Factors Affecting Power Cable Current Ratings

Technical Publication[1]

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Abstract

As well as the construction of the cables themselves, there are various installation conditions which affect the current rating of cables installed in both air and soil. For cables in air; ambient air temperature and exposure to direct solar radiation. For buried cables; soil dry-out, soil thermal resistivity, phase spacing, ambient soil temperature and backfill construction. For cables both in air and in soil; conductor size, conductor material, circuit grouping, duct size and duct material affect current rating. It's important to consider these factors during the modelling for an accurate calculation of current rating and to match them with the specific installation conditions of your cable project.

Keywords: High voltage power cables; Current rating; Finite element method

I. Introduction

The current rating of cables is affected by the installation conditions, the cables system design and the materials and construction of the cables themselves. In this report a parametric study of the factors which affect current ratings is presented. Modelling was performed using ELEK™ Cable HV Software, which performs calculations in accordance with the IEC 60287 standards (1; 2; 3), equations published by Neher and McGrath (4) and uses the finite-element method.

For cables in air, the effect on current rating of the following parameters is studied: conductor size, conductor material, sheath bonding arrangement, ambient air temperature, enclosing in duct, duct size, duct material, exposure to direct solar radiation and separation between groups of cables in air.

For buried cables, the effect on current rating of the following parameters is studied: soil dry-out, soil thermal resistivity, phase separation, standing voltage, single core sheath loss factor, multi-core sheath loss factor, multiple buried circuits, soil ambient temperature, backfill thermal resistivity and backfill construction.

ELEK™ Cable HV Software can be used to model cables from Low Voltage (LV) up to 500 kV (5 kV DC). In this study the cables modelled were extruded 11 kV XLPE insulated, screened cables. The principles demonstrated in this parametric study apply for power cables of any AC voltage level. The calculated current ratings have been compared with and validated by those published by the cable manufacturers.

II. Common Parameters

The following common parameters were used for modelling of the cables:

- Load factor = 1.0
- Sheath bonding = Solid
- Conductor material = Copper
- Ambient air temperature = 40 °C
- Ambient soil temperature = 25 °C
- Maximum conductor temperature = 90 °C
- Depth of burial = 0.8 metres
- Native soil thermal resistivity = 1.2 °C.m/W
- Dry soil thermal resistivity = 2.5 °C.m/W
- Dry soil critical temperature = 40 °C
- Cable sheath solar absorption coefficient, σ = 0.8
- PVC duct thermal resistance = 6 °C.m/W
- Metal duct thermal resistance = 0 °C.m/W
- Backfill thermal resistivity = 1 °C.m/W

The models for the 11 kV cables used in the parametric study are included in the Appendix.

III. Cables in Air

3.1. Varying conductor sizes and materials

The conductor size has been varied from 35 mm^2 up to 800 mm^2. Cables are modelled as installed spaced from a wall in trefoil arrangement.

Figure 1 shows current rating increases with conductor size. The DC resistance of a conductor is inversely proportional to its size, however, note that doubling of the conductor size does not double the current rating. This is because for AC currents the contribution of the skin and proximity effects to conductor resistance, especially for large conductors, is significant.

As expected, the conductor material affects the current rating and cables with copper conductors have a higher current rating due to higher conductivity compared with aluminium. Bear in mind there are significant advantages to using aluminium conductors, which makes them a popular choice, such as a much lower material cost and they are lighter to physically handle.

The larger the conductor size the larger the circulating current losses (significant for solidly bonded cables but not applicable for single-point bonded cables) and eddy current losses. Circulating current losses are generally much larger than eddy current losses

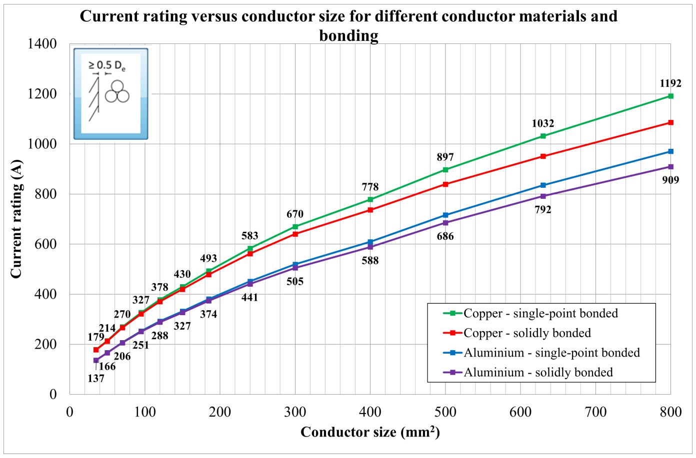


Figure 1 Current rating versus conductor size – Copper and aluminium cables in air

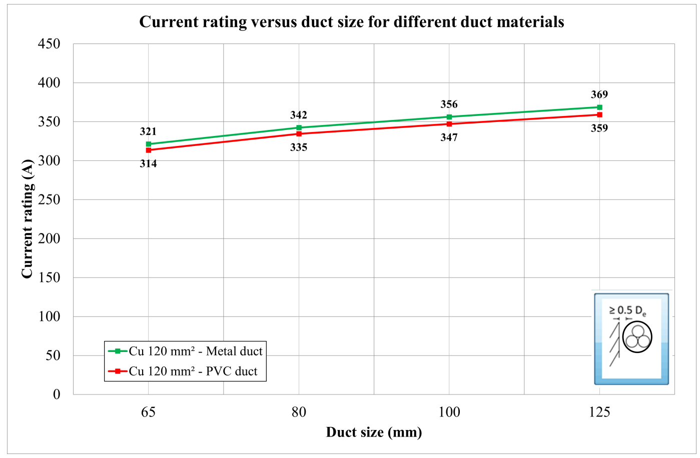


Figure 3 Current rating versus duct size – cables in air

hence we see from Figure 1 the current rating for solidly bonded cables is lower than for single-point bonded cables.

3.2. Ambient air temperature

For all cables as ambient (environment) temperature, whether it be air or soil, is increased nearer to the maximum conductor temperature limit the current rating is reduced.

For cables in air specifically, Figure 2 confirms that the relationship of current rating and air temperature is a non-linear function of the excess of cable surface temperature above ambient air temperature and also depends on the outer surface area (size) of the cable - since as can be seen the rate of change in current rating with ambient air temperature is different for the cable sizes (diameters).

3.3. Enclosed in ducts in air

The current rating of cables installed in air enclosed in ducts is reduced compared with those which are unenclosed. This can be seen by comparing Figure 3 with the previous Figure 1 for the 120 mm^2. This difference is caused by the added thermal resistance of the duct wall and the raised temperature of the air enclosed inside the duct.

The duct material influences the current rating of a cable, depending on the thermal resistivity. For example, PVC has a higher thermal resistivity than a metal duct which has negligible thermal resistivity, thus a cable in a PVC duct will have a lower current rating. This difference can be seen in Figure 3.

Figure 3 also shows that as the duct size gets larger for the same cable, so does the current rating. This is due to the reduced external thermal resistivity experienced by the cables which as it lowers the current rating increases.

3.4. Exposure to direct solar radiation

Exposure to direct solar radiation increases the operating temperature and hence reduces the current rating of cables installed in air. The slope of the plots in Figure 4 shows that the current rating is reduced more for larger (greater surface area) cables than smaller (less surface area) cables.

The solar radiation intensity depends on the geographical location (latitude and longitude) and the day of the year and hour of the day. IEC 60287-3-1 (3) states when no information about the intensity of solar radiation is available a value of 1000 W/m^2 should be adopted. The surface absorption coefficient depends on the material type of the outer cable sheath.

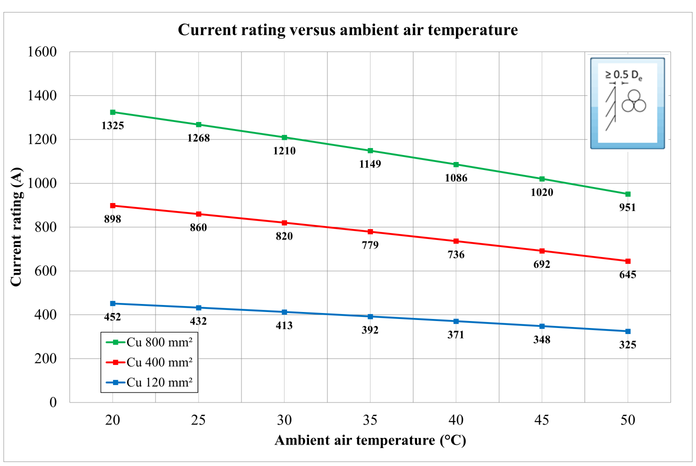


Figure 2 Current rating versus ambient air temperature

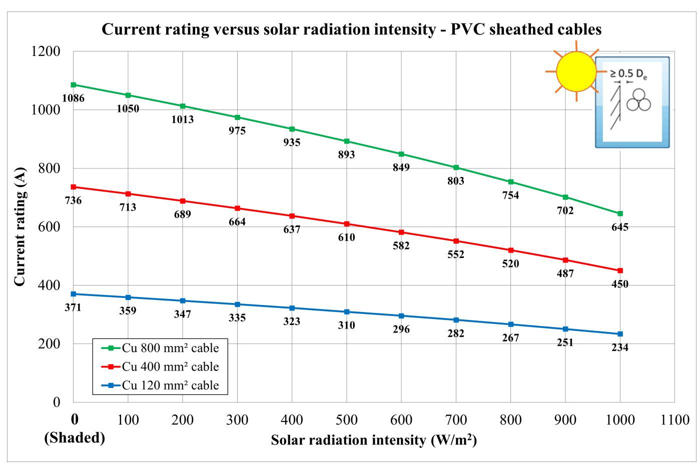


Figure 4 Current rating of 120 mm^2, 400 mm^2 and 800 mm^2 cables exposed to varying solar radiation intensity

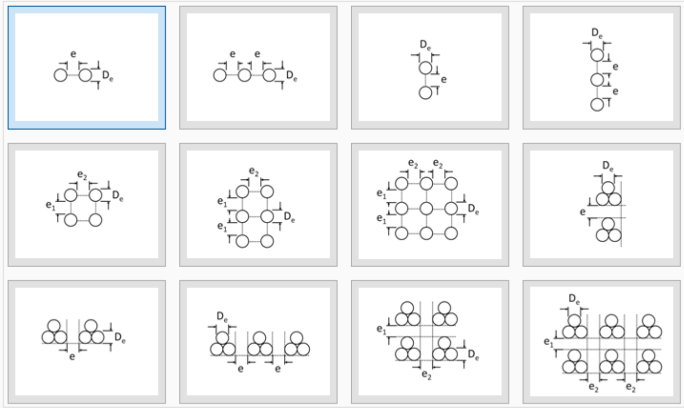


Figure 5 Cables installed in groups – standardised arrangements as available in ELEK^{TM} Cable HV software.

3.5. Groups of cables in air

When cables are installed in groups in air as shown in Figure 5 the rating of the hottest cable will be lower than in the case when the same cable is installed in isolation. This reduction is caused by mutual heating.

The effects of grouping in air on current ratings are dependent on the ratio of the cable diameter (De) and the separation between circuits (e). If the separation between groups exceeds the critical ratio of e/De then the thermal proximity effects which cause de-rating of the circuits can be neglected. Figure 6 depicts this relationship between separation of groups and current rating.

IV. Buried Cables

4.1. Varying conductor sizes and soil dry-out

The conductor size has been varied from 16 mm2 up to 800 mm2. Cables are modelled as direct buried in a trefoil and touching arrangement.

The phenomenon of soil dry-out requires explanation. Soil thermal resistivity is not constant and is highly dependent on soil moisture content. As soil heats up caused by the loading of the cables, moisture may tend to migrate away from the cable surface. A dried-out zone of soil can develop around the cables in which the thermal resistivity is increased. This in turn tends to increase the temperature of the cables which reduces their ratings.

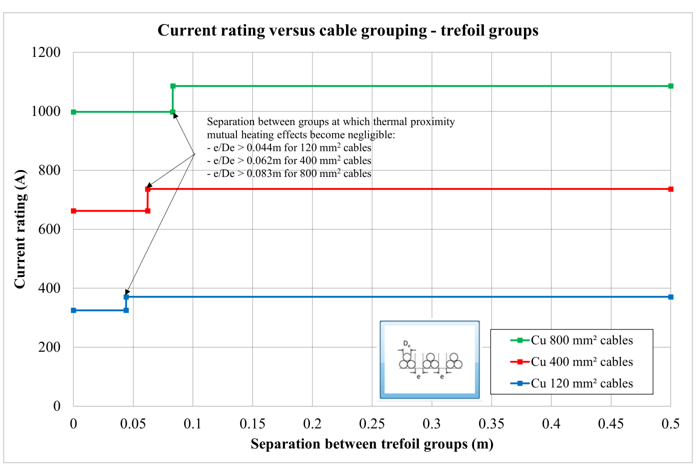


Figure 6 Current rating versus separation between trefoil groups

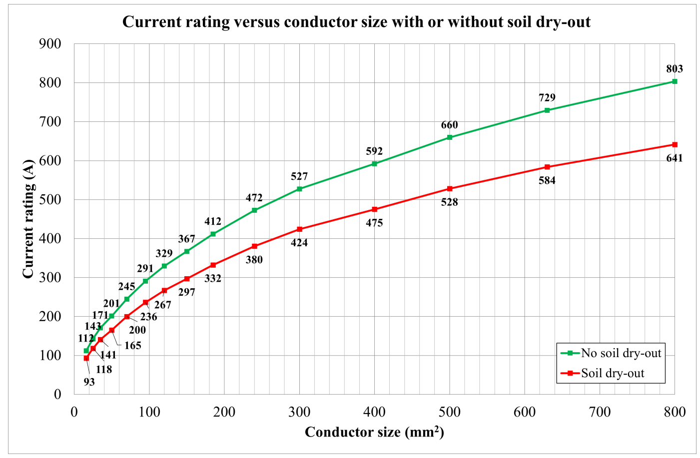


Figure 7 Current rating versus conductor size – cables direct buried

The complex effect of moisture migration on cable rating calculations as depicted in Figure 7 is addressed by a two-zone model for the soil surrounding loaded cables. The concept of the model is summarised as follows. Moist (native) soil is assumed to have a uniform thermal resistivity; however, if the heat dissipated from a loaded cable and its surface temperature are raised above a certain critical temperature then the soil immediately surrounding the cable will dry out resulting in a zone which is assumed to have a higher uniform thermal resistivity.

Comparing Figure 7 (buried in soil) to Figure 1 (in air), the increase in current rating with conductor size is more non-linear and the current ratings are lower for cables in soil compared with cables in air.

4.2. Soil thermal resistivity

The thermal resistivity of the native soil for direct buried cables laid in flat and touching arrangement was varied from 0.4 up to 4.0 °C.m/W. Figure 8 shows the current rating of cables is highly dependent on and reduces significantly (more for larger cables) with increasing soil thermal resistivity and follows a hyperbolic function.

Soils which are composed of clay or peat have resistivities as low as 0.8 °C.m/W while fast-draining sands may have resistivities

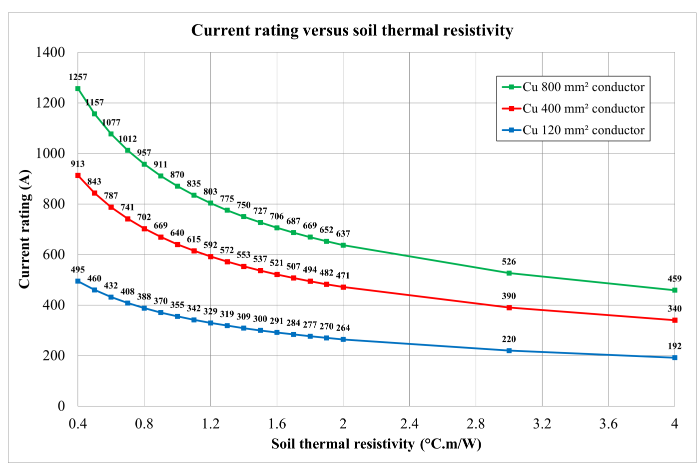


Figure 8 Current rating versus native soil thermal resistivity

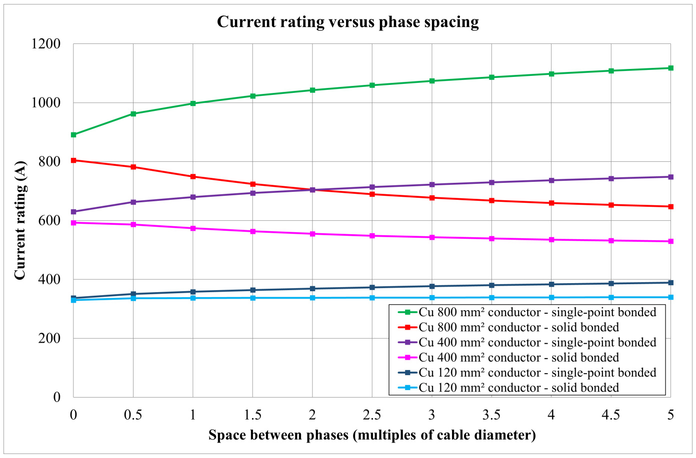


Figure 9 Current rating versus spacing (separation) between phases

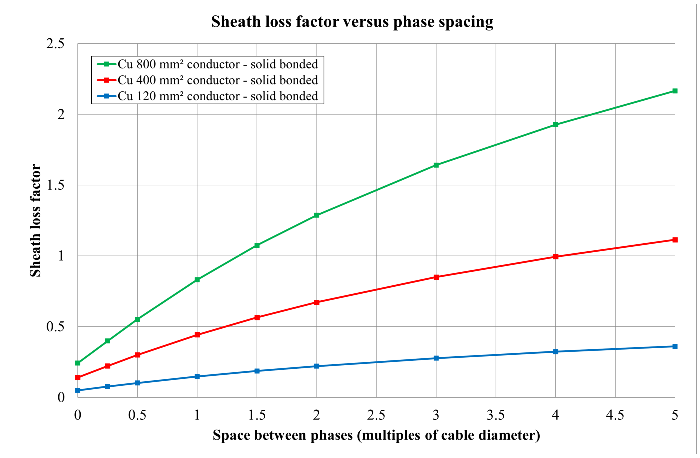


Figure 11 Sheath loss factor versus spacing (separation) between phases

in the order of 2.5 °C.m/W. Ground which is composed of building rubble and as such has air gaps may have resistivity higher than 3 °C.m/W.

4.3. Spacing between phases and sheath losses

Figure 9 shows that as the spacing between phases is increased the current rating also increases, except for large cables with solid bonding (explained in the next sections). This is due to a reduction in the mutual heating effects between phases.

Increasing the phase spacing has the following positive and negative effects:

Single-point bonded cables – current rating increases often significantly; and sheath standing voltage (which is a safety concern) is increased due to increased mutual inductances between sheath and conductor. This increase in standing voltage can be seen in Figure 10.

Solid bonded cables – losses in the sheath (or screen) increases with conductor spacing as the reactance of the sheath X_s increases according to

$$X_s \propto ln(\frac{s}{d})$$

where s is phase spacing and d is screen diameter. For large cables the current rating reduces with phase spacing as the increase in sheath loss factor has a greater impact on current rating than the reduction in mutual heating effects. For smaller cables with lower sheath loss factors an increase in phase spacing causes a slight increase in current rating. The increase in sheath loss factor can be seen in Figure 11.

For certain solidly bonded cases there is a point where the effect of increased circulating currents becomes less than the reduction of mutual heating effects and the current rating slightly increases.

In comparison, the sheath loss factor in a solidly bonded multicore cable is much lower than for single core cables and this difference is observed in Figure 12. Note that the modelled arrangement for the single core circuit is trefoil and touching.

4.4. Touching and non-touching cables

When cables are touching or laid in close proximity to each other, the heat flux of a cable will be distorted by that of other cables that are nearby. In general, this distortion becomes significant with cables which are spaced by less than two cable diameters. For this reason the empirical equations given by the IEC Standard (2) for touching cables are different to those for spaced cables, the latter of which were originally derived using the finite element method

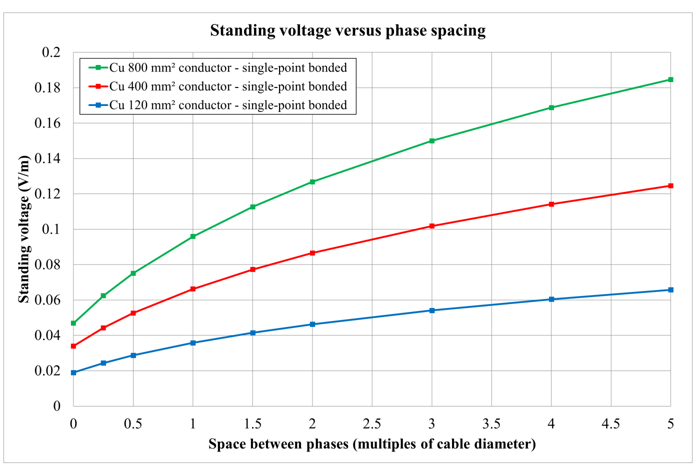


Figure 10 Standing voltage versus spacing (separation) between phases

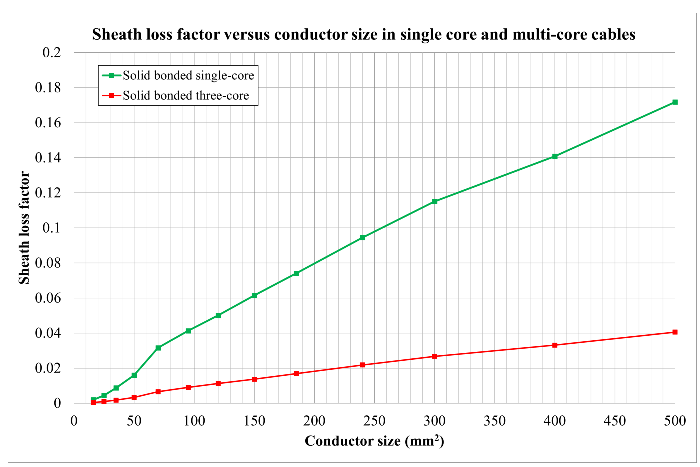
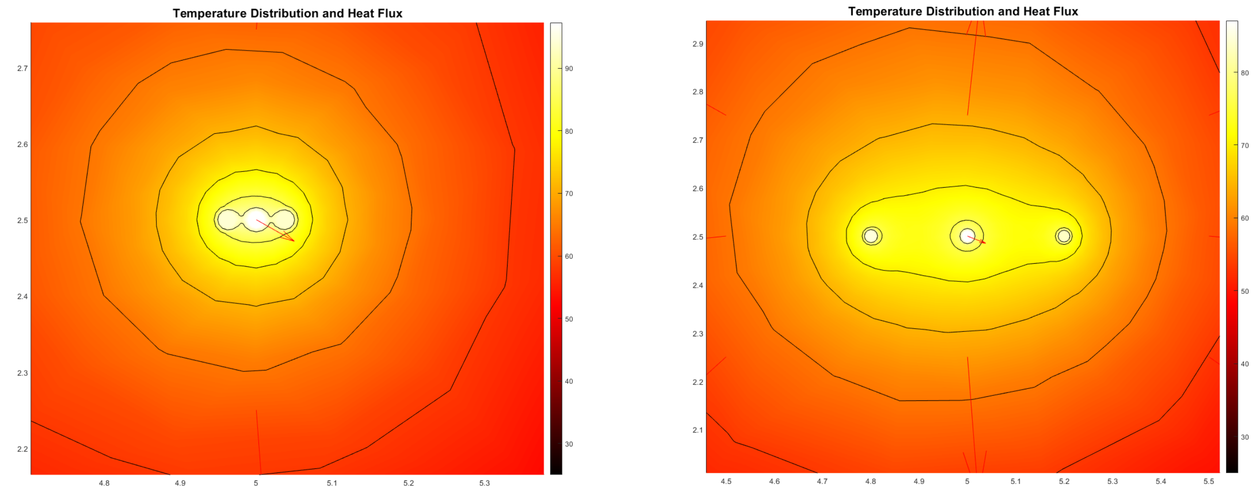


Figure 12 Sheath loss factor versus conductor size in single core and multicore cables



(a) Touching **(b)** Spaced 0.2 m per phase

Figure 13 Heat fluxes for a buried circuit in a flat configuration

to account for the heat flux distortion.

Heat emanates radially from the conductor, which is the hottest component and the main heat source inside the cable. The heat fields for both touching and spaced cables are shown in Figure 13, and were calculated using the finite element method. The meshed layouts are given in Figure 14, where the hottest points on the outer surfaces of the cables (caused by the mutual heating between cables) are indicated with yellow-coloured crosses.

4.5. Multiple Buried Circuits

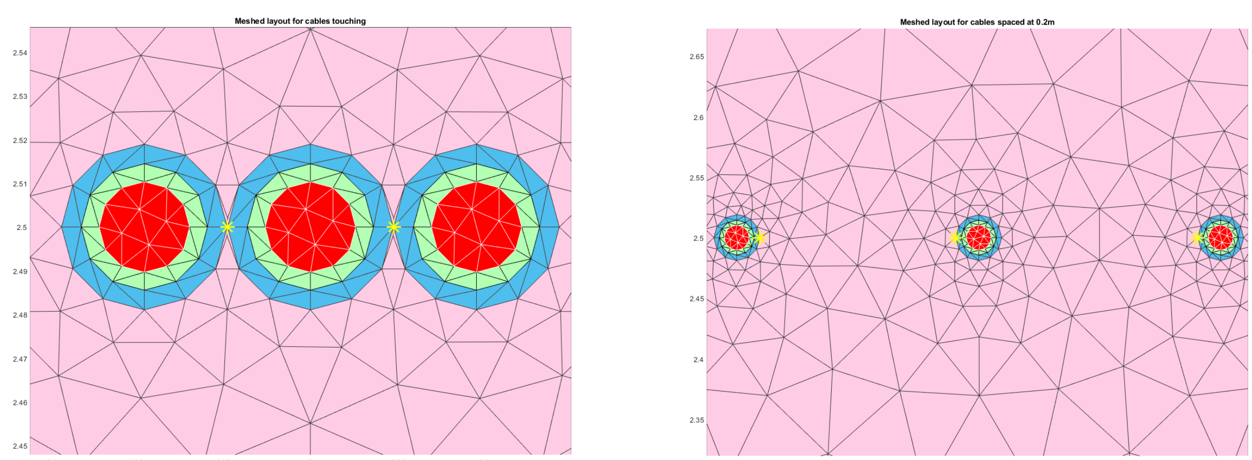
Often multiple circuits are buried inside the same trench. Due to the mutual heating effects between the cables the current rating of the circuits will be reduced. Since there are an infinite number of arrangements for this scenario there are no general rules to follow. However, in general the higher the number of circuits and the closer they are spaced the more their current ratings are reduced due to the mutual heating.

As an example, Figure 15 shows an arrangement of four identical buried single core trefoil circuits spaced by 0.2 m from each other.

The isolated current rating for a single core trefoil circuit is 534 A. For identical trefoil circuits that are equally loaded, where mutual heating is considered, the current rating is reduced by 33.7 % to 354 A.

The mutual heating effect can be clearly examined when the circuits are unequally loaded. For circuits that are unequally loaded, such as shown in Figure 16, the cable circuits in the middle of the arrangement have a higher degree of mutual heating and thus a lower current rating compared with the outer circuits, 334 A and 391 A respectively.

When there are both single-core and multi-core circuits buried near each other, the multi-core cables tend to have a slightly higher degree of mutual heating than the single-core cables, due to the additional cores. Subsequently, the multi-core circuit has a greater thermal resistivity increase than the single core circuit, which ends up decreasing the current rating of the multi-core circuit slightly more than the single core circuit. This decrease can be seen in



(a) Touching **(b)** Spaced 0.2 m per phase

Figure 14 Meshings for a buried circuit in a flat configuration

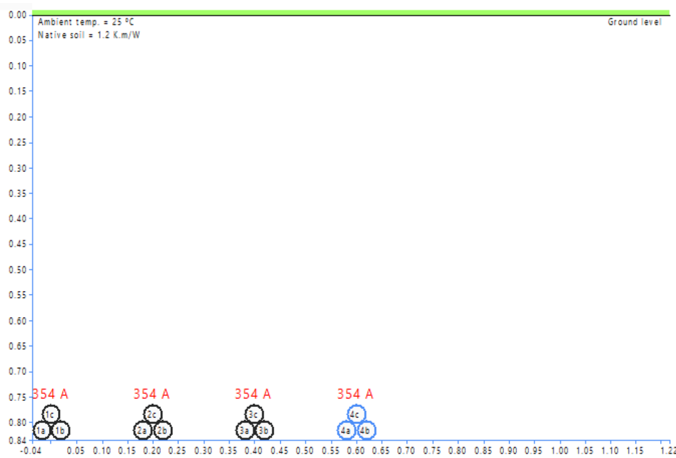


Figure 15 Multiple buried identical trefoil circuits - equally loaded

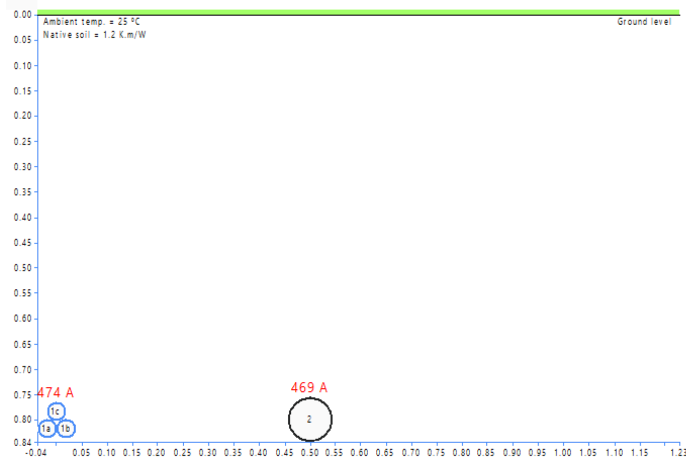


Figure 17 Single core and multicore buried circuits

Figure 17.

Without considering mutual heating, the multi-core circuit in Figure 17 has a current rating of 531 A and the single-core circuit has a current rating of 534 A. However, when mutual heating is considered, the multi-core circuit drops to 469 A, whereas the single-core circuit drops to 474 A. The multi-core circuit has had a greater current rating loss than the single-core circuit.

4.6. Ambient soil temperature

The ambient soil temperature affects the cable rating and is dependent on climatic factors as well as installation specific factors. The ambient soil temperature can either be measured or taken from relevant meteorological data sources. Applicable national standards exist which specify the ambient temperatures at which cable ratings shall be calculated for your country or a region, however where these are not available then IEC 60287-3-1 (3) may be referred to.

Figure 18 shows that as soil ambient temperature goes up cable current rating goes down linearly. The drop in current rating is greater for larger cables than it is for smaller cables due to surface area.

It is often commercially advantageous, particularly when burying cables at depths greater than 1 metre, to consider and to propose to your client to use expected soil ambient temperature and not a conservative value such as 25 °C from the standards. The expected average soil ambient temperature can be calculated based on the following data:

1. Annual average temperature.
2. Maximum annual temperature variation from average.
3. Soil thermal diffusivity (inertia).
4. Time of year.
5. Depth of burial.

For example, a particular installation in a moderate climate the average annual temperature is 12 °C and the maximum temperature is 35 °C. Therefore, the maximum annual temperature variation is 23 °C. The soil composition resembles wet sand hence the soil thermal diffusivity is 0.01 cm^2/s. The anticipated depth of burial of cables is 1 metre.

Figure 19 shows that during summer at a depth of 1 metre the soil temperature is 21.64 °C. As can be seen, as depth of burial approaches infinity the soil ambient temperature approaches average ambient temperature.

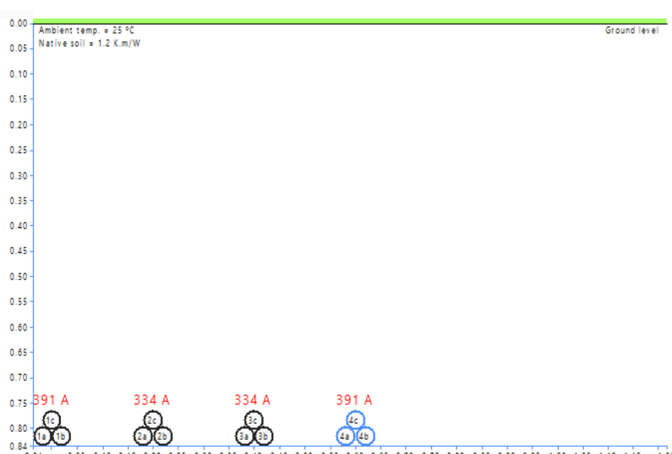


Figure 16 Multiple buried identical trefoil circuits - unequally loaded

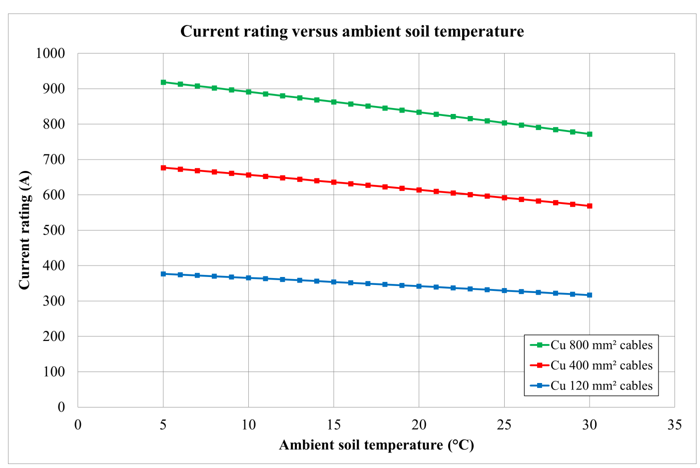


Figure 18 Current rating versus ambient soil temperature

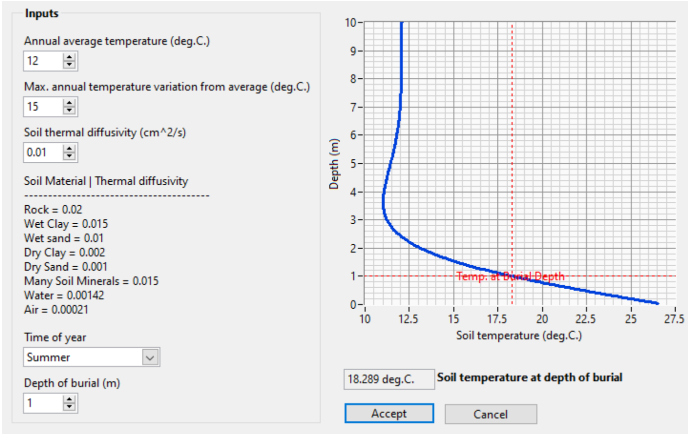


Figure 19 Calculation of soil ambient temperature at a particular depth and time of year – ELEK^{TM} Cable HV

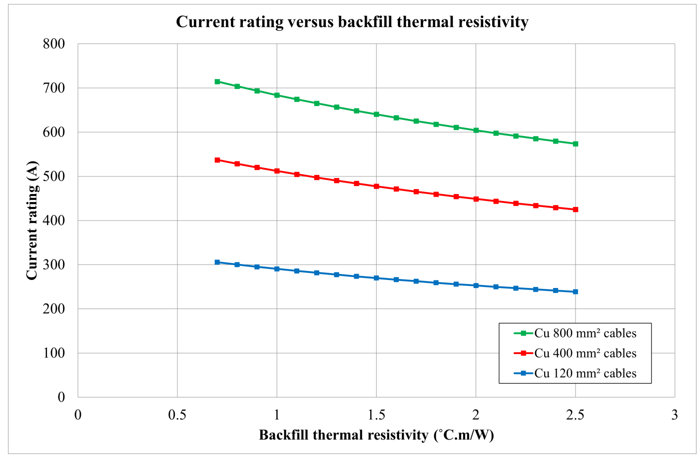


Figure 21 Current rating of cables versus backfill thermal resistivity

4.7. Thermal backfills

To achieve the highest possible current rating for buried circuits, cables can be installed in an envelope of a material with better thermal heat conduction properties than the native soil. This additional material is referred to as a thermal backfill. A typical arrangement is depicted in Figure 20.

The thermal resistivity of a backfill material is determined by the level of compaction and grain size distribution and should be known (since it is measured) to be considered in a design. Figure 21 shows that a lower backfill thermal resistivity improves the cable current ratings for a native soil thermal resistivity of 2.5 °C.m/W, rather than 1.2 as stated in the common parameters of this report. Note that the IEC equations are inaccurate where the backfill thermal resistivity is greater than that of the native soil.

The overall dimensions of the thermal backfill also affects the cable current ratings. Figure 22 shows as the backfill area increases there is a marked increase in the current rating but that as the backfill area gets larger this improvement is diminishing. It is often worthwhile to do a cost-benefits-analysis of the savings due to improved current ratings and the additional costs associated with a backfill.

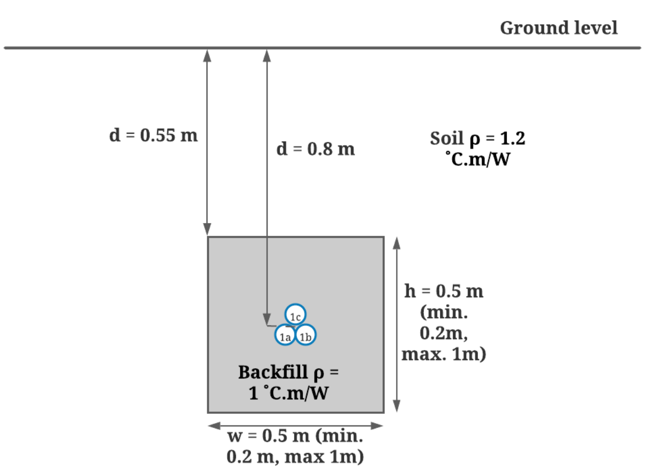


Figure 20 Modelled backfill area. Note the circuit remains in the centre.

V. CONCLUSIONS

Accurate determination of cable ratings and performance is important for providing an economical, functional, and safe design. Access to powerful and insightful software tools for performing power cable rating calculations is imperative.

5.1. Cables in air

The conductor size and material significantly affect current rating as well as the sheath bonding arrangement. Ambient air temperature affects current rating. The current rating of cables in air which are enclosed in ducts depends on the duct material and size. Current ratings of cables in close proximity to other groups of cables or exposed to direct solar radiation are also affected.

5.2. Buried cables

The soil resistivity and soil ambient temperature both have a major effect. To a lesser degree spacing between phases of buried single core cables affects current rating. For single-point bonded cables phase spacing affects the sheath standing voltage which is an important safety-related consideration for designers. Sheath loss factor affects current rating, and sheath loss factor in multi-core

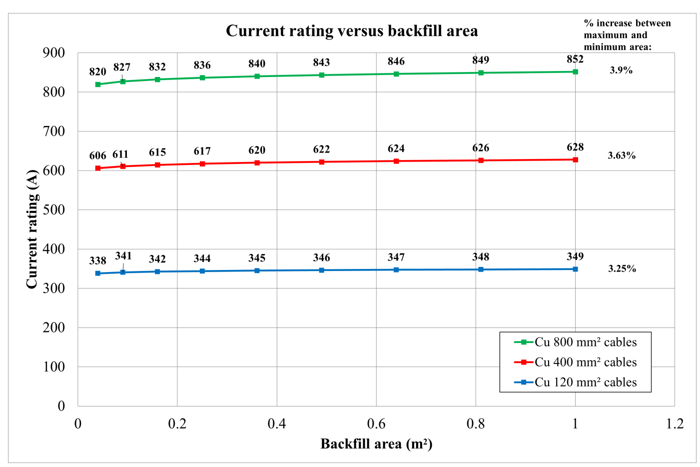


Figure 22 Current rating of cables versus backfill thermal resistivity

cables is much lower than in single-core cables. Mutual heating between cables installed in grouped buried circuit arrangements reduces their current rating however for accuracy this should be assessed on a case specific basis. Backfill composition and volume also affect current rating.

References

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Appendix

Cable dimensions are required for modelling in ELEK™ Cable HV software. The following cable data was taken from the Olex HV cable catalogue (5).

Cable data for the single core cable in Figure 23:

- Description: 6.35/11 kV Single Core Screened and PVC Sheathed.
- Conductor material: Stranded copper or Aluminium

Cable data for the three core cable in Figure 24:

- Description: 6.35/11 kV Cu Multi Core XLPE Insulated, Screened, PVC bedded and PVC Sheathed
- Conductor material: Stranded copper

Table 1 Cable dimensions for modelling single core cables. All dimensions are in mm unless otherwise specified

Cable Size (mm^2)	120	400	800
Nominal conductor diameter	13.1	23.6	35.9
Conductor screen thickness	0.55	0.7	0.9
Insulation thickness	3.4	3.4	3.4
Semi-conductive insulation screen thickness	0.8	0.9	0.9
Copper screen wire thickness	1.35	1.35	1.35
PVC sheath thickness	2.05	2.45	3

Table 2 Cable dimensions for modelling three core cables. All dimensions are in mm unless otherwise specified

Cable Size (mm^2)	120	400
Nominal conductor diameter	3 x 13.1	3 x 23.6
Conductor screen thickness	3 x 0.55	3 x 0.7
Insulation thickness	3 x 3.4	3 x 3.4
Semi-conductive insulation screen thickness	3 x 0.8	3 x 0.9
Copper screen wire thickness	3 x 0.85	3 x 0.85
PVC sheath thickness	7.77	9.72
PVC sheath diameter	67.9	95.5

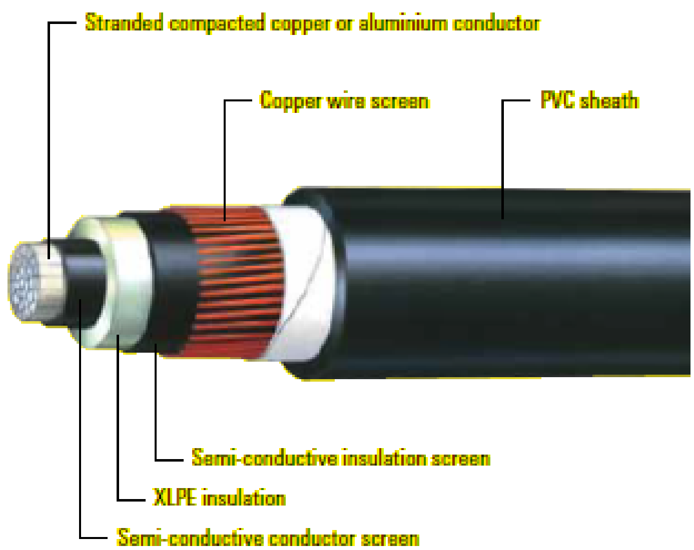

Figure 23 Cross-sectional view of 11 kV cable modelled

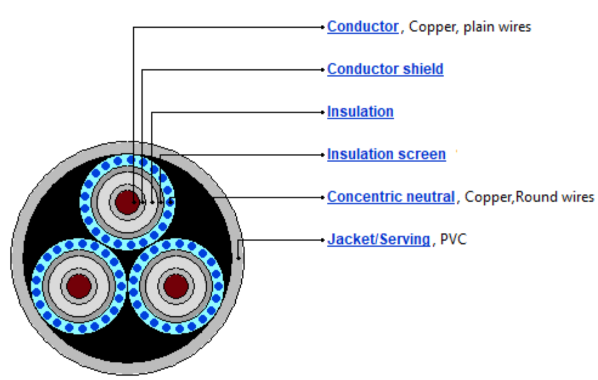

Figure 24 Cross-sectional view of 11 kV multi-core cable modelled