RESEARCH ARTICLE OPEN ACCESS

Under Ground Cable Sizing Using MAT LAB

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Abstract
The main theme of this paper is to explain the procedure to calculate the cross sectional area of a conductor of an underground cable for a specified power & voltage ratings. This paper will also explain one of the simplest ways to calculate the cross section. In this paper we analyzed various factors that effect in deciding the ampacity of the conductor. We developed a Mat lab code to find the cross sectional area by including some of the parameters and also the voltage drop , maximum permissible voltage drop for that size of the conductor and also the number of runs of the cable that are to be laid.
Key words: Conduction cross section, derating factor, XLPE cable, MATLAB

I. INTRODUCTION

CABLE (or conductor) sizing is the process of selecting appropriate sizes for electrical power cable conductors. Cable sizes are typically described in terms of cross-sectional area, American Wire Gauge (AWG) or kcmil, depending on geographic region. In this we have taken CCI (Cable Corporation of India) standards into consideration for calculating cable size.

The purpose of Conductor and Cable Sizing is to determine the best to transport a given current, determined by voltage, through an insulated conductive material. Conductor size must be calculated by taking factors like distance, raceways and environmental conditions into account which includes minimizing heat generated from resistance or impedance of the cable itself.

Proper sizing of an electrical (load bearing) cable ensures that the cable can:

1. Operate continuously under full load without being damaged
2. Withstand the worst short circuit currents flowing through the cable
3. Provide suitable voltage to the load (and avoid excessive voltage drops)
4. Ensures operation of protective devices during an earth fault

II. PROBLEM STATEMENT

Consider a 3-phase, 11 kV substation, from which a 1 MVA power is to be transferred to a load which is situated at certain distance from the substation, through a 3 core cable. This article gives the sizing of a cable in a generalized way i.e., from a substation at any voltage level transferring a certain power to the load.

III. GENERAL METHODOLOGY

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

1. Gathering data about the cable, its installation conditions, and the load that it has to carry.
2. Determine the minimum cable size based on continuous current carrying capacity.
3. Determine the minimum cable size based on voltage drop considerations
4. Select the cable size based on the highest of the sizes calculated in step 2 and 3.

Step 1:

The first step is to collate the relevant information that is required to perform the sizing calculation

Load Details

- The type of load to which cable is connected i.e., feeder or motor (This article generally deals with feeder type of cables).
- Three phase, single phase or DC (here 3-phase) .
- System / source voltage at which cables is operating.
- Full load current (A) - or calculate this if the load is defined in terms of power (kW) .
- Desired full load power factor (p.u) at which system should operate.
- 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:

- Material of conductor (normally copper or aluminum).
- Shape of conductor (like circular or shaped).
- Type of conductor (like stranded or solid).
- Conductor surface coating (like plain (no coating), tinned, silver or nickel).
- Insulation type (mostly preferred PVC, XLPE, EPR)

- Number of cores - single core or multicore (2-core ,3-core, etc..,).

Installation Conditions:

How the cable will be installed:

- 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 grouping, i.e. the number of cables that are grouped together.
- Cable spacing, i.e. whether cables are installed touching or spaced from each other.
- Soil thermal resistivity.
- Depth of laying.
- For single core three-phase cables, are the cables installed in trefoil or laid flat?

Note:35^0C ground temperature for cables directly buried in ground, the depth of laying being 900 mm and soil thermal resistivity being 150^0C cm/W is assumed.

STEP 2:

The substation rating from which cable is to be sized is to be given (V in 3-phase) and the power (in MW or MVA) that is to be transferred through this cable (say P) is to be given. The current (I) passing through the cable is calculated as [5]

$$I = \frac{P\ (MW)}{\sqrt{3} * V * \cos\phi} \quad (1)$$

$$I = \frac{P\ (MVA)}{\sqrt{3} * V} \quad (2)$$

Current at 110% loading (I_{fl}) is given as

Let, $I_{fl} = I\ (1.1)$ (3)

This is here considered in order to ensure that cable can withstand over loading up to some extent which prevents damage of the cable and the electrical equipment (load) connected to the delivering end of the cable. This value can be taken higher for more safety but it increases the losses and also the amount of material used which is waste of economy.

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 component parts that make up the cable (e.g. conductors, insulation, bedding, sheath, armour, etc.) 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 without damaging the cable's insulation and other components (e.g. bedding, sheath, etc.). It is sometimes also referred to as the continuous current rating or ampacity of a cable.

Cables with larger conductor cross-sectional areas have lower resistive losses and are able to dissipate the heat better than smaller cables. Therefore we can say that 16 mm^2 cables will have a higher current carrying capacity than a 4 mm^2 cables.

Base Current Ratings

International standards and manufacturers of cables will quote base current ratings of different types of cables in tables such as the one shown below. The tables given below are given by Cable Corporation of India (CCI).

TABLE I: ALUMINIUM COND. 3 CORE CABLES FROM 3.3 kV TO 33 kV (E) [1]

Conductor Cross-Section	3.3 kV to 11(UE) Direct in ground	22 kV to 33 (E) Direct in ground
Sq.mm	Amps	Amps
25	95	
35	110	110
50	130	130
70	160	160
95	190	190
120	215	210
150	245	240
185	275	270
240	320	310
300	360	350
400	410	400

TABLE II: COPPER COND. 3 CORE CABLES FROM 3.3kV TO 33kV (E) [1]

Conductor Cross-Section	3.3kV to 11(UE) Direct in ground	22kV to 33(E) Direct in Ground
Sq.mm	Amps	Amps
25	120	
35	145	145
50	170	165
70	205	205
95	245	240
120	280	275
150	310	305

185	350	345
240	405	395
300	455	445
400	510	505

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.

[3]

Id=It * DF (4)

Where I_d the installed current rating (A)

I_t is the current rating (A)

DF are the product of all the derating factors

The various factors that cause derating of current carrying capacity of a cable are ground thermal resistivity, grouping of cables, ground temperature and air temperature. The values of derating factors for the above mentioned parameters for some standard values are:

TABLE III: GROUND THERMAL RESISTIVITY [2]

Thermal Resistivity (K.m/W)	Direct in ground
1,0	1,08
1,2	1,00
1,5	0,93
2,0	0,83
2,5	0,78

TABLE IV: GROUPING OF CABLES [2]

No of cables in Group	Direct in Ground				
	Axial Spacing (mm)				
	Touching	150	300	450	600
2	0.81	0.87	0.91	0.93	0.94
3	0.70	0.78	0.84	0.87	0.90
4	0.63	0.74	0.81	0.86	0.89
5	0.59	0.70	0.78	0.83	0.87
6	0.55	0.67	0.76	0.82	0.86

TABLE V: GROUND TEMPERATURE [2]

Maximum Conductor Temp (ºC)	Ground temperatures (ºC)					
	25	30	35	40	45	50
70(PVC)	1.00	0.95	0.90	0.85	0.80	0.70
90(XLPE)	1.00	0.96	0.92	0.88	0.82	0.76

TABLE VI: AIR TEMPERATURE [2]

Maximum conductor temp(ºC)	Air temperature (ºC)			
	30	35	40	45
70(PVC)	1.00	0.94	0.87	0.79
90(XLPE)	1.00	0.95	0.89	0.84

For example, suppose a cable had an ambient temperature derating factor 0.94 and a group derating factor of 0.9 then the overall derating factor will be (0.94*0.9) which is approximately equal to 0.855. This derating value is taken in the code just as reference but this can vary depending on the operating and environmental conditions (which can also be changed in the Mat lab code).

a) Cable Selection

When sizing cables for feeders, the cross-section of cables is also typically selected to protect the cable against damage from thermal overload. The cross-section of cable 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:

Id ≥ Ifl (5)

Here if this inequality is not satisfied with any of the values given in the Table 1 or Table 2(according to the material chosen) then the base current rating of the cable is multiplied by an integral factor 'r' (where r=1,2,3,…) i.e., the current carrying capacity of the cable is increased by laying it in 'r' runs.

r(Id)≥Ifl (6)

STEP 3:

A cable's conductor can be seen as an impedance and therefore whenever current flows through a cable, there will be a voltage drop across it, which can be derived from 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

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. The following typical cable impedances given by CCI (Cable

Corporation of India) can be used in the absence of any other data.

TABLE VII RESISTANCE VALUES OF 3CORE CABLES [2]

Conductor Cross Section	Max D.C Resistance At 20˚C	Approx A.C Resistance At 90˚C	Max D.C Resistance At 20˚C	Approx A.C Resistance At 90˚C
	Aluminum		Copper	
Sq.mm	Ohm/km	Ohm/km	Ohm/km	Ohm/km
25	1.200	1.5500	0.7270	0.9260
35	0.8680	1.1200	0.5240	0.6680
50	0.6410	0.8280	0.3870	0.4930
70	0.4430	0.2720	0.2680	0.3410
95	0.3200	0.4140	0.1930	0.2460
120	0.2530	0.3270	0.1530	0.1950
150	0.2060	0.2660	0.1240	0.1580
185	0.1640	0.2120	0.0991	0.1260
240	0.1250	0.1620	0.0754	0.0961
300	0.1000	0.1290	0.0601	0.0766
400	0.0778	0.1010	0.0470	0.0600

TABLE VIII REACTANCE OF 3CORE CABLE [2]

Conductor Cross Section	Reactance of 3core Cables conforming to IS:7098(pt-2)-1985				
	Approx Reactance at 50Hz				
	3.8/6.6 Kv	6.6/6.6 & 6.35/11 Kv	11/11 Kv	12.7/22 Kv	19/33 Kv
25	0.126	0.133	0.145	---	---
35	0.12	0.126	0.138	0.141	---
50	0.144	0.118	0.129	0.132	0.146
70	0.107	0.116	0.124	0.125	0.138
95	0.102	0.107	0.116	0.119	0.13
120	0.0977	0.102	0.112	0.114	0.125
150	0.0953	0.0994	0.108	0.111	0.122
185	0.0926	0.0969	0.105	0.107	0.118
240	0.0902	0.0936	0.102	0.104	0.113
300	0.09	0.0926	0.0999	0.102	0.111
400	0.0872	0.0886	0.0954	0.0969	0.106

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: [3]

$$V_{3\phi} = \frac{\sqrt{3}I(R_c \cos\phi + X_c \sin\phi)L}{1000} \quad (7)$$

Where

$V_{3ø}$ is the three phase voltage drop (V)
$I=I_{fl}$ nominal full load 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 ø is the load power factor (pu)
L is the length of the cable (m)

For a single phase system: [3]

$$V_{1\phi} = \frac{2I(R_c \cos\phi + X_c \sin\phi)L}{1000} \quad (8)$$

Where $V_{1ø}$ is the single phase voltage drop (V)
I is the nominal full load 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 ø is the load power factor (pu)
L is the length of the cable (m)

For a DC system:[3]

$$V_{dc} = \frac{2IR_cL}{1000} \quad (9)$$

Where

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

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

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

L is the length of the cable (m)

It is customary for standards (or clients) to specify maximum permissible voltage drops, which is the highest voltage drop that is allowed across a cable. If your cable exceeds this voltage drop, then a larger cable size should be selected.

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 5 – 10% at full load.

The following table give the maximum permissible voltage drop that can allowed while current is flowing in the cable. These standards are given by CCI.

TABLE IX ESTIMATED VOLTAGE DROP [2]

Conductor Cross-section	Estimated Voltage Drop for XLPE Aluminum conductor armored 3-Core Cables				
	Voltage Drop V/km/A				
	3.8/6.6KV	6.6/6.6 & 6.35/11 KV	11/11 KV	12.7/22 KV	19/33KV
25	2.67	2.67	2.67	---	---
35	1.94	1.94	1.94	1.94	---
50	1.44	1.44	1.44	1.44	1.44
70	1.00	1.00	1.01	1.01	1.44
95	0.70	0.74	0.74	0.74	0.74
120	0.56	0.59	0.60	0.60	0.60
150	0.48	0.49	0.49	0.49	0.50
185	0.40	0.40	0.41	0.41	0.44
240	0.30	0.32	0.33	0.33	0.32
300	0.26	0.27	0.28	0.28	0.29
400	0.21	0.23	0.24	0.24	0.25

For a cable to be selected it should not only satisfy the inequality $I_d \geq I_{fl}$, but also should not exceed its permissible voltage drop i.e.,

$$VD \leq VD_t \quad (10)$$

Where

VD is the calculated voltage drop

VD_t is the voltage drop taken according to Table 5 with respect to the corresponding cable size selected that satisfies the current inequality (used in Mat lab code)

Note: Here voltage drop calculation is done in V/Km/A i.e., the equation for voltage drop calculation for 3 phase system is rewritten as

$$VD = \frac{\sqrt{3} \times (R_c \cos\emptyset + X_c Sin\,\emptyset)}{r} \quad (11)$$

Where ‘r’ is the no: of runs

STEP 4:

The size of the cable which satisfies full load current inequality and voltage drop inequality is selected for laying.

Alternatively, the size of the cable can be calculated using Mat lab. The flow chart below explains how the Mat lab code [4] code calculates the size of the cable for desired voltage and power rating at a desired power factor.

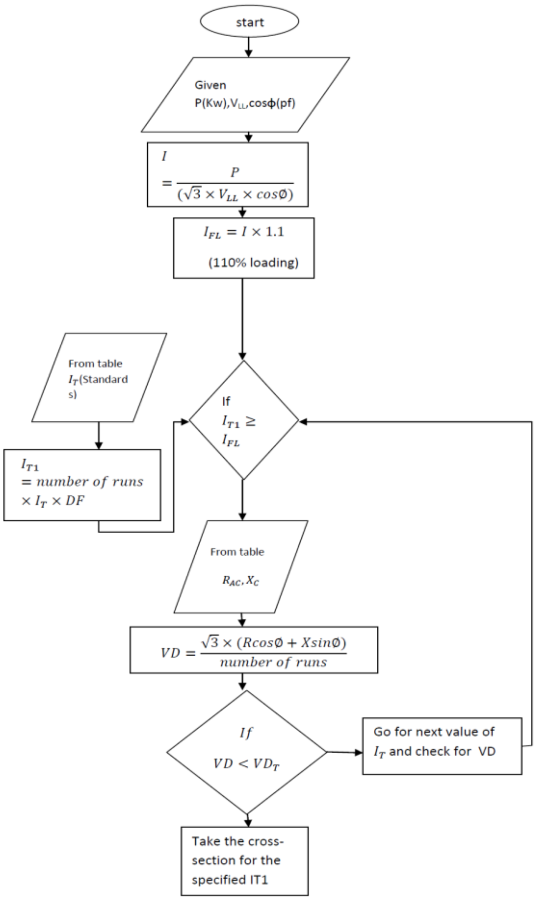


Fig.1 Flowchart for calculating cable sizing

IV. RESULT

These are the two results we have obtained by executing the mat lab code.

1. ENTER BASIC CABLE SPECIFICATIONS

Enter 1 for copper or 2 for aluminium: 1

Enter nominal load voltage (3.3kV or 6.6kV or 11kV or 22kV 0r 33kV) only: 33

Enter full load power factor: 0.8

Enter power in MW: 22

- OUTPUT

Current in the cable = 481.1252

Full load current = 529.237

Derating factor = 0.8550

Voltage drop in the cable = 0.1729

Maximum permissible voltage drop taken from standards = 0.4900

REQUIRED PARAMETERS

Required cross section of the cable = 150

Number of runs: r = 2

Note:

[Current: amps; voltage drop: volts; crossection: mm]

2. ENTER BASIC CABLE SPECIFICATIONS

Enter 1 for copper or 2 for aluminum: 2

Enter nominal load voltage (3.3kV or 6.6kV or 11kV or 22kV 0r 33kV) only: 11

Enter full load power factor: 0.85

Enter power in MW: 8.5

- OUTPUT

Current in the cable = 524.8639

Full load current = 577.3503

Derating factor = 0.8550

Voltage drop in the cable = 0.1405

Maximum permissible voltage drop taken from standards =

0.2800

REQUIRED PARAMETERS

Required cross section of the cable = 300

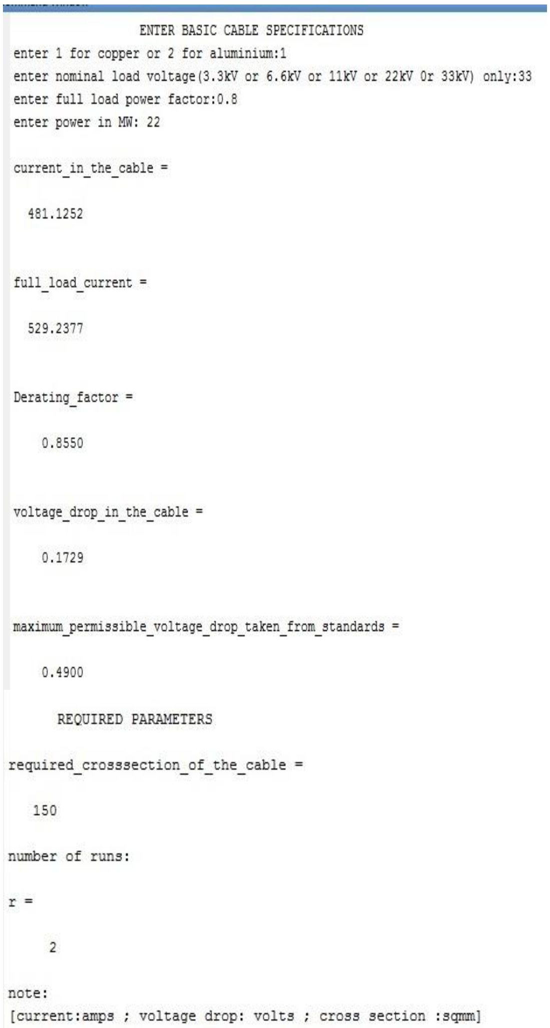
Number of runs: r = 2

Note:

[Current: amps; voltage drop: volts; crossection: mm]

V. SCREEN SHOTS

1. Matlab output screen shots (copper cable)



2. Matlab output screen shots (Aluminum cable)

```
ENTER BASIC CABLE SPECIFICATIONS
enter 1 for copper or 2 for aluminium:2
enter nominal load voltage(3.3kV or 6.6kV or 11kV or 22kV Or 33kV) only:11
enter full load power factor:0.85
enter power in MW: 8.5

current_in_the_cable =

  524.8639


full_load_current =

  577.3503


Derating_factor =

    0.8550


voltage_drop_in_the_cable =

    0.1405


maximum_permissible_voltage_drop_taken_from_standards =

    0.2800
       REQUIRED PARAMETERS

required_crosssection_of_the_cable =

   300

number of runs:

r =

     2

note:
[current:amps ; voltage drop: volts ; cross section :sqmm]
```

VI. CONCLUSION

We have discussed a novel method by which we can estimate the approximate size of the cable considering various effects that effect the ampacity of the cable. We have discussed a simplified approach for calculating the size using mat lab coding there by reducing human effort greatly. In future we would like to extend this program in order to include other parameters which effect the ampacity and also to apply this approach for other different cables.

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