Technical Guide

“Cable Size Selection”

Small and Medium Enterprises Development Authority

Ministry of Industries & Production

Government of Pakistan

www.smeda.org.pk

HEAD OFFICE

4th Floor, Building No. 3, Aiwan-e-Iqbal Complex, Egerton Road,Lahore
Tel:(92 42)111 111 456, Fax:(92 42) 36304926-7
helpdesk@smeda.org.pk

REGIONAL OFFICE PUNJAB	REGIONAL OFFICE SINDH	REGIONAL OFFICE KHYBER PAKHTUNKHWA	REGIONAL OFFICE BALOCHISTAN
3rdFloor, Building No. 3, Aiwan-e-Iqbal Complex, Egerton Road Lahore, Tel: (042) 111-111-456 Fax: (042) 36304926-7 helpdesk.punjab@smeda.org.pk	5TH Floor, Bahria Complex II, M.T. Khan Road, Karachi. Tel: (021) 111-111-456 Fax: (021) 5610572 helpdesk-khi@smeda.org.pk	Ground Floor State Life Building The Mall, Peshawar. Tel: (091) 9213046-47 Fax: (091) 286908 helpdesk-pew@smeda.org.pk	Bungalow No. 15-A Chaman Housing Scheme Airport Road, Quetta. Tel: (081) 831623, 831702 Fax: (081) 831922 helpdesk-qta@smeda.org.pk

Table of Contents

1 Disclaimer

This information memorandum is to introduce the subject matter and provide a general idea and information on the said matter. Although, the material included in this document is based on data/information gathered from various reliable sources; however, it is based upon certain assumptions, which may differ from case to case. The information has been provided on AS IS WHERE IS basis without any warranties or assertions as to the correctness or soundness thereof. Although, due care and diligence has been taken to compile this document, the contained information may vary due to any change in any of the concerned factors, and the actual results may differ substantially from the presented information. SMEDA, its employees or agents do not assume any liability for any financial or other loss resulting from this memorandum in consequence of undertaking this activity. The contained information does not preclude any further professional advice. The prospective user of this memorandum is encouraged to carry out additional diligence and gather any information which is necessary for making an informed decision, including taking professional advice from a qualified consultant/technical expert before taking any decision to act upon the information.

For more information on services offered by SMEDA, please contact our website: www.smeda.org

2 Introduction to SMEDA

The Small and Medium Enterprises Development Authority (SMEDA) was established in October 1998 with an objective to provide fresh impetus to the economy through development of Small and Medium Enterprises (SMEs).

With a mission "to assist in Employment Generation and Value Addition to the national income, through development of SME sectors, by helping increase the number, scale and competitiveness of SMEs", SMEDA has carried out 'sectoral research' to identify Policy, Access to Finance, Business Development Services, strategic initiatives and institutional collaboration & networking initiatives.

Preparation and dissemination of prefeasibility studies in key areas of investment has been a successful hallmark of SME facilitation by SMEDA.

Concurrent to the prefeasibility studies, a broad spectrum of Business Development Services is also offered to the SMEs by SMEDA. These services include identification of experts and consultants and delivery of need-based capacity building programs of different types in addition to business guidance through help desk services.

2.1 Industry Support Program

In order to enhance competitiveness of SMEs and achieve operational excellence, SMEDA established an Industry Support Cell (ISC) for provision of foreign technical support and knowledge transfer in collaboration with International Development Organizations. SMEDA's Industry Support Program (ISP) initially launched with Japan International Cooperation Agency (JICA) and actively engaged in reducing energy inefficiencies and improving production and quality of products with the support of Japanese Experts. Later on, similar activities with other international partner organizations like German Corporation for International Cooperation (GIZ), Training and Development Centers of the Bavarian Employers' Association (bfz), Germany, and United Nations Industrial Development Organization (UNIDO) were also successfully implemented.

3 Cable Size Selection

Every electrical machine/appliance requires a cable for electrical connection. The size of this cable majorly depends on the electrical load of that particular machine/appliance and some other factors.

Cable size selection for a specific application depends on a number of factors, e.g., amperage, environment, number of phases etc. Hence selection is never a simple task. Selection is also made difficult as there is such a large variety of cables available in market.

Therefore, for the proper sizing of an electrical (load bearing) cable is important to ensure that the cable can

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

4 Factors Affecting Cable Size Selection

Cable size selection depends on a number of factors. We will discuss them in detail in following section.

4.1 Rated Voltage

It is necessary to select a power cable capable of supporting a particular system voltage (e.g. 230 V_{ac} single phase, 415V_{ac} three phase or DC voltage etc)

In case of AC system, the rated voltage of power cable should always be equal to or greater than the system voltage.

To determine rated voltage consider following formula

$$\boldsymbol{V = \sqrt{3}\, Vo}$$

Where V_o is the rated cable voltage between each conductor and earth and V is the rated cable voltage between phase conductors.

The exact rated voltage selection of power cable depends on earth fault withstand limits and specification considerations that are made by the power system designers.

As per IEC standards following three classifications exist:

Category A: The earth fault must be cleared within 1 second

Category B: Earth fault cleared within 1 hour for IEC-183 type cables, and cleared within 8 hours for IEC-502 type cables

Category C: All systems not covered under A and B

For categories A and B, cables with same rated voltage as system voltage can be chosen. However, for Category C, the rated voltage of cable should be higher than system voltage.

e.g., for 3.3 kV system voltage, cable with rated voltage of 6.6 kV should be selected.

4.2 Current Carrying Capacity

Each power cable is designed to operate under certain temperature and load conditions.

Current carrying capacity of power cable is also dependent on conductor material (Copper / Aluminium) and insulation type. Thus, copper conductor cable has greater current carrying capacity than Aluminium conductor

XLPE (Cross linkage polyethylene) insulation is better than PVC (Poly vinyl chloride), hence the current carrying capacity of XLPE cable is more than that of PVC insulated cable.

Operating a cable continuously beyond its rated current carrying capacity shortens the lifespan of the cable, as the insulation becomes prone to failure and can cause short circuit.

The current carrying capacity is also dependent on operating temperature. Higher the temperature, lower is the current carrying capacity of the cable and vice versa.

4.3 Derating Factor

A power cable designed with standard operating conditions may differ in actual reality and may not perform the same in practical. Therefore, the current carrying capacity may get affected.

Some examples of this, cables installed underground will have reduced current carrying capacity than cables installed overhead. This is due to multiple factors like soil temperature, soil thermal resistivity etc. In order to deal with this, a derating factor is associated with cables to calculate the actual value of current carrying capacity. For this actual current carrying capacity we will consider the following formula

$$\begin{aligned}&\boldsymbol{Actual\ current\ carrying\ capacity}\\&\boldsymbol{= Derating\ Factor\ X\ Current\ Carrying\ Capacity\ under\ standard\ conditions}\end{aligned}$$

Thus for a 100 amperes cable with a derating factor of 0.8, the actual current carrying capacity would be 80 amperes (100 X 0.8 = 80)

4.4 Voltage Drop

A power cable manufacturer provides the value of voltage drop as part of data sheet. A voltage drop across the length of the power cable is very important. It is expressed as milli-volts per ampere meter as mentioned below

$$Voltage\ drop = \frac{mV}{Am}$$

The voltage drop per unit length of cable should be as low as possible in order to get the same voltage at delivery side as on supply side.

4.5 Short Circuit Withstand

A power cable in case of short circuit event should be able to withstand the high current values without any damage to the cable and insulation.

The selection of short circuit current withstand capacity of a power cable is directly dependent on the specification of connected protection device.

For example, if a breaker connected to a power cable is set to trip at 100 A in 1 second then we need to select the appropriate cable that can withstand the high current of 100 A for a period of 1 second.

4.6 Availability of Cables

Cables are manufactured in certain minimum length segments. For example, it will be difficult to procure a 30 meter length of 300 mm^2 cable than a 300 meter length of same cable.

Also, the costing may vary largely between the two quantities.

Therefore, before selecting any cable for a specific application market data should be gathered from cable manufacturers/dealers and appropriate cable should be selected considering size and length.

4.7 Bending Radius

Different types of cables have different bending radii and bending radius also increases as the size of the cable increases. Furthermore, insulation type also affects bending radius.

A same size multi-core XLPE cable has more bending radius than a PVC cable. In order to overcome this, a contractor might have to shift from XLPE to PVC or he might have to select separate single core cables.

4.8 Other Factors

There are some other factor which influence cable size selection.

Care needs to be taken while dealing with Aluminum conductor cables, as the metal tends to oxidize quickly when exposed to air and develops a thin layer of dielectric coating. Aluminum conductor cables are not used in case of generating stations and substations installations.

Aluminum is preferred for other application areas due to its high conductivity to weight ratio.
Large sized cables are quite rigid and difficult to bend, install and terminate.

5 Methodology for Cable Size Selection

There is a six step basic methodology for cable size selection. First we will enlist these steps and then discuss them in detail one by one

- ✓ **Step 1** - Data Gathering (Gathering data about the cable, installation conditions and load etc)
- ✓ **Step 2** - Determine the minimum cable size based on continuous current carrying capacity
- ✓ **Step 3** - Determine the minimum cable size based on voltage drop considerations
- ✓ **Step 4** - Determine the minimum cable size based on short circuit temperature rise
- ✓ **Step 5** - Determine the minimum cable size based on earth fault loop impedance
- ✓ **Step 6** - Select the cable based on the sizes calculated in step 2,3,4 and 5

5.1 Step 1 – Data Gathering

The first step is to collect the relevant information that is required for cable size selection. Typically load details, cable construction and installation conditions are required to select the cable size

5.1.1 Load Details

Load characteristics which are required for cable size selection are mentioned below

- ✓ Load type (Motor etc)
- ✓ Supply (Three phase/Single phase/DC)
- ✓ System / source voltage
- ✓ Full load current
- ✓ Full load power factor
- ✓ Distance between load and the source (This length should be as minimum as possible)

5.1.2 Cable Construction

Following basic characteristics of cable should be considered

- ✓ Conductor material (Copper/Aluminium)
- ✓ Conductor shape
- ✓ Conductor type (Solid/Stranded)
- ✓ Conductor surface coating (Plain/tinned/silver coated/nickel coated)
- ✓ Insulation type (PVC/XLPE)
- ✓ Number of cores (single core/multi core)

5.1.3 Installation Conditions

Following installation conditions should be considered before selecting cable size

- ✓ Underground or above ground
- ✓ Installation arrangement (For underground cables , either directly buried or buried in conduit and for cables above ground, either installed on cable tray/ladder or against a wall)
- ✓ Ambient temperature of installation site (Soil temperature in case of underground)
- ✓ Cable bunching
- ✓ Cable spacing
- ✓ Soil thermal resistivity (For underground cables)
- ✓ Depth of laying (For underground cables)

5.2 Step 2 – Cable selection based on current rating

Current flowing through a cable generates heat through resistive losses in the conductor, dielectric losses through the insulation and resistive losses from the current flowing through any cable screen/shield or cable armour.

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

Normally cable manufacturers will quote base current ratings of different types of cables depending upon cable insulation (PVC or XLPE insulated), installation conditions (ambient temperature, installation method) etc.

Normally a derating factor is multiplied with base current rating of a cable to get the actual current carrying capacity of that particular cable under particular conditions. Cable manufacturers will provide derating factor for a range of installation conditions. e.g., ambient/soil temperature, grouping or bunching of cables, soil thermal resistivity etc. The actual installed current rating is calculated by multiplying the base current rating with each of the derating factors as shown below

$$\boldsymbol{I_c = I_b \times k_d}$$

Where
I_c = Installed current capacity (A)
I_b = Base current capacity (A)
k_d = 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 = 0.94 x 0.85 = 0.799. For a cable with base current rating of 42A, the installed current rating will be as below

$$I_c = 0.799 \times 42$$

$$\boldsymbol{I_c = 33.6\ A}$$

While sizing cables with respect to given load, the upstream protective devices (fuse, circuit breaker, overload relays etc) are typically selected to also protect the cable against damage due to thermal overloading. The protective devices must therefore be selected to exceed the full load current, but not exceed the cable's installed current rating, i.e., the following inequality must be met

$$\boldsymbol{I_f \le I_p \le I_c}$$

Where
I_f = Full load current (A)
I_p = Protective device rating (A)
I_c = Installed cable current rating (A)

5.3 Step 3 – Voltage drop

Cable 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

$$\boldsymbol{V = I Z}$$

Where
V = Voltage
I = Current
Z = Impedance

The voltage drop will depend upon two things

- ✓ Current – the higher the current flow, the higher will be the voltage drop
- ✓ Impedance – the larger the impedance of the conductor, higher will be the voltage drop

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 cable reactance /resistance in Ω/km (ohms per km).

5.3.1 Calculating Voltage Drop

For AC systems, the method of calculating voltage drop based on load power factor is normally 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:

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

Where
$V_{3\varphi}$ = Three phase voltage drop
I = Nominal full load current or starting current as applicable
R_c = AC resistance of the cable (Ω/km)
X_c = AC reactance of the cable (Ω/km)
Cos φ = Load power factor
L = Length of the cable (m)

For a single phase system

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

Where
$V_{1\varphi}$ = Single phase voltage drop
I = Nominal full load current or starting current as applicable
R_c = AC resistance of the cable (Ω/km)
X_c = AC reactance of the cable (Ω/km)
Cos φ = Load power factor
L = Length of the cable (m)

For a DC system

$$V_{dc} = \frac{2\ I\ R_c\ L}{1000}$$

Where
V_{dc} = DC voltage drop
I = Nominal full load current or starting current as applicable
R_c = DC resistance of the cable (Ω/km)
L = Length of the cable (m)

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

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

5.3.2 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 permissible voltage drop (e.g. 5% of nominal voltage at full load) rather than the voltage drop itself.

The maximum cable length that can be achieved can be calculated by rearranging the voltage drop equations and substituting the maximum permissible voltage drop (5% of 415V nominal voltage = 20.75V)

For three phase system:

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

Where
L_{max} = Maximum length of the cable (m)
$V_{3\varphi}$ = Maximum permissible three phase voltage drop
I = Nominal full load current or starting current as applicable
R_c = AC resistance of the cable (Ω/km)
X_c = AC reactance of the cable (Ω/km)
Cos φ = Load power factor

For a single phase system:

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

Where
L_{max} = Maximum length of the cable (m)
$V_{1\varphi}$ = Maximum permissible single phase voltage drop
I = Nominal full load current or starting current as applicable
R_c = AC resistance of the cable (Ω/km)
X_c = AC reactance of the cable (Ω/km)
Cos φ = Load power factor

For a DC system:

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

Where
L_{max} = Maximum length of the cable (m)
V_{dc} = Maximum permissible DC voltage drop
I = Nominal full load current or starting current as applicable
R_c = DC resistance of the cable (Ω/km)

5.4 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 temperature can trigger unwanted reactions in the cable insulation, sheath materials and other components, which can prematurely degrade the condition of the cable. As the cross-sectional area of the cable increases, it can dissipate higher fault currents for a given temperature rise. Therefore, cables should be sized to withstand large short circuit currents.

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

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

Where
A = Minimum cross-sectional area of the cable (mm^2)
i = Prospective short circuit current (A)
t = Duration of short circuit (s)

k = Short circuit temperature rise constant

The temperature rise constant is calculated depending upon the material properties of the conductor and the initial and final conductor temperatures. IEC 60364-5-54 calculates the temperature rise constant as follows

For copper conductors:

$$\boldsymbol{k = 226\sqrt{ln\left(1+\left(\frac{\theta_f-\theta_i}{234.5+\theta_i}\right)\right)}}$$

For aluminium conductors:

$$\boldsymbol{k = 148\sqrt{ln\left(1+\left(\frac{\theta_f-\theta_i}{228+\theta_i}\right)\right)}}$$

Where

θ_i = Conductor initial temperature (^oC)

θ_f = Conductor final temperature (^oC)

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.

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 fuses or protective relays), the short circuit energy chosen should be the maximum prospective let through energy of the protective device, which can be found form manufacturer datasheet.

5.5 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 conductor. During such 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, the maximum disconnection time of 5 sec is sufficient, though for portable equipment and socket outlets, a faster disconnection time is desirable (i.e., <1 sec and will definitely require earth fault protection)

However for circuits that do not have earth fault protection, the upstream protective devices (fuse/circuit breaker) must trip within the maximum disconnection time. In order for the protective devices 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 5 sec, then the fault current exceed the fuse melting current at 5 sec.

By simple application of Ohm's law

$$\boldsymbol{I_A = \frac{V_o}{Z_S}}$$

Where

I_A = Earth fault current required to trip the protective device within the minimum disconnection time (A)
V_0 = Phase to earth voltage at the protective device (V)
Z_S = Impedance of the earth fault loop (Ω)

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

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

The earth fault loop impedance can be found by

$$\boldsymbol{Z_s = Z_c + Z_E}$$

Where
Z_S = Earth fault loop impedance (Ω)
Z_c = Impedance of the active conductor (Ω)
Z_E = Impedance of the earth conductor (Ω)

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

$$\boldsymbol{Z_S = \frac{L}{1000}\sqrt{(R_C + R_E)^2 + (X_C + X_E)^2}}$$

Where
Z_S = Earth fault loop impedance (Ω)
L= Length of the cable (m)
R_C = Ac resistance of active conductor (Ω/km)
R_E = Ac resistance of earth conductor (Ω/km)
X_C = Ac reactance of active conductor (Ω/km)
X_E = Ac reactance of earth conductor (Ω/km)

The maximum earth fault loop impedance can be found by rearranging the above equation

$$\boldsymbol{Z_{s.max} = \frac{V_0}{I_A}}$$

Where
$Z_{s.max}$ = Maximum earth fault loop impedance (Ω)
V_0 = Phase to earth voltage at the protective device (V)
I_A = 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 formula

$$\boldsymbol{L_{max} = \frac{1000V_0}{I_A\sqrt{(R_C + R_E)^2 + (X_C + X_E)^2}}}$$

Where
L_{max} = Maximum cable length (m)
V_0 = Phase to earth voltage at the protective device (V)
I_A = Earth fault current required to trip the protective device within the minimum disconnection time (A)
R_C = Ac resistance of active conductor (Ω/km)
R_E = Ac resistance of earth conductor (Ω/km)
X_C = Ac reactance of active conductor (Ω/km)
X_E = Ac reactance of earth conductor (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 bus-bar. This voltage is normally represented by applying some factor c to the nominal voltage. A conservative value of c=0.8 can be used.

Thus

$$V_0 = cV_n$$

Finally

$$V_0 = 0.8\, V_n$$

Where
V_n = Nominal phase to earth voltage (V)

5.6 Step 6 – Final cable selection

Considering all the factors mentioned in Step 2 to Step 5 the final cable size is selected.

6 Conclusion

CEO / Owner of every factory should emphasize on proper sizes of power cable for all machinery because under sized cables can cause many problems like system malfunction, machine breakdown, more heat losses, short circuits and many more. With the help of proper cable size selection system efficiency and capacity can be increased.

Furthermore, a factory CEO / Owner can enjoy following benefits by selecting the appropriate size of power cable

- ✓ Improved system capacity
- ✓ Reduced system losses
- ✓ Improved system voltage
- ✓ Less breakdown time
- ✓ Less heat losses
- ✓ Less voltage drop
- ✓ Less faults