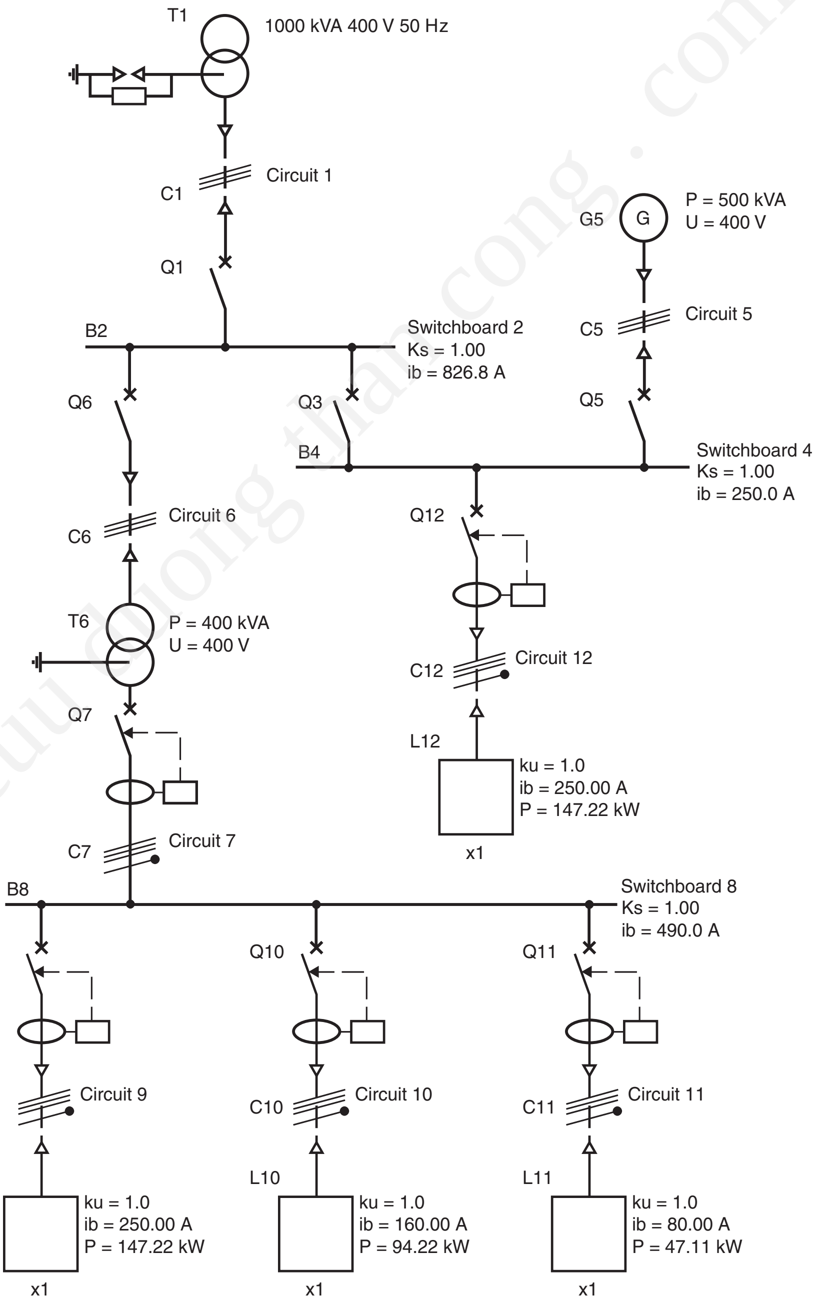


Fig. G65 : Example of single-line diagram

Calculation using software Ecodial 3.3

General network characteristics	
Earthing system	IT
Neutral distributed	No
Voltage (V)	400
Frequency (Hz)	50
Transformer T1	
Number of transformers	1
Upstream fault level (MVA)	500
Rating (kVA)	1,000
Short-circuit impedance voltage (%)	6
Resistance of MV network (mΩ)	0.0351
Reactance of MV network (mΩ)	0.351
Transformer resistance RT (mΩ)	2.293
Transformer reactance XT (mΩ)	10.333
3-phase short-circuit current Ik3 (kA)	23.3
Cable C1	
Maximum load current (A)	1,374
Type of insulation	PVC
Conductor material	Copper
Ambient temperature (°C)	30
Single-core or multi-core cable	Single
Installation method	F
Number of circuits in close proximity (table G21b)	1
Other coefficient	1
Selected cross-sectional area (mm²)	6 x 95
Protective conductor	1 x 120
Length (m)	5
Voltage drop ΔU (%)	.122
Voltage drop ΔU total (%)	.122
3-phase short-circuit current Ik3 (kA)	23
1-phase-to-earth fault current Id (kA)	17
Circuit-breaker Q1	
3-ph short-circuit current Ik3 upstream of the circuit-breaker (kA)	23
Maximum load current (A)	1,374
Number of poles and protected poles	3P3D
Circuit-breaker	NT 16
Type	H 1 – 42 kA
Tripping unit type	Micrologic 5 A
Rated current (A)	1,600

Busbars B2	
Maximum load current (A)	1,374
Type	Standard on edge
Ambient temperature (°C)	30
Dimensions (m and mm)	1 m 2x5 mm x 63 mm
Material	Copper
3-ph short-circuit current Ik3 (kA)	23
3-ph peak value of short-circuit current Ik (kA)	48
Resistance of busbar R (mΩ)	2.52
Reactance of busbar X (mΩ)	10.8
Circuit-breaker Q6	
3-ph short-circuit current upstream of the circuit-breaker Ik3 (kA)	23
Maximum load current (A)	560
Number of poles and protected poles	3P3D
Circuit-breaker	NS800
Type	N – 50 kA
Tripping unit type	Micrologic 2.0
Rated current (A)	800
Limit of discrimination (kA)	Total
Cable C6	
Maximum load current (A)	560
Type of insulation	PVC
Conductor material	Copper
Ambient temperature (°C)	30
Single-core or multi-core cable	Single
Installation method	F
Number of circuits in close proximity (table G20)	1
Other coefficient	1
Selected cross-sectional area (mm²)	1 x 300
Protective conductor	1 x 150
Length (m)	15
Voltage drop ΔU (%)	.38
Voltage drop ΔU total (%)	.54
3-phase short-circuit current Ik3 (kA)	20
1-phase-to-earth fault current Id (kA)	13.7
Specific sizing constraint	Overloads

Fig. G66 : Partial results of calculation carried out with Ecodial software (Merlin Gerin)

The same calculation using the simplified method recommended in this guide

Dimensioning circuit C1

The MV/LV 1,000 kVA transformer has a rated no-load voltage of 420 V. Circuit C1 must be suitable for a current of

$$I_B = \frac{1,000 \times 10^3}{\sqrt{3} \times 420} = 1,374 \text{ A per phase}$$

Six single-core PVC-insulated copper cables in parallel will be used for each phase. These cables will be laid on cable trays according to method F. The “k” correction factors are as follows:

k_1 = 1 (see table G12, temperature = 30 °C)

k_4 = 0.87 (see table G17, touching cables, 1 tray, ⩾ 3 circuits)

Other correction factors are not relevant in this example.

The corrected load current is:

$$I'_B = \frac{I_B}{k_1 \cdot k_4} = \frac{1,374}{0.87} = 1,579 \text{ A}$$

Each conductor will therefore carry 263 A. Figure G21a indicates that the c.s.a. is 95 mm².

The resistances and the inductive reactances for the six conductors in parallel are, for a length of 5 metres:

$$R = \frac{22.5 \times 5}{95 \times 6} = 0.20\ m\Omega \quad \text{(cable resistance: 22.5 m}\Omega\text{.mm}^2\text{/m)}$$

X = 0.08 x 5 = 0.40 mΩ (cable reactance: 0.08 mΩ/m)

Dimensioning circuit C6

Circuit C6 supplies a 400 kVA 3-phase 400/400 V isolating transformer

$$\text{Primary current} = \frac{400.10^3}{420.\sqrt{3}} = 550\ A$$

A single-core cable laid on a cable tray (without any other cable) in an ambient air temperature of 30 °C is proposed. The circuit-breaker is set at 560 A

The method of installation is characterized by the reference letter F, and the “k” correcting factors are all equal to 1.

A c.s.a. of 240 mm^2 is appropriate.

The resistance and inductive reactance are respectively:

$$R = \frac{22.5 \times 15}{240} = 1.4\ m\Omega$$

X = 0.08 x 15 = 1.2 mΩ

Calculation of short-circuit currents for the selection of circuit-breakers Q 1 and Q 6 (see **Fig. G67**)

Circuits components parts	R (mΩ)	X (mΩ)	Z (mΩ)	Ikmax (kA)
500 MVA at the MV source network	0.04	0.36		
1 MVA transformer	2.2	9.8	10.0	23
Cable C1	0.20	0.4		
Sub-total for Q1	**2.44**	**10.6**	**10.9**	**23**
Busbar B2	3.6	7.2		
Cable C6	1.4	1.2		
Sub-total for Q6	**4.0**	**8.4**	**9.3**	**20**

Fig. G67 : Example of short-circuit current evaluation

The protective conductor

Thermal requirements: Figures G58 and G59 show that, when using the adiabatic method the c.s.a. for the protective earth (PE) conductor for circuit C1 will be:

$$\frac{34{,}800 \times \sqrt{0.2}}{143} = 108\ mm^2$$

A single 120 mm^2 conductor dimensioned for other reasons mentioned later is therefore largely sufficient, provided that it also satisfies the requirements for indirect-contact protection (i.e. that its impedance is sufficiently low).

For the circuit C6, the c.s.a. of its PE conductor should be:

$$\frac{29{,}300 \times \sqrt{0.2}}{143} = 92\ mm^2$$

In this case a 95 mm^2 conductor may be adequate if the indirect-contact protection conditions are also satisfied.

8 Worked example of cable calculation

Protection against indirect-contact hazards

For circuit C6 of Figure G65, Figures F45 and F61, or the formula given page F27 may be used for a 3-phase 3-wire circuit.

The maximum permitted length of the circuit is given by :

$$Lmax = \frac{0.8 \times 240 \times 230\sqrt{3} \times 1,000}{2 \times 22.5\left(1+\frac{240}{95}\right) \times 630 \times 11} = 70 \text{ m}$$

(The value in the denominator 630 x 11 = Im i.e. the current level at which the instantaneous short-circuit magnetic trip of the 630 A circuit-breaker operates).

The length of 15 metres is therefore fully protected by “instantaneous” overcurrent devices.

Voltage drop

From Figure G28 it can be seen that:

- For the cable C1 (6 x 95mm^2 per phase)

$$\Delta U = \frac{0.42\ (V\ A^{-1}\ km^{-1}) \times 1,374\ (A) \times 0.008}{3} = 1.54\ V$$

$$\Delta U\% = \frac{100}{400} \times 1.54 = 0.38\%$$

- For the circuit C6

$$\Delta U = \frac{0.21\ (V\ A^{-1}\ km^{-1}) \times 433\ (A) \times 0.015}{3} = 1.36\ V$$

$$\Delta U\% = \frac{100}{400} \times 1.36 = 0.34\%$$

At the circuit terminals of the LV/LV transformer the percentage volt-drop $\Delta U\%$ = 0.72%