

Chapter G

Sizing and protection of conductors

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G1

1 General

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

1.1 Methodology and definition

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.

G2

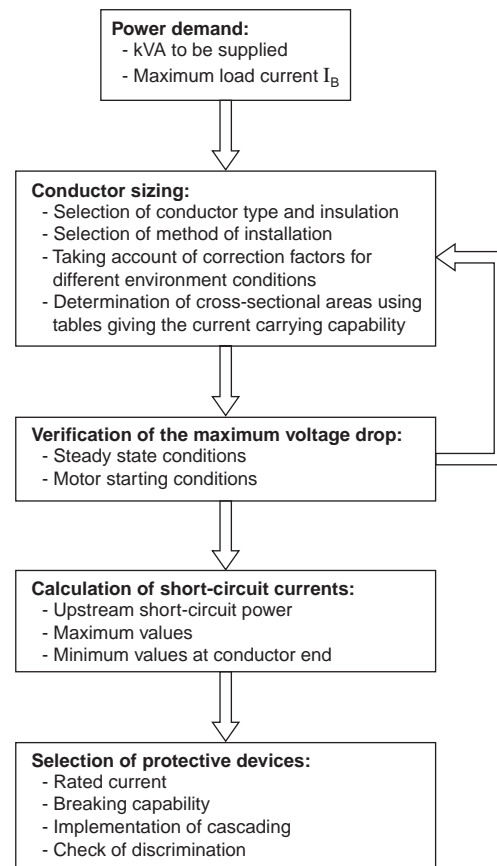


Fig. G1 : Flow-chart for the selection of cable size and protective device rating for a given circuit

(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.

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, k_s and k_u respectively, as shown in **Figure G2**.

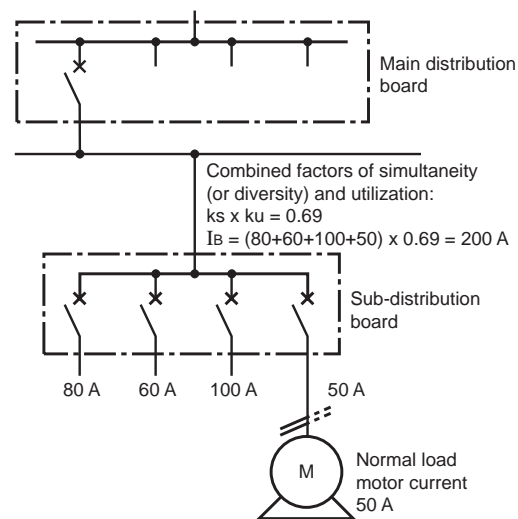


Fig. G2 : Calculation of maximum load current I_b

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 conductor.

where

t: Duration of short-circuit current (seconds)

S: Cross sectional area of insulated conductor (mm²)

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 ($\theta_{a1} > \theta_{a2}$), I_{z1} is less than I_{z2} (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
- I_r (or I_{rth})⁽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.

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 I_n is greater than the maximum load current I_B but less than the maximum permissible current I_z for the circuit, i.e. $I_B \leq I_n \leq I_z$ 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 I_f) which will operate the fuse in the conventional time.

G4

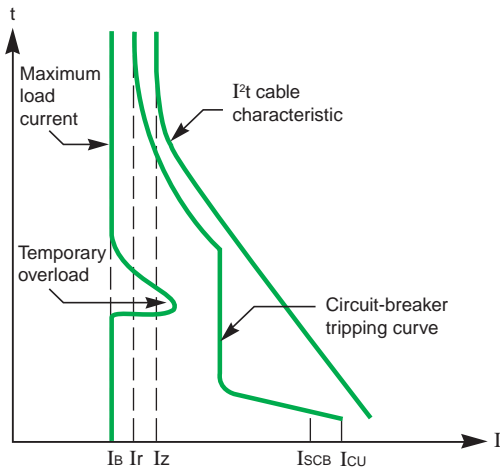


Fig. G3 : Circuit protection by circuit-breaker

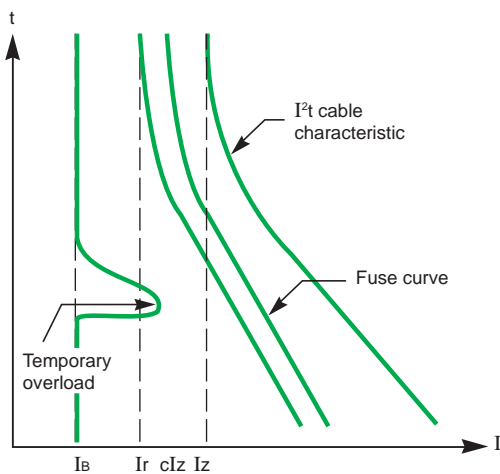


Fig. G4 : Circuit protection by fuses

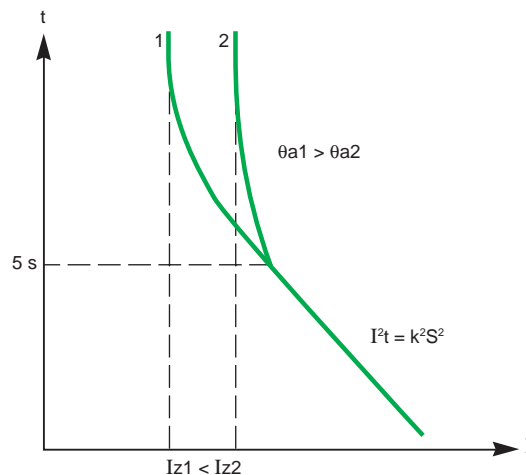


Fig. G5 : I^2t characteristic of an insulated conductor at two different ambient temperatures

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

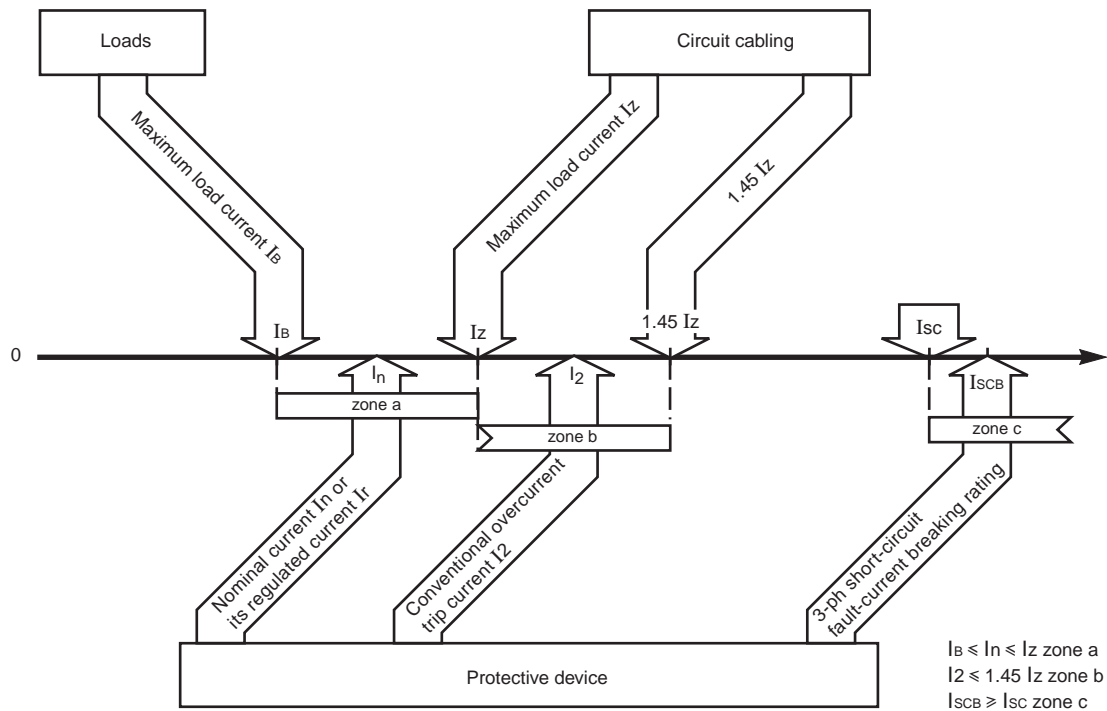


Fig. G6 : Current levels for determining circuit breaker or fuse characteristics

G5

- 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 $1.45 I_n$ (or $1.45 I_r$) so that the condition $I_2 \leq 1.45 I_r$ (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 $I_2 \leq 1.45 I_z$ must be taken into account, where I_2 is the fusing (melting level) current, equal to $k_2 \times I_n$ (k_2 ranges from 1.6 to 1.9) depending on the particular fuse concerned.

A further factor k_3 has been introduced ($k_3 = \frac{k_2}{1.45}$) such that $I_2 \leq 1.45 I_z$ will be valid if $I_n \leq I_z/k_3$.

For fuses type gG:

$I_n < 16 \text{ A} \rightarrow k_3 = 1.31$

$I_n \geq 16 \text{ A} \rightarrow k_3 = 1.10$

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.

Criteria for circuit-breakers:
 $I_B \leq I_n \leq I_z$ and $I_{scB} \geq I_{sc}$.

Criteria for fuses:
 $I_B \leq I_n \leq I_z/k_3$ and $I_{scF} \geq I_{sc}$.

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

In practice 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

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.

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

G6

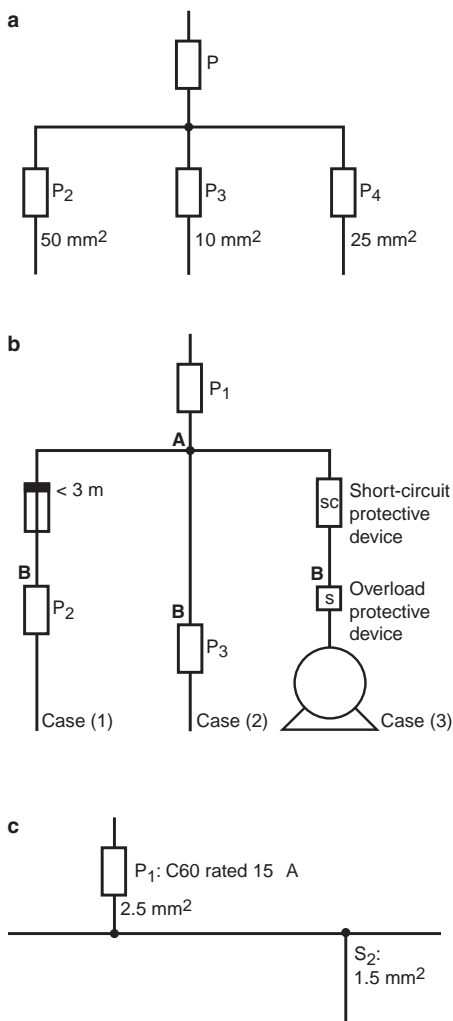


Fig. G7 : Location of protective devices

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 conjunction 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.

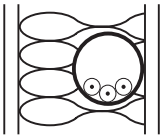
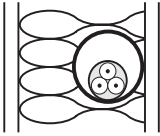
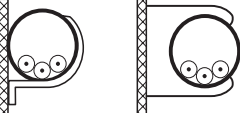
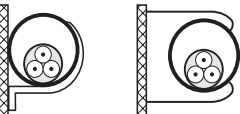
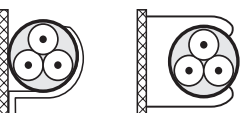
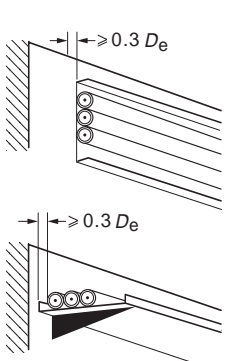
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
1	 Room	Insulated conductors or single-core cables in conduit in a thermally insulated wall	A1
2	 Room	Multi-core cables in conduit in a thermally insulated wall	A2
4		Insulated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

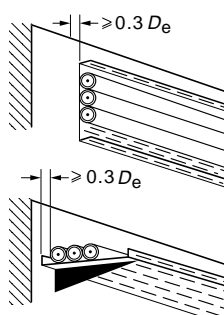
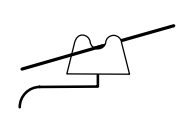
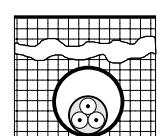
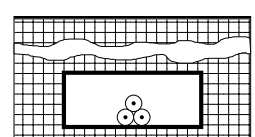
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
31		On perforated tray	E or F
36		Bare or insulated conductors on insulators	G
70		Multi-core cables in conduit or in cable ducting in the ground	D
71		Single-core cable in conduit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

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

Correction factors:

In order to take environment 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, \dots :

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

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		Methods E and F		
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				
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.

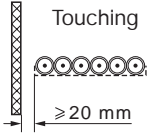
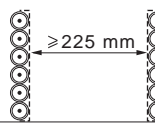
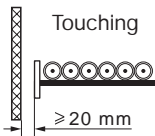
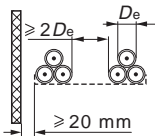
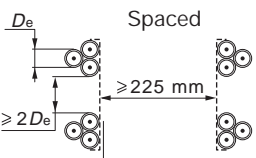
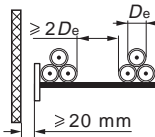
Method of installation			Number of tray	Number of three-phase circuits			Use as a multiplier to rating for
				1	2	3	
Perforated trays	31		1	0.98	0.91	0.87	Three cables in horizontal formation
			2	0.96	0.87	0.81	
			3	0.95	0.85	0.78	
Vertical perforated trays	31		1	0.96	0.86		Three cables in vertical formation
			2	0.95	0.84		
Ladder supports, cleats, etc...	32 33 34		1	1.00	0.97	0.96	Three cables in horizontal formation
			2	0.98	0.93	0.89	
			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 33 34		1	1.00	1.00	1.00	
			2	0.97	0.95	0.93	
			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 k_4 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 k_5 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 k_5 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.

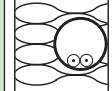
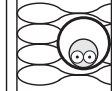
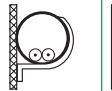
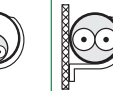
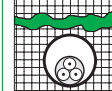

Nominal cross-sectional area of conductors (mm ²)	Installation methods					
	A1	A2	B1	B2	C	D
1						
	2	3	4	5	6	7
Copper						
1.5	13.5	13	15.5	15	17.5	18
2.5	18	17.5	21	20	24	24
4	24	23	28	27	32	31
6	31	29	36	34	41	39
10	42	39	50	46	57	52
16	56	52	68	62	76	67
25	73	68	89	80	96	86
35	89	83	110	99	119	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											
	2	3	4	5	6	7	8	9	10	11	12	13
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 unperforated trays	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)

G17

■ Buried cables:

Installation method	Size mm ²	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**.

G18

°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.

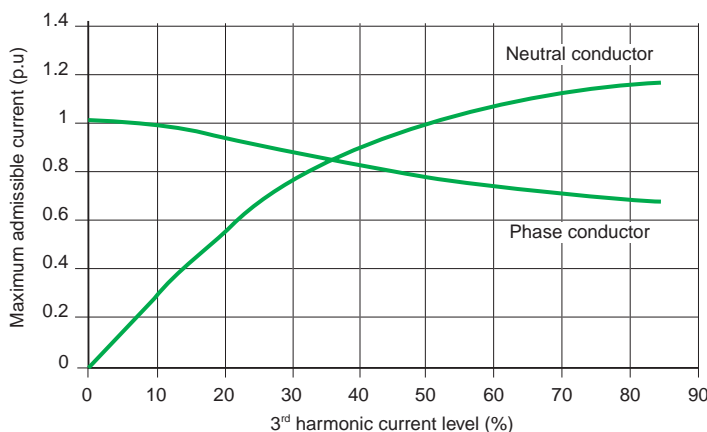


Fig. G23b : Maximum admissible currents (p.u.) in a busbar trunking system as functions of the 3rd harmonic level.

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 : $I_n = \Sigma (I_B \cdot k_s)$.

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 $\pm 5\%$ 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**).

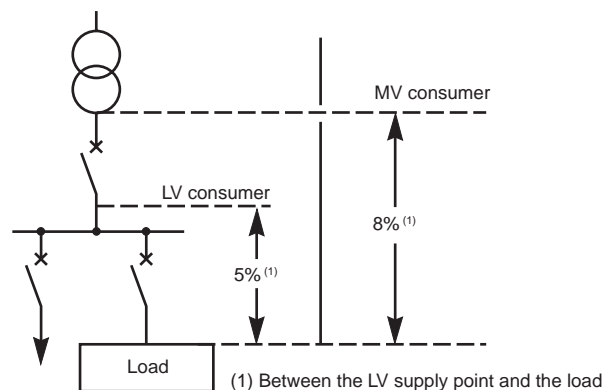


Fig. G26 : Maximum voltage drop

3.2 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

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

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

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 $0.08 \Omega/\text{km}$.

- φ : phase angle between voltage and current in the circuit considered, generally:

□ Incandescent lighting: $\cos \varphi = 1$

□ Motor power:

- At start-up: $\cos \varphi = 0.35$

- In normal service: $\cos \varphi = 0.8$

- U_n : phase-to-phase voltage

- V_n : phase-to-neutral voltage

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

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

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 $\cos \varphi$ close to 0.8, or lighting with a $\cos \varphi$ close to 1.

- Type of cable; single-phase or 3-phase

Voltage drop in a cable is then given by:

$$K \times I_B \times L$$

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 " $\cos \varphi = 0.35$ " 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).

c.s.a. in mm ²		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

G22

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:

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

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

$$\Delta U \text{ for the cable} = 1 \times 100 \times 0.05 = 5 \text{ V}$$

$$\Delta U \text{ total} = 10 + 5 = 15 \text{ V i.e.}$$

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

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

- Voltage drop during motor start-up:

$$\Delta U_{\text{cable}} = 0.52 \times 500 \times 0.05 = 13 \text{ V}$$

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.

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

$$\Delta U \text{ distribution board} = 14 \text{ V}$$

$$\Delta U \text{ for the motor cable} = 13 \text{ V}$$

$$\Delta U \text{ total} = 13 + 14 = 27 \text{ V i.e.}$$

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

a value which is satisfactory during motor starting.

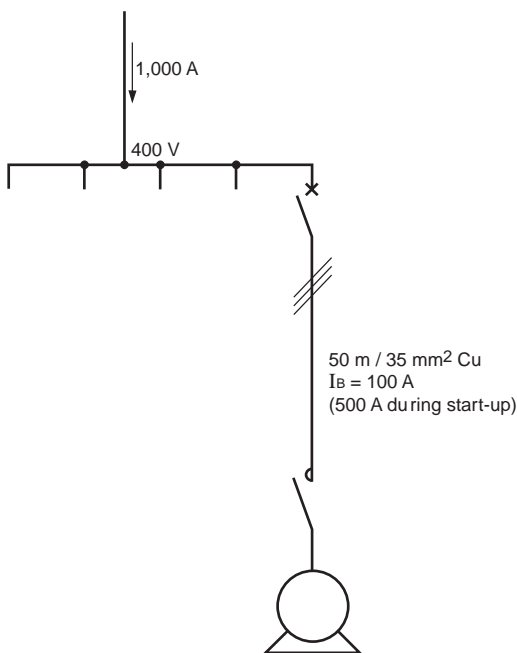


Fig. G29 : Example 1

Example 2 (see Fig. G30)

A 3-phase 4-wire copper line of 70 mm² 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 mm² c.s.a. copper 20 m long, and each passing 20 A.

It is assumed that the currents in the 70 mm² 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:

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

Figure G28 shows 0.55 V/A/km

$$\Delta U_{\text{line}} = 0.55 \times 150 \times 0.05 = 4.125 \text{ V phase-to-phase}$$

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

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

$$\Delta U \text{ for a single-phase circuit} = 18 \times 20 \times 0.02 = 7.2 \text{ V}$$

The total voltage drop is therefore

$$7.2 + 2.38 = 9.6 \text{ V}$$

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

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

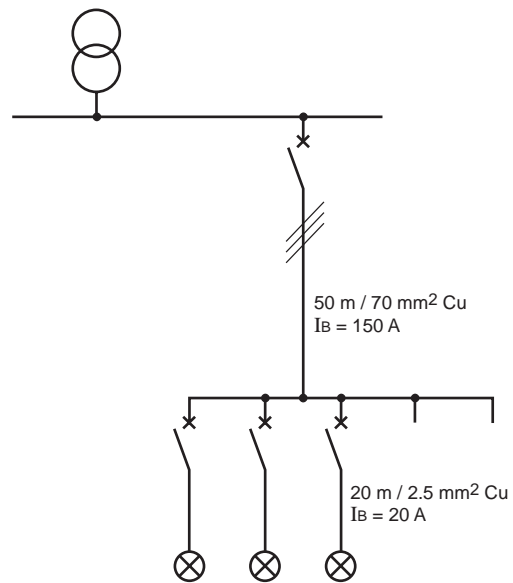


Fig. G30 : Example 2

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

A knowledge of 3-phase symmetrical short-circuit current values (I_{sc}) 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: $I_{sc} = \frac{I_n \times 100}{U_{sc}}$ where $I_n = \frac{P \times 10^3}{U_{20} \sqrt{3}}$ and:

P = kVA rating of the transformer

U_{20} = phase-to-phase secondary volts on open circuit

I_n = nominal current in amps

I_{sc} = short-circuit fault current in amps

U_{sc} = short-circuit impedance voltage of the transformer in %.

Typical values of U_{sc} for distribution transformers are given in **Figure G31**.

Transformer rating (kVA)	U _{sc} in %	
	Oil-immersed	Cast-resin dry type
50 to 750	4	6
800 to 3,200	6	6

Fig. G31 : Typical values of U_{sc} for different kVA ratings of transformers with MV windings ≤ 20 kV

■ Example

400 kVA transformer, 420 V at no load

$U_{sc} = 4\%$

$$I_n = \frac{400 \times 10^3}{420 \times \sqrt{3}} = 550 \text{ A} \quad I_{sc} = \frac{550 \times 100}{4} = 13.7 \text{ kA}$$

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 I_{sc} 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.

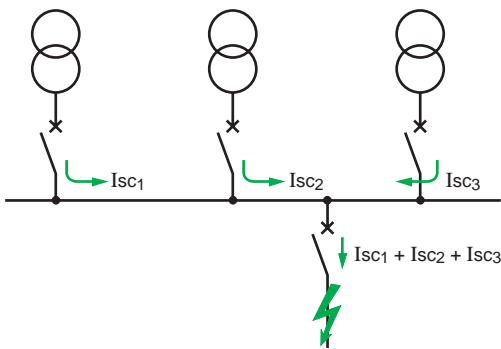


Fig. G32 : Case of several transformers in parallel

4.2 3-phase short-circuit current (I_{sc}) at any point within a LV installation

In a 3-phase installation I_{sc} at any point is given by:

$$I_{sc} = \frac{U_{20}}{\sqrt{3} Z_T} \quad \text{where}$$

U₂₀ = 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)

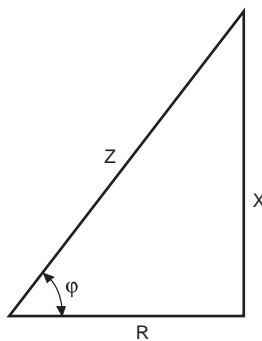


Fig. G33 : Impedance diagram

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:

$$R_3 = \frac{R_1 \times R_2}{R_1 + R_2} \quad \text{or for reactances } X_3 = \frac{X_1 \times X_2}{X_1 + X_2}$$

It should be noted that the calculation of X₃ concerns only separated circuit without mutual inductance. If the circuits in parallel are close together 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.

P _{sc}	U ₀ (V)	R _a (mΩ)	X _a (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:

$$Z_s = \frac{U_0^2}{P_{sc}}$$

where

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

U₀ = phase-to-phase no-load LV voltage, expressed in volts

P_{sc} = MV 3-phase short-circuit fault level, expressed in kVA

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

Figure G36 gives values for R_a and X_a 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: $\sqrt{3} E_L I_{sc}$ where:

■ E_L = phase-to-phase nominal system voltage expressed in kV (r.m.s.)

■ I_{sc} = 3-phase short-circuit current expressed in kA (r.m.s.)

(2) up to 36 kV

■ Transformers (see Fig. G35)

The impedance Z_{tr} of a transformer, viewed from the LV terminals, is given by the formula:

$$Z_{tr} = \frac{U_{20}^2}{P_n} \times \frac{U_{sc}}{100}$$

where:

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

P_n = rating of the transformer (in kVA)

U_{sc} = the short-circuit impedance voltage of the transformer expressed in %

The transformer windings resistance R_{tr} can be derived from the total losses as follows:

$$P_{cu} = 3I_n^2 \times R_{tr} \text{ so that } R_{tr} = \frac{P_{cu} \times 10^3}{3I_n^2} \text{ in milli-ohms}$$

where

P_{cu} = total losses in watts

I_n = nominal full-load current in amps

R_{tr} = 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).

$$X_{tr} = \sqrt{Z_{tr}^2 - R_{tr}^2}$$

For an approximate calculation R_{tr} may be ignored since $X \approx Z$ in standard distribution type transformers.

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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: $R_c = \rho \frac{L}{S}$

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, for more precise calculation, particularly in the case of large motors and/or numerous smaller motors, the total contribution can be estimated from the formula:

$I_{scm} = 3.5 I_n$ from each motor i.e. $3.5mI_n$ 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	$\frac{R_a}{X_a} = 0.1$	$X_a = 0.995 Z_a; Z_a = \frac{U_{20}^2}{P_{sc}}$
Transformer Figure G35	$R_{tr} = \frac{P_{cu} \times 10^3}{3I_n^2}$ R _{tr} is often negligible compared to X _{tr} for transformers > 100 kVA	$\sqrt{Z_{tr}^2 - R_{tr}^2}$ with $Z_{tr} = \frac{U_{20}^2}{P_n} \times \frac{U_{sc}}{100}$
Circuit-breaker	Negligible	$X_D = 0.15 \text{ m}\Omega/\text{pole}$
Busbars	Negligible for $S > 200 \text{ mm}^2$ in the formula: $R = \rho \frac{L}{S}^{(1)}$	$X_B = 0.15 \text{ m}\Omega/\text{m}$
Circuit conductors ⁽²⁾	$R = \rho \frac{L}{S}^{(1)}$	Cables: $X_c = 0.08 \text{ m}\Omega/\text{m}$
Motors	See Sub-clause 4.2 Motors (often negligible at LV)	
Three-phase short circuit current in kA	$I_{sc} = \frac{U_{20}}{\sqrt{3} \sqrt{R_T^2 + X_T^2}}$	

U₂₀: Phase-to-phase no-load secondary voltage of MV/LV transformer (in volts).
 P_{sc}: 3-phase short-circuit power at MV terminals of the MV/LV transformers (in kVA).
 P_{cu}: 3-phase total losses of the MV/LV transformer (in watts).
 P_n: Rating of the MV/LV transformer (in kVA).
 U_{sc}: Short-circuit impedance voltage of the MV/LV transformer (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 P _{sc} = 500 MVA	0.035	0.351			
Transformer 20 kV/420 V P _n = 1000 kVA U _{sc} = 5% P _{cu} = 13.3 x 10 ³ watts	2.24	8.10			
Single-core cables 5 m copper 4 x 240 mm ² /phase	$R_c = \frac{22.5}{4} \times \frac{5}{240} = 0.12$	$X_c = 0.08 \times 5 = 0.40$	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 mm ² copper	$R_c = 22.5 \times \frac{100}{95} = 23.68$	$X_c = 100 \times 0.08 = 8$	26.1	18.5	I _{sc3} = 7.4 kA
Three-core cable 20 m 10 mm ² copper final circuits	$R_c = 22.5 \times \frac{20}{10} = 45$	$X_c = 20 \times 0.08 = 1.6$	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 I_{sc} at the receiving end of a feeder as a function of the I_{sc} 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 detailed 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 I_{sc} (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 I_{sc} 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 I_{sc} capacity of 25 kA (such as a NS160 unit) can be used to protect the 160 A circuit.

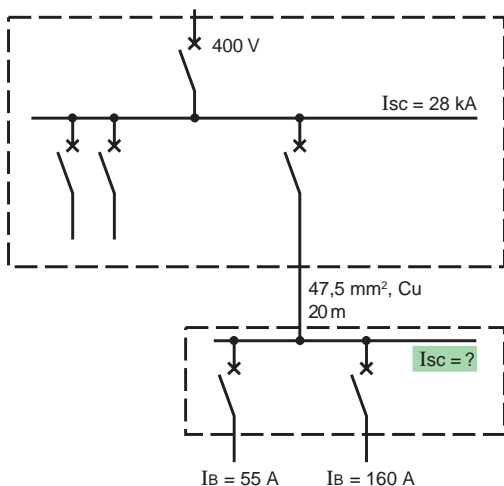


Fig. G38 : Determination of downstream short-circuit current level I_{sc} using Figure G39

G28

Copper 230 V / 400 V																																		
c.s.a. of phase conductors (mm ²)	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	2.8	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 (mm ²)	Length of circuit (in metres)																																	
2.5																																		
4																																		
6																																		
10																																		
16																																		
25																																		
35																																		
47.5																																		
70																																		
95																																		
120																																		
150																																		
185																																		
240																																		
300																																		
2x120																																		
2x150																																		
2x185																																		
2x240																																		
3x120																																		
3x150																																		
3x185																																		
3x240																																		

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

