Cable Sizing Calculation

Introduction

The proper sizing of an electrical (load bearing) cable is important to ensure that the cable can:

- Operate continuously under full load without being damaged
- Withstand the worst short circuits currents flowing through the cable
- Provide the load with a suitable voltage (and avoid excessive voltage drops)
- (optional) Ensure operation of protective devices during an earth fault

General Methodology

All cable sizing methods more or less follow the same basic six step process:

1) Gathering data about the cable, its installation conditions, the load that it will carry, etc
2) Determine the minimum cable size based on continuous current carrying capacity
3) Determine the minimum cable size based on voltage drop considerations
4) Determine the minimum cable size based on short circuit temperature rise
5) Determine the minimum cable size based on earth fault loop impedance
6) Select the cable based on the lowest of the sizes calculated in step 2, 3, 4 and 5

Step 1: Data Gathering

The first step is to collate the relevant information that is required to perform the sizing calculation. Typically, you will need to obtain the following data:

Load Details

The characteristics of the load that the cable will supply, which includes:

- Load type: motor or feeder
- Three phase, single phase or DC
- System / source voltage
- Full load current (A) - or calculate this if the load is defined in terms of power (kW)
- Full load power factor (pu)

- Locked rotor or load starting current (A)
- Starting power factor (pu)
- Distance / length of cable run from source to load - this length should be as close as possible to the actual route of the cable and include enough contingency for vertical drops / rises and termination of the cable tails

Cable Construction

The basic characteristics of the cable's physical construction, which includes:

- Conductor material - normally copper or aluminium
- Conductor shape - e.g. circular or shaped
- Conductor type - e.g. stranded or solid
- Conductor surface coating - e.g. plain (no coating), tinned, silver or nickel
- Insulation type - e.g. PVC, XLPE, EPR
- Number of cores - single core or multicore (e.g. 2C, 3C or 4C)

Installation Conditions

How the cable will be installed, which includes:

- Above ground or underground
- Installation / arrangement - e.g. for underground cables, is it directly buried or buried in conduit? for above ground cables, is it installed on cable tray / ladder, against a wall, in air, etc.
- Ambient or soil temperature of the installation site
- Cable bunching, i.e. the number of cables that are bunched together
- Cable spacing, i.e. whether cables are installed touching or spaced
- Soil thermal resistivity (for underground cables)
- Depth of laying (for underground cables)
- For single core three-phase cables, are the cables installed in trefoil or laid flat?

Step 2: Cable Selection Based on Current Rating

Current flowing through a cable generates heat through the resistive losses in the conductors, dielectric losses through the insulation and resistive losses from current flowing through any cable screens / shields and armouring.

The cable components (particularly the insulation) must be capable of withstanding the temperature rise and heat emanating from the cable. The current carrying capacity of a cable is the maximum current that can flow continuously through a cable. It is sometimes also referred to as the continuous current rating or ampacity of a cable.

Cables with larger conductor cross -sectional areas (i.e. more copper or aluminium) have lower resistive losses and are able to dissipate the heat better than smaller cables. Therefore a 16 mm^2 cable will have a higher current carrying capacity than a 4 mm^2 cable.

Base Current Ratings

International standards and manufacturers of cables will quote base curre nt ratings of different types of cables in tables such as the one shown below. Each of these tables pertain to a specific type of cable construction (e.g. copper conductor, XLPE insulated, etc) and a base set of installation conditions (e.g. ambient temperature, installation method, etc). It is important to note that the current ratings are only valid for the quoted types of cables and base installation conditions.

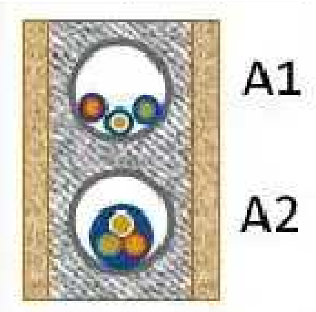
Size (mm^2)	Current Rating for 3 x XLPE Insulated Copper Conductors											
	Reference Installation Method											
	A1	A2	B1	B2	C	D1	D2	E	F		G	
									Trefoil	Laid Flat	Horizontal	Vertical
1.5	17	16.5	20	19.5	22	21	23	23	–	–	–	–
2.5	23	22	28	26	30	28	30	32	–	–	–	–
4	31	30	37	35	40	36	39	42	–	–	–	–
6	40	38	48	44	52	44	49	54	–	–	–	–
10	54	51	66	60	71	58	65	75	–	–	–	–
16	73	68	88	80	96	75	84	100	–	–	–	–
25	95	89	117	105	119	96	107	127	135	141	182	161
35	117	109	144	128	147	115	129	158	169	176	226	201
50	141	130	175	154	179	135	153	192	207	216	275	246
70	179	164	222	194	229	167	188	246	268	279	353	318
95	216	197	269	233	278	197	226	298	328	342	430	389
120	249	227	312	268	322	223	257	346	383	400	500	454

150	285	259	342	300	371	251	287	399	444	464	577	527
185	324	295	384	340	424	281	324	456	510	533	661	605
240	380	346	450	398	500	324	375	538	607	634	781	719
300	435	396	514	455	576	365	419	621	703	736	902	833
400	–	–	–	–	–	–	–	–	823	868	1085	1008
500	–	–	–	–	–	–	–	–	946	998	1253	1169
630	–	–	–	–	–	–	–	–	1088	1151	1454	1362

Reference Installation Method

Reference installation method mentioned in above table is explained below:

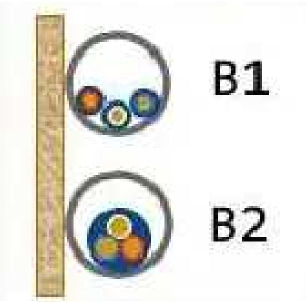
Method A



- A1 - Insulated single core conductors in conduit in a thermally insulated wall
- A2 - Multicore cable in conduit in a thermally insulated wall

This method also applies to single core or multicore cables installed directly in a thermally insulated wall (use methods A1 and A2 respectively), conductors installed in mouldings, architraves and window frames.

Method B



- B1 - Insulated single core con ductors in conduit on a wall

- B2 - Multicore cable in conduit on a wall

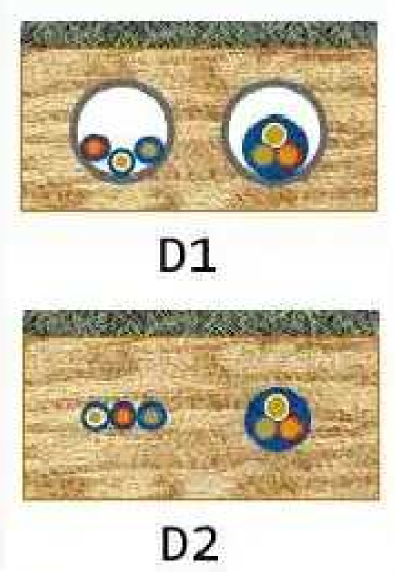
This method applies when a conduit is installed inside a wall, against a wall or spaced less than 0.3 x D (overall diameter of the cable) from the wall. Method B also applies for cables installed in trunking / cable duct against a wall or suspended from a wall and cables installed in building cavities.

Method C

- C - Single core or multi-core cable on a wooden wall

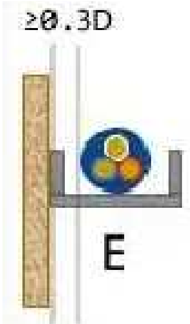
This method also applies to cables fixed directly to walls or ceilings, suspended from ceilings, installed on unperforated cable trays (run horizontally or vertically) and installed directly in a masonry wall (with thermal resistivity less than 2 K.m/W).

Method D



- D1 - Multicore or single core cables installed in conduit buried in the ground
- D2 - Multicore or single core cables buried directl y in the ground

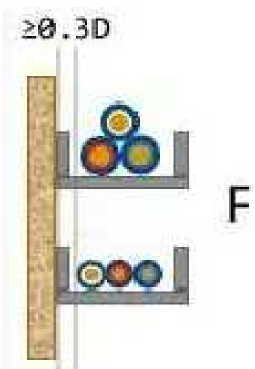
Method E



- E - Multicore cable in free-air

This method applies to cables installed on cable ladder, perforated cable tray or cleats provided that the cable is spaced more than 0.3 x D (overall diameter of the cable) from the wall. Note that cables installed on unperforated cable trays are classifie d under Method C.

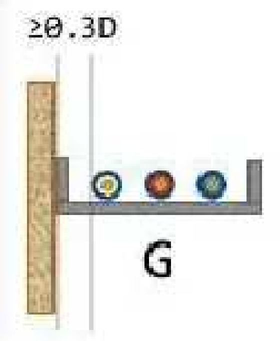
Method F



- F - Single core cables touching in free -air

This method applies to cables installed on cable ladder, perforated cable tray or cleats provided that the cable is spaced more than 0.3 x D (overall diameter of the cable) from the wall. Note that cables installed on unperforated cable trays are classified under Method C.

Method G



- G - Single-core cables laid flat and spaced in free-air

This method applies to cables installed on cable ladder, perforated cable tray or cleats provided that the cable is spaced more than 0.3 x D (overall diameter of the cable) from the wall and with at least 1 x D spacings between cables. Note that cables installed on unperforated cable trays are classified under Method C. This method also applies to cables installed in air supported by insulators.

Installed Current Ratings

When the proposed installation conditions differ from the base conditions, derating (or correction) factors can be applied to the base current ratings to obtain the actual installed current ratings.

International standards and cable manufacturers will provide derating factors for a range of installation conditions, for example ambient /soil temperature, grouping or bunching of cables, soil thermal resistivity, etc. The installed current rating is calculated by multiplying the base current rating with each of the derating factors, i.e.

$$I_c = I_b . k_d$$

where I_c is the installed current rating (A)

I_b is the base current rating (A)

k_d are the product of all the derating factors

For example, suppose a cable had an ambient temperature derating factor of k_{amb} = 0.94 and a grouping derating factor of k_g = 0.85, then the overall derating factor k_d = 0.94x0.85 = 0.799. For a cable with a base current rating of 42A, the installed current rating would be I_c = 0.799x42 = 33.6A.

Cable Selection and Coordination with Protective Devices

When sizing cables for loads, the upstream protective device (fuse or circuit breaker) is typically selected to also protect the cable against damage from thermal overload. The protective device must therefore be selected to exceed the full load current, but not exceed the cable's installed current rating, i.e. this inequality must be met:

$$I_l \leq I_p \leq I_c$$

Where I_l is the full load current (A)

I_p is the protective device rating (A)

I_c is the installed cable current rating (A)

Step 3: Voltage Drop

A cable's conductor can be seen as an impedance and as a result, whenever current flows through a cable, there will be a voltage drop across it, derived by Ohm's Law (i.e. V = IZ). The voltage drop will depend on two things:

#Current flow through the cable– the higher the current flow, the higher the voltage drop

#Impedance of the conductor– the larger the impedance, the higher the voltage drop

Cable Impedances

The impedance of the cable is a function of the cable size (cross-sectional area) and the length of the cable. Most cable manufacturers will quote a cable's resistance and reactance in Ω/km.

Calculating Voltage Drop

For AC systems, the method of calculating voltage drops based on load power factor is commonly used. Full load currents are normally used, but if the load has high startup currents (e.g. motors), then voltage drops based on starting current (and power factor if applicable) should also be calculated.

For a three phase system:

$$V_{3\phi} = \frac{\sqrt{3}I(R_c \cos\phi + X_c \sin\phi)L}{1000}$$

Where $V_{3\phi}$ is the three phase voltage drop (V)

I is the nominal full load or starting current as applicable (A)

R_c is the ac resistance of the cable (Ω/km)

X_c is the ac reactance of the cable (Ω/km)

$\cos\phi$ is the load power factor (pu)

L is the length of the cable (m)

For a single phase system:

$$V_{1\phi} = \frac{2I(R_c \cos\phi + X_c \sin\phi)L}{1000}$$

Where $V_{1\phi}$ is the single phase voltage drop (V)

I is the nominal full load or starting current as applicable (A)

R_c is the ac resistance of the cable (Ω/km)

X_c is the ac reactance of the cable (Ω/km)

$\cos\phi$ is the load power factor (pu)

L is the length of the cable (m)

For a DC system:

$$V_{dc} = \frac{2IR_cL}{1000}$$

Where V_{dc} is the dc voltage drop (V)

I is the nominal full load or starting current as applicable A)

R_c is the dc resistance of the cable (Ω/km)

L is the length of the cable (m)

Maximum Permissible Voltage Drop

Maximum voltage drops across a cable are specified because load consumers (e.g. appliances) will have an input voltage tolerance range. This means that if the voltage at the appliance is lower than its rated minimum voltage, then the appliancemay not operate correctly.

In general, most electrical equipment will operate normally at a voltage as low as 80% nominal voltage. For example, if the nominal voltage is 230VAC, then most appliances will run at >184VAC. Cables are typically sized for a more conservative maximum voltage drop, in the range of 4– 10% at full load.

Calculating Maximum Cable Length due to Voltage Drop

It may be more convenient to calculate the maximum length of a cable for a particular conductor size given a maximum permissibe voltage drop (e.g. 5% of nominal voltage at full load) rather than the voltage drop itself. For example, by doing this it is possible to construct tables showing the maximum lengths corresponding to different cable sizes in order to speed up the selection of similar type cables.

The maximum cable length that will achieve this can be calculated by rearranging the voltage drop equations and substituting the maximum permissible voltage drop (e.g. 5% of 415V nominal voltage = 20.75V).

For a three phase system:

$$L_{max} = \frac{1000V_{3\phi}}{\sqrt{3}I(R_c \cos\phi + X_c \sin\phi)}$$

Where L_{max} is the maximum length of the cable (m)

$V_{3\phi}$ is the maximum permissible three phase voltage drop (V)

I is the nominal full load or starting current as applicable (A)

R_c is the ac resistance of the cable (Ω/km)

X_c is the ac reactance of the cable (Ω/km)

$\cos\phi$ is the load power factor (pu)

For a single phase system:

$$L_{max} = \frac{1000V_{1\phi}}{2I(R_c \cos\phi + X_c \sin\phi)}$$

Where L_{max} is the maximum length of the cable (m)

$V_{1\phi}$ is the maximum permissible single phase voltage drop (V)

I is the nominal full load or starting current as applicable (A)

R_c is the ac resistance of the cable (Ω/km)

X_c is the ac reactance of the cable (Ω/km)

$\cos\phi$ is the load power factor (pu)

For a DC system:

$$L_{max} = \frac{1000V_{dc}}{2IR_c}$$

Where L_{max} is the maximum length of the cable (m)

V_{dc} is the maximum permissible dc voltage drop (V)

I is the nominal full load or starting current as applicable (A)

R_c is the dc resistance of the cable Ω/km)

L is the length of the cable (m)

Step 4: Short Circuit Temperature Rise

During a short circuit, a high amount of current can flow through a cable for a short time. This surge in current flow causes a temperature rise within the cable. High temperatures can trigger unwanted reactions in the cable insulation, sheath materials and other components, which can prematurely degrade the condition of the cable. As the crosssectional area of the cable increases, it can dissipate higher fault currents for a given temperature rise. Therefore, cables should be sized to withstand the largest short circuit that it is expected to see.

Minimum Cable Size Due to Short Circuit Temperature Rise

The minimum cable size due to short circuit temperature rise is typically calculated with an equation of the form:

$$A = \frac{\sqrt{i^2t}}{k}$$

Where A is the minimum cross-sectional area of the cable (mm^2)

i is the prospective short circuit current (A)

t is the duration of the short circuit (s)

k is a short circuit temperature rise constant

The temperature rise constant is calculated based on the material properties of the conductor and the initial and final conductor temperatures. Different international standards have different treatments of the temperature rise constant, but by way of example, IEC 60364-5-54 calculates it as follows:

$$k = 226\sqrt{\ln\left(1 + \frac{\theta_f - \theta i}{234.5 + \theta_i}\right)}$$ (for copper conductors)

$$k = 148\sqrt{\ln\left(1 + \frac{\theta_f - \theta i}{228 + \theta_i}\right)}$$ (for aluminium conductors)

Where θ_i is the initial conductor temperature (deg C)

θ_i is the final conductor temperature (deg C)

Initial and Final Conductor Temperatures

The initial conductor temperature is typically chosen to be the operating temperature of the cable. The final conductor temperature is typically chosen to be the limiting temperature of the insulation.

Short Circuit Energy

The short circuit energy i^2t is normally chosen as the maximum short circuit that the cable could potentially experience. However for circuits with current limiting devices (such as HRC fuses), then the short circuit energy chosen should be the maximum prospective let-through energy of the protective device, which can be found from manufacturer data.

Step 5: Earth Fault Loop Impedance

Sometimes it is desirable (or necessary) to consider the earth fault loop impedance of a circuit in the sizing of a cable. Suppose a bolted earth fault occurs between an active conductor and earth. During such an earth fault, it is desirable that the upstream protective device acts to interrupt the fault within a maximum disconnection time so as to protect against any inadvertent contact to exposed live parts.

Ideally the circuit will have earth fault protection, in which case the protection will be fast acting and well within the maximum disconnection time. The maximum disconnection time is chosen so that a dangerous touch voltage does not persist for long enough to cause injury or death. For most circuits, a maximum disconnection time of 5s is sufficient, though for portable equipment and socket outlets, a faster disconnection time is desirable (i.e. <1s and will definitely require earth fault protection).

However for circuits that do not have earth fault protection, the upstream protective device (i.e. fuse or circuit breaker) must trip within the maximum disconnection time. In order for the protective device to trip, the fault current due to a bolted short circuit must exceed the value that will cause the protective device to act within the maximum disconnection time. For example, suppose a circuit is protected by a fuse and the maximum disconnection time is 5s, then the fault current must exceed the fuse melting current at 5s (which can be found by cross-referencing the fuse time-current curves).

By simple application of Ohm's law:

$$I_A = \frac{V_0}{Z_s}$$

Where I_A is the earth fault current required to trip the protective device within the minimum disconnection time (A)

V_0 is the phase to earth voltage at the protective device (V)

Z_s is the impedance of the earth fault loop (Ω)

It can be seen from the equation above that the impedance of the earth fault loop must be sufficiently low to ensure that the earth fault current can trip the upstream protection.

The Earth Fault Loop

The earth fault loop can consist of various return paths other thanthe earth conductor, including the cable armour and the static earthing connection of the facility. However for practical reasons, the earth fault loop in this calculation consists only of the active conductor and the earth conductor.

The earth fault loop impedance can be found by:

$$Z_s = Z_c + Z_e$$

Where Z_s is the earth fault loop impedance (Ω)

Z_c is the impedance of the active conductor (Ω)

Z_e is the impedance of the earth conductor (Ω)

Assuming that the active and earth conductors have identical lengths, the earth fault loop impedance can be calculated as follows:

$$Z_s = \frac{L}{1000}\sqrt{(R_c + R_e)^2 + (X_c + X_e)^2}$$

Where L is the length of the cable (m)

R_c and R_e are the ac resistances of the active and earth conductors respectively (Ω/km)

X_c and X_e are the reactances of the active and earth conductors respectively (Ω/km)

Maximum Cable Length

The maximum earth fault loop impedance can be found by re-arranging the equation above:

$$Z_{s,max} = \frac{V_0}{I_A}$$

Where Z_s is the maximum earth fault loop impedance (Ω)

V_0 is the phase to earth voltage at the protective device (V)

I_A is the earth fault current required to trip the protective device within the minimum disconnection time (A)

The maximum cable length can therefore be calculated by the following:

$$L_{max} = \frac{1000 V_0}{I_A\sqrt{(R_c + R_e)^2 + (X_c + X_e)^2}}$$

Where L_{max} is the maximum cable length (m)

V_0 is the phase to earth voltage at the protective device (V)

I_A is the earth fault current required to trip the protective device within the minimum disconnection time (A)

R_c and R_e are the ac resistances of the active and earth conductors respectively (Ω/km)

X_c and X_e are the reactances of the active and earth conductorsrespectively (Ω/km)

Note that the voltage V_0 at the protective device is not necessarily the nominal phase to earth voltage, but usually a lower value as it can be downstream of the main busbars. This voltage is commonly represented by applying some factor C to the nominal voltage. A conservative value of C = 0.8 can be used so that:

$$V_0 = cV_n = 0.8V_n$$

Where V_n is the nominal phase to earth voltage (V)