

## Circuit Design Guide: Cable Selection

Before we start our circuit design, we must understand what is required when selecting a cable. This is done by following a number of steps using BS7671:2018 Requirements for Electrical Installations and the IET On-site guide

The equation is made up of steps taking into account a number of different factors. These factors will help determine the size of cable to be installed.

What is in the equation?

**I<sub>b</sub>** – Design current. This is the current flowing through the circuit in normal operation.

How do we find **I<sub>b</sub>**?

This will depend on your supply voltage. Either single phase or three-phase.

Single phase – 
$$\frac{\text{power (watts)}}{\text{voltage (V)}}$$

Three phase - 
$$\frac{\text{power (watts)}}{\sqrt{3} \times 400}$$

For example: A 3KW load on a single-phase circuit. What is **I<sub>b</sub>**?

$$I_b = \frac{\text{Power}}{\text{voltage}} = \frac{3000}{230} = 13.04 \text{ A}$$

A 4.5KW load on a three-phase circuit. What is **I<sub>b</sub>**?

$$I_b = \frac{\text{power}}{\sqrt{3} \times VL} = \frac{4500}{1.73 \times 400} = \frac{4500}{692} = 6.50 \text{ A}$$

Certain loads may require us to consider power factor. Typically, inductive loads such as motors will produce a power factor value that needs to be incorporated into our design current calculation.

For example: A 16KW three-phase motor has a full load power factor of 0.8. What is  $I_b$ ?

$$I_b = \frac{\text{power}}{\sqrt{3} \times VL \times p.f} = \frac{16000}{1.73 \times 400 \times 0.8} = 28.9A$$

$I_n$  – Protective device rating – A device must be selected that is equal to or greater than  $I_b$ . Choose the protective device that meets these requirements (BS7671:2018 Page 61-63)

$$I_n \text{ must be } \geq I_b$$

$I_t$  – Tabulated carrying capacity of the cable – within Appendix 4 you will find the tabulated current carrying capacity for your selected type of cable.

$I_z$  – Current carrying capacity of cable for continued service, under particular installation conditions concerned – the amount of current you expect to flow in your circuit taking into account rating factors.

$$I_z \text{ must be } \geq I_n$$

BS7671:2018 Appendix 4 gives us guidance on selecting a circuit conductor size. Whilst calculating  $I_z$  is an acceptable method, it is recognised that this will involve a certain amount of ‘trial and error’.

Another method is suggested where rating factors are applied to  $I_n$  or  $I_b$  depending if overload protection is to be utilised. This method substitutes  $I_z$  for  $I_t$  and actually removes the requirement to know the value of  $I_z$ .

After calculating  $I_b$  and selecting a protective device  $I_n$ , we will lead on to this equation that is the alternative method suggested in BS7671:2018

$$I_t \geq \frac{I_n}{C_a \times C_g \times C_f \times C_c \times C_i}$$

We already know what  $I_t$  and  $I_n$  are, but what are the others components to the equation? These are known as rating factors. These can affect the outcome of the cable size. All of them can be found in BS7671:2018

**Ca** – Ambient temperature for the cable when working in normal operation.

**Cg** – Grouping of circuits. This is to calculate how other circuit conductors can affect our cables heat dissipation.

**Cf** – Rating factor that is applied only for a BS-3036 semi enclosed fuse in the event of an overload.

**Cc** – Rating factor that is applied for cables buried in the ground. This will need to be applied as the soil will act as an insulator and can affect the cable's heat dissipation in the event of an overload.

**Ci** – Rating factor for cables totally surrounded/embedded in thermal insulation.

Depending on the value of each correction factor your required current carrying capacity is more than likely going to increase (there will be occasions where it will decrease)

**Example:**

Design current ( $I_b$ ) 17.03A

Protective device selected ( $I_n$ ) 20 amp (being  $\geq$  than  $I_b$ )

In a typical installation the cable could be clipped direct on a wall in a single layer (reference method C), grouped with 3 other cables and run through 200mm of thermal insulation.

$$It \geq \frac{In}{Ca \times Cg \times Cf \times Cc \times Ci}$$

Fill in the information we know.

$$It \geq \frac{20}{1 \times 0.75 \times 1 \times 1 \times 0.63} \quad \text{or} \quad It \geq \frac{20}{0.75 \times 0.63}$$

If the rating factor is not used you must replace it with the value of 1 if you use the full equation, or you can simplify the equation by removing the correction factors which are unused.

$$It \geq \frac{20}{0.4725}$$

The safest way to complete the equation is to carry-out the bottom part of the equation first. (This means you are not struggling to insert brackets on your calculator)

$$It \geq 42.32 \text{ amps}$$

As you can see our new current capacity required for our circuit is 42.32 amps. This takes into account the heat dissipation of the cable installed with 3 other cables and in thermal insulation.

***It is this figure we select our cable size from, NOT the value of Ib.***

Once we have performed this calculation, we can choose a cable size from the appropriate table in Appendix 4 of BS7671:2018. Ensuring we select a cable with a value of **It** greater than the outcome of our calculation.

## Circuit Design Guide: Voltage Drop

Once you have selected your cable size from applying cable factors to  $I_b$  and  $I_n$ , you must now see if the cable size meets the requirements for permissible volt-drop.

Volt-drop limits are found within BS-7671 and the percentage volt-drop permitted is shown on table 4Ab BS-7671 (as shown below).

Volt-drop	Lighting	Other uses
Low voltage installations supplied directly from a public low voltage distribution system.	3%	5%
Low voltage installation supplied from a private LV supply.	6%	8%

The equation for volt-drop is 
$$VD = \frac{mV/A/m \times Ib \times l}{1000}$$

$mV/A/m$  – Milli-volts per amp per metre for selected cable size

$Ib$  – design current. ( $I_b$ )

$l$  - length of cable in metres

1000 – We must divide the top line by 1000 as volt-drop is given in milli-volts and we require the answer to be in Volts

**Example:** we have decided that a 2.5mm<sup>2</sup> flat PVC 70°C cable is suitable for installation as the design current is 5 Amps and the run is 45 metres. The supply is 230V.

Our first requirement is to look in BS-7671 on page 409 table 4D5. Looking along the table we see in section 8 that the  $mV/A/m$  value in this case is 18mV per ampere per meter. (Take care when looking for volt-drop as each cable type has a different page and column)

We can now fill in the equation.

$$\text{Volt-drop} = \frac{18 \times 5 \times 45}{1000} \quad \text{Volt-drop} = \frac{4050}{1000} \quad \text{Volt-drop} = 4.05 \text{ Volts}$$

Our next stage is to see if this complies with the regulations for volt-drop, so we need to look back in the BS-767 table 4Ab.

The table show the maximum % volt-drop allowed for circuits. In this case the cable will be used for other uses so our maximum volt-drop will be 5%. To find the 5% volt-drop on our supply we need to carry out the following equation.

$$230 \div 100 \times 5 = 11.5\text{volts}$$

If our circuit is 3-phase we change the supply voltage from 230V to 400V as shown below.

$$400 \div 100 \times 5 = 20\text{volts}$$

Once we have worked out our maximum volt-drop permitted we simply compare the two figures, if we have selected the right cable size our volt-drop on the cable will be within the permitted limits.

If the cable is not within the permitted volt-drop you go back and select a larger cable size and repeat the volt-drop equation again until it complies with the requirements of volt-drop in BS7671.

### **Circuit Design Guide: Earth Fault Loop Impedance (Zs)**

Calculating the circuits Zs requires us to look at the following equation.

$$Z_s = Z_e + (R_1 + R_2)$$

The above equation is suitable for calculating the Zs for circuits in operation as Ze, R1 and R2 are measured and simply adding together equals Zs. We cannot use this equation for circuit design. The reason for this is that the equation does not take into account the maximum operating temperature or length of conductor.

We need use the following equation.

$$Z_s = Z_e + \frac{(R_1 + R_2) \times L \times F}{1000}$$

L = Length in metres.

F = Operating temperature coefficient (On-Site Guide page 198 table I3)

$R1+R2$  = Resistance of conductors per meter (On-Site Guide page 196 table I1)

Example:

We are using a flat PVC 6.0mm<sup>2</sup> cable (R1) which has a 2.5 mm<sup>2</sup> CPC (R2).

Using Appendix I in the On-Site Guide, Table I1 shows that a 6.0 mm<sup>2</sup> cable with 2.5mm<sup>2</sup> cpc has a resistance of 10.49 milli-Ω-per metre.

We have a length of 50 metres and the CPC is incorporated within our cable. Ze for the installation is measured at 0.23 Ω

$$Z_s = 0.23 + \frac{10.49 \times 50 \times 1.20}{1000}$$

We must remember to divide by 1000 as R1 and R2 values are in milli-Ω and we require Ω.

Equation continued.

$$Z_s = 0.23 + \frac{629.4}{1000}$$

$$Z_s = 0.23 + 0.63$$

$$Z_s = 0.86 \Omega$$

This is then checked against the protective devices tabulated values in the BS-7671 and not the On-Site Guide as those values have already been adjusted to include the 80% rule which is not applicable at the design stage.

## Circuit Design Guide: Prospective Fault Current (I<sub>pf</sub>)

Before moving on to complete our circuit design using the adiabatic equation, we must calculate the prospective earth fault current that will be generated under a fault condition from our circuit design.

To find the earth fault current we are required to carry out the following equation as shown below:

$$I = \frac{U_0}{Z_s}$$

I – Prospective earth fault current generated under a fault condition.

U<sub>0</sub> – The nominal voltage to earth.

Z<sub>s</sub> – is the earth fault loop impedance related to the circuit in question.

Please note: The prospective earth fault current is measured between a single phase line conductor (L1, L2, L3) to Circuit protective conductor (R2) (230V) not between phases (400V)

Example:

If we use the information from the previous step we have a calculated Z<sub>s</sub> of 0.86Ω.

$$I = \frac{U_0}{Z_s} \qquad I = \frac{230}{0.86}$$

$$I = 267.44 \text{ amps}$$

As we can see from the calculation under a fault condition the fault current will be 267.44A. If the circuit has been designed correctly this fault current will be large enough to disconnect the circuit protective device in the permitted time.

We check this by consulting the time/current curves in Appendix 3 of BS7671 or reviewing manufacturers data.

Section 6.3.1 of the IET Electrical Installation Design Guide recommends a **C<sub>max</sub>** factor of 1.1 to be applied to the nominal voltage when estimating maximum fault currents.

However, the guide also states ‘...a designer knowing his voltages may be higher or lower than these figures may be wise if he uses his own best estimate.’

For the purposes of this design guide, we have omitted this part of the formula. If you were to apply this factor, the formula would be shown as follows:

$$I = \frac{U_o \times C_{max}}{Z_s}$$

### **Circuit Design Guide: Adiabatic Equation**

To finally complete the design of the circuit you must check to see if your selected CPC is adequate. You check this by using the Adiabatic equation.

The Adiabatic equation can be found in BS7671 chapter 54

$$S = \frac{\sqrt{I^2 t}}{k}$$

S – Nominal cross-sectional area of the conductor in mm<sup>2</sup>.

I – Fault current calculated from total Z<sub>s</sub> and nominal voltage.

t – Disconnection time in seconds of the protective device at fault current. To find the time in which the protective device will operate, look in time/current curves in Appendix 3 of BS7671.

k – Correction factor taking into account resistivity, temperature coefficient and heat capacity of the conductor material. K values can be found in Chapter 54. Depending on your cable selection you will use different tables.

Example:

$$S = \frac{\sqrt{267.44^2 \times t}}{K}$$

$$S = \frac{\sqrt{71524.15 \times 0.1}}{115}$$

$$S = \frac{\sqrt{7152.415}}{115}$$

$$S = \frac{84.57}{115}$$

$$S = 0.74 \text{ mm}^2$$

In this case we selected a 2.5mm<sup>2</sup> cable so the minimum size of 0.74 mm<sup>2</sup> has been achieved.

If the CSA of the CPC has been selected using table 54.7 of BS7671 then there is no requirement to carry out the adiabatic calculation.