International Journal of Innovative Solutions in Engineering
2026, Vol. 2 No. 2 (pages 1–9)
DOI: 10.47960/3029-3200.2026.2.2.1

Review Article

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Investigation on Ampacity for Direct Burial Low-Voltage Power Cables

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Abstract
Generally, cable ampacity is the physically allowable continuous current that a cable can carry under real installation conditions. Allowable continuous current is the current in a conductor limited by the temperature rise in the insulation. Cable ampacity for low-voltage systems is defined by various standards. In addition, most manufacturers provide their own user guides. Today, cable ampacity analyses are commonly performed using different software tools. Although cable ampacity results should be unique, variations may occur that can significantly affect cable health and service life. These differences arise from variations in the current calculations. Software analysis is numerical, and calculations using standards are analytical. The objective of this paper is to compare real cable ampacity values obtained through software modeling with those calculated using standards and manufacturers' guidelines. The paper deals with direct-buried cables. The differences in cable ampacity are calculated and presented. Multiple case studies were analyzed. For direct-buried cables, the ampacity values derived from the reviewed standards, manufacturers' user guides, and software models are similar across the case studies, with deviations of no more than 4%. Furthermore, numerical cable ampacity analysis accounting for load factors (dynamic loading) and soil thermal resistivity was performed for direct-buried cable systems. It is concluded that these two factors significantly influence cable ampacity.

Article history
Received: 7. 1. 2026.
Revised: 18. 2. 2026.
Accepted: 3. 3. 2026.

Keywords
Power Cable,
Cable Ampacity,
Correction Factor,
Load Factor,
Soil Thermal Resistivity.

1 Introduction

Cable ampacity for low-voltage systems (up to 1000 V) is defined by various standards. Generally, cable ampacity I_n [1] is the physically allowable continuous current for the cable under real installation conditions. Allowable continuous current is the current limited by the temperature rise in the insulation. The most commonly used standards in this area in Europe are DIN VDE 0276-603, IEC 60364-5-52, and IEC 60287. Other standards addressing this topic also exist. In addition, most manufacturers provide their own user guides. Generally, cable ampacity, or cable current-carrying capacity, is the maximum steady-state current a cable can carry without exceeding its allowable temperature. This is fundamentally a balance between heat generated in the conductor (I^2R losses) and heat dissipated to the environment.

Cable ampacity analysis is described in detail in [2]. Numerical modeling of power cables is presented in [3]. Cable analysis under cyclic loading can be applied to direct-buried cables [4]. This approach is implemented in several standards, such as IEC (M-factor) and VDE. Finite Element Analysis (FEA) is increasingly used to validate or extend IEC-based methods for complex installations. Studies comparing FEM and IEC calculations highlight the impact of soil heterogeneity, conduit arrangements, and trefoil formations on ampacity predictions used in practical calculations [5]. For the presented calculations, cable ampacity can vary by up to 12% between the IEC and FEM methods.

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Thermal assessments of power cables in modern literature emphasize environmental impacts, such as seasonal soil temperature variation and moisture content, on LV cable ampacity [6]. Reviews of high-current LV cables show that installation conditions significantly affect current ratings, reinforcing the need for standards-based corrections and advanced modeling [7]. Today, most cable analyses are performed using various commercial software tools. For example, the Cableizer software applies additional cable ampacity calculation methods derived from standards, technical publications, and books [8]. The International Electrotechnical Commission (IEC) is the primary source of technical standards in electrical engineering, and the Cableizer software is mainly based on IEC standards. Technical brochures (TBs) published by CIGRE, as well as its magazine Elektra, are valuable resources for a deeper understanding of electrotechnical topics and sometimes provide methods not included in IEC standards, many of which have been implemented in software. IEC 60287 provides the primary framework for steady-state current rating calculations. Part 1-1 presents the current rating equations and loss calculation methods [1]. Part 2 details thermal resistance calculations for cable layers, which are essential for modeling heat transfer from the conductor to the ambient. The IEC framework includes correction factors for grouping, soil resistivity, and installation methods, and is complemented by IEC/TR 62095 for FEM-based extensions [9]. DIN VDE 0276-603 specifies LV cable types and calculates current ratings harmonized with IEC 60287. While primarily normative, VDE standards guide practical LV installations and derating factors for real-world scenarios [10]. In [11], a comprehensive review of the IEC standard method for calculating the ampacity of energy cables, with particular focus on the influence of seasonal and climate-related changes, is presented.

In addition, the Cableizer software uses several technical books and selected manufacturer user guides. The designer of a cable system should therefore select the appropriate source for determining cable ampacity [8]. Cableizer software automates IEC 60287 and CIGRE-based calculations, incorporating correction factors for grouping, burial, ambient conditions, and installation configuration.

According to the Cableizer software, the ampacity of direct-buried cables is generally determined as follows:

$$I_n = \sqrt{\frac{\theta_c - \theta_a + (v_4 - 1)\Delta\theta_x - v_4\Delta\theta_p - \Delta\theta_d}{R_c\left(T_1 + n_c(1+\lambda_1)T_2 + (1+\lambda_1+\lambda_2+\lambda_3)\left(n_c T_3 + n_{cc}\left(T_{4i} + T_{4ii} + T_{4\mu}v_4\right)\right) + n_{cc}\lambda_4\left(\frac{T_{4ii}}{2} + T_{4\mu}v_4\right)\right)}} \quad \text{Eq 1}$$

where θ_c is conductor temperature [°C]; θ_a is ambient temperature [°C]; v_4 is the ratio of thermal resistivity of dry/moist soil; $\Delta\theta_x$ is the critical soil temperature rise, $\Delta\theta_p$ is the temperature rise caused by other buried objects, $\Delta\theta_d$ is the temperature rise due to dielectric losses. R_c is the electrical resistance of a conductor; T_1, T_2 and T_3 are thermal resistances of conductor layers per unit of length [Km/W]; T_4, T_{4i}, T_{4ii}, $T_{4\mu}$ are thermal resistance of the cable surface to the environment per unit of length [Km/W]; n_c is the number of sources in the system and n_{cc} is the number of loaded conductors; λ_1 is the ratio between losses in the metal screen and total losses in the conductors; λ_2 is the ratio between losses in the metal armor and total losses in the conductors; λ_3 is a loss factor for steel pipe, pipe-type cable, and λ_4 is a loss factor in the magnetic duct.

According to IEC 60287 and VDE, general cable ampacity can be defined as follows:

$$I_n = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2+T_3+T_4)]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}} \quad \text{Eq 2}$$

where $\Delta\theta$ is conductor temperature increase above ambient temperature 20 °C; R is electrical resistance [Ω/m]; T_1, T_2, T_3 are the thermal resistance of conductor layers by unit of length [Km/W]; T_4 is the thermal resistance of the cable surface against the environment by unit of length [Km/W]; W_d is dielectric losses by unit of length [W/m]; n is the number of current-flown conductors in one cable; λ_1 is the ratio between losses in the metal screen and total losses in the conductors; λ_2 is the ratio between losses in the metal armor and total losses in the conductors. It can be defined to that $0.5T_1$ This means that only half of the conductor thermal resistance is affected by dielectric losses (under the IEC assumption). The sum $n(T_2 + T_3 + T_4)$ means that dielectric losses heat all surrounding layers and all parallel cables. The cable thermal resistance model is shown in Figure 1.

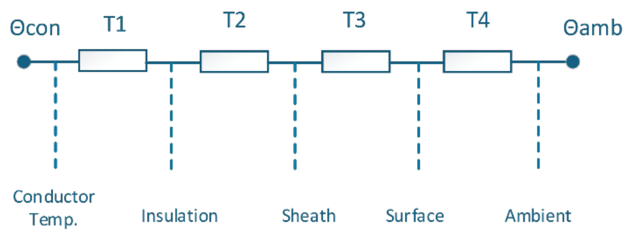

Figure 1 Cable thermal resistance model

A simplified formula is provided in [12]. The calculation is performed in accordance with IEC 60287 for steady-state conditions. The term steady state is intended to mean a continuous, constant current (100% load factor) just sufficient to asymptotically achieve the maximum conductor temperature, with the surrounding ambient conditions assumed constant.

In particular, Eq. 2 is applied to buried cables for which soil drying does not occur. The cable current rating depends on the cable's electrical and thermal parameters and on the soil's thermal parameters [13].

On the other hand, dynamic current ratings, rather than static ratings, allow the cable ampacity to be increased. Underground cables have been taken into account when applying the concepts of dynamic rating, as reviewed in [14].

Software calculations are numerical calculations comparing analytical calculations in Norms. Numerical calculations are usually less conservative because they model all heat paths and mutual effects explicitly, rather than relying on generalized derating factors. This can be more precise in various situations (e.g., multiple cable-laying operations, cable in ducts).

The real cable ampacity (I_r) can be obtained by multiplying the cable ampacity Eq 1(2) and all correction factors [2-1]:

$$I_r = I_n \cdot \sum_{i=1}^{n} f_i \qquad \text{Eq 3}$$

and

$$\sum_{i=1}^{n} f_i = f_1 \cdot f_2 \cdot f_3 \cdot f_4 \qquad \text{Eq 4}$$

...where f_i can be f_1-factor depending on burial depth, f_2-soil thermal resistivity, f_3-ambient temperature and f_4- cable grouping.

A review of major factors affecting cable ampacity is presented in [2].

2 Methodology

Regarding low-voltage cable ampacity, several methods/concepts of calculations are used in engineering practice:

- Calculation using manufacturer instructions;
- Calculation using Standards;
- Software modelling calculations.

All methods are mainly based on standards. Although cable ampacity results should be unique, they can vary, which may significantly affect cable health and service life.

The difference is obtained due to a difference in I_n current and in the correction factor data.

In manufacturer data, cable ampacity is usually given for:

- Burial depth: 70 cm;
- Soil thermal resistivity: 1 Km/W;
- Ambient temperature: 20 °C.

This is valid too for DIN VDE 0276-603.

On the other hand, in IEC 60364, cable ampacity is given for:

- Burial depth:70 cm;
- Soil thermal resistivity: 2,5 Km/W;
- Ambient temperature: 20 °C.

Regarding software analysis, results depend on cable modelling.

Regarding correction factors, the f_1 factor, which depends on burial depth, is equal to 1 (no ampacity reduction), because the burial depth of 70 cm is common to all analyzed cases.

Differences among the presented case studies arise from variations in soil thermal resistivity, ambient temperature, and the number of cables installed in the same trench. However, in all cases, direct-buried cables were analyzed.

Tables 1–3 present correction factors provided by a cable manufacturer.

Table 1 presents the correction factor for soil thermal resistivity.

Table 1 Correction factor due to soil thermal resistivity

Conductor Cross-Section [mm²]	Soil Thermal Resistivity [Km/W]			
	1	1.5	2	2.5
<25	1	0.87	0.78	0.72
35 to 95	1	0.86	0.76	0.7
120 to 240	1	0.85	0.76	0.69
300	1	0.85	0.75	0.68

Table 2 presents the correction factor related to ambient temperature.

Table 2 Correction factor due to ambient temperature

Ambient Temp. [°C]	PVC	XLPE
15	1.05	1.04
20	1	1
25	0.95	0.96
30	0.89	0.93
35	0.84	0.89

Table 3 presents the correction factor for the number of cables installed in the same trench.

Table 3 Correction factor due to the number of cables in the same trench

Number of Cables in Same Trench		3	5	10
Cable Spacing	Touch	0.69	0.58	0.46
	7 cm	0.75	0.64	0.53
	15 cm	0.77	0.68	0.58
	25 cm	0.78	0.71	0.62

On the other hand, IEC 60364 gives correction factors as follows.

Table 4 presents the correction factor related to soil thermal resistivity.

Table 4 Correction factor due to soil thermal resistivity

Conductor Cross-Section [mm²]	Soil Thermal Resistivity [Km/W]			
	1	1.5	2	2.5
All	1.5	1.28	1.12	1

Table 5 presents the correction factor for ambient temperature.

Table 5 Correction factor due to ambient temperature

Ambient Temp. [°C]	PVC	XLPE
15	1.05	1.04
20	1	1
25	0.95	0.96
30	0.89	0.93
35	0.84	0.89

Table 6 presents the correction factor related to the number of cables installed in the same trench. It can be observed that the differences between manufacturer instructions and the IEC standard lie in the definition of correction factors for the number of cables in the same trench and for soil thermal resistivity.

Table 6 Correction factor due to the number of cables in the same trench

Number of Cables in Same Trench		3	5	14
Cable Spacing	Touch	0.65	0.55	0.34
	Cable Dimeter	0.70	0.55	0.40
	12.5 cm	0.75	0.65	0.49
	25 cm	0.78	0.70	0.58

When comparing manufacturer user guides and the IEC standard, cable ampacity is typically given as 1 Km/W in most manufacturer brochures, whereas the IEC standard uses 2.5 Km/W. On the other hand, the DIN VDE 0276-1000 provides correction factors f_1 and f_2. The factor f_1 is defined as follows.

In Table 7, correction factors are defined with respect to soil temperature, soil thermal resistivity, and load factor.

Table 7 Correction factor f1 according to VDE 0276-1000

Permissible operating T [°C]	Soil temperature [°C]	Soil Thermal Resistivity= 2.5 Km/W
		Load level=1
90	15	0.84
	20	0.81
	25	0.78
	30	0.75

Factor f_2 is defined for a cable spacing of 7 cm and is presented in Table 8:

Table 8 Data of the analyzed cable

Distance between cables [cm]	Number of circuits	Soil Thermal Resistivity= 2.5 Km/W
		Load level=1
7	3	0.67
	5	0.60
	10	0.54

Regarding software analysis, the results depend on cable modeling.

3 Material and Methods

Analyzed cable is as follows regarding the manufacturer's datasheet - generally (Figure 2):

where:

1. Conductor in this case - aluminum rope NA2XY;
2. XLPE compound insulation;
3. Extruded plastomer filling;
4. PVC sheath.

Table 9 presents data on the analysed cable for modelling purposes.

Table 9 Data of the analyzed cable

Conductor Cross-Section [mm²]	Cable data			
	Insu Thick. [mm]	Sheath Thick. [mm]	Overall Diamet [mm]	Max. Resist. [Ω/km]
185	1.6	2.5	49.4	0.164

The data in the table are unique to each manufacturer and comply with the relevant standards. The goal of this study is to compare cable ampacity obtained through software modeling with the values provided by standards and cable manufacturers. Differences in cable ampacity will be calculated and presented.

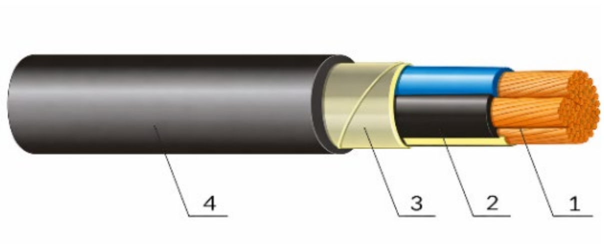

Figure 2 Analyzed low-voltage cable

Relevant standards include IEC 60364-5-52 and DIN VDE 0276-603.

The presented cable is modeled in the software Cableizer using manufacturer data, as shown in Table 9.

In each case, it is valid:

- Burial depth: 70 cm;
- Ambient temperature: 20 °C.

In all cases, the soil thermal resistivity is 1 Km/W, except for IEC 60364-5-52, where cable ampacity is provided for a soil thermal resistivity of 2.5 Km/W; this value must therefore be recalculated.

For a single direct-buried cable, ampacity data are presented in Table 10. The data from the manufacturer's user guide is considered relevant for the actual cable used. In each case, the soil thermal resistivity is 1 Km/W. Table 10 also presents the percentage differences among the data sources.

Table 10 Data of the analyzed cable

Source of data	Ampacity (A)	Diff. (%)
DIN VDE 0276-603	342	0
IEC 60364-5-52	375	9.64
CABLEIZER (software)	358	4.67
Manufacturer's user guide	342	Relevant

Percent difference is calculated as:

$$Diff.(\%) = \frac{y_{sourceofdata} - y_{catalogue}}{y_{catalogue}} \quad \text{Eq 5}$$

Direct burial single-cable ampacity for a burial depth of 70 cm, ambient temperature 20 °C, and a soil thermal resistivity of 1 Km/W is shown in Figure 3.

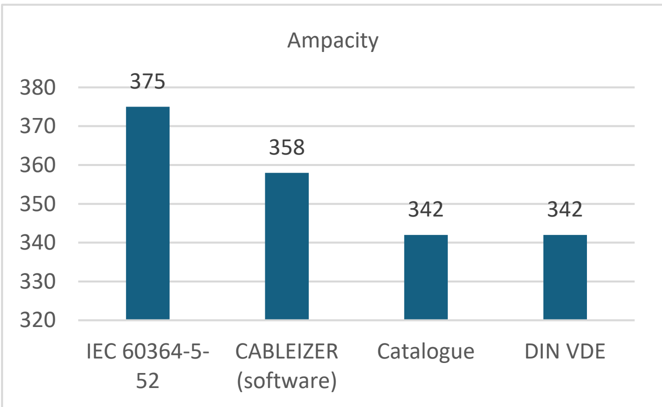

Figure 3 Direct buried single cable ampacity

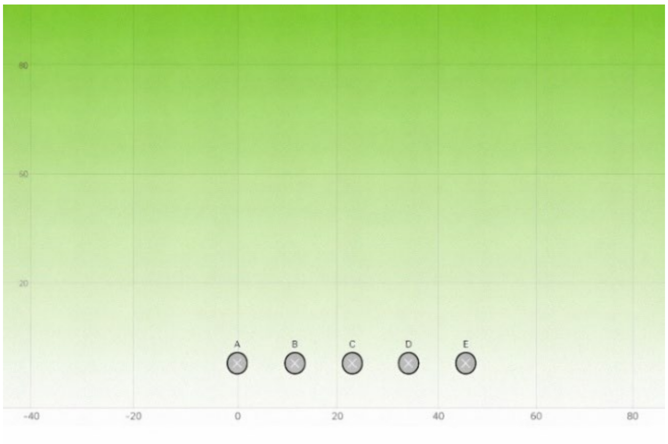

Figure 4 Case study 1

Figure 5 Case study 2

It can be observed that the highest ampacity is specified in IEC 60364-5-52, whereas the manufacturer's data are identical to those in DIN VDE 0276-603. The software results fall between the standard values and those specified in the manufacturer's user guide. The differences are all below 10%.
Furthermore, four case studies will be analyzed for cable ampacity comparison as follows:

1. 5 cables direct burial, cable to cable distance 7 cm;
2. 3 cables direct burial, cable to cable distance 12.5 cm;
3. Load factor impact on cable ampacity;
4. The impact of soil thermal resistivity on cable ampacity.

In each case is valid:

- Burial depth: 70 cm;
- Ambient temperature: 25 °C;
- Soil thermal resistivity of 2.5 Km/W

Case studies 1 and 2 are presented in Figures 4 and 5. The goal is to analyze and compare different approaches regarding low-voltage cable ampacity.

4 Results

For case study 1: 5 cables direct burial, cable to cable distance 7 cm is obtained (results in Table 11):

Table 11 Results of case study 1

Source of data	Ampacity (A)	Diff. (%)
IEC 60364-5-52	144	-0.7
CABLEIZER (software)	140.2	-3.4
DIN VDE 0276-603	141	-2.7
Manufacturer's user guide	145	Relevant

The manufacturer's user guide reports a maximum ampacity that is 3.4% higher than the values specified in the DIN and IEC standards and in the software model. When comparing the standards with the software results, the differences are below 3%.
For Case Study 2, which involves three direct-buried cables with a cable-to-cable spacing of 12.5 cm, the results are presented in Table 12. The cable ampacity for Case Study 1 is shown in Figure 6.

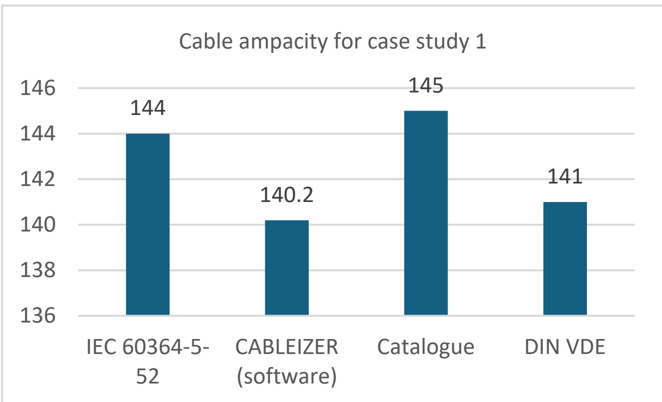

Figure 6 The cable ampacity for Case Study 1

Table 12 Results of case study 2

Source of data	Ampacity (A)	Diff. (%)
IEC 60364-5-52	180	+4
CABLEIZER (software)	179.2	+3.5
Manufacturer's user guide	173	Relevant

The cable ampacity for case study 1 is presented in Figure 7:

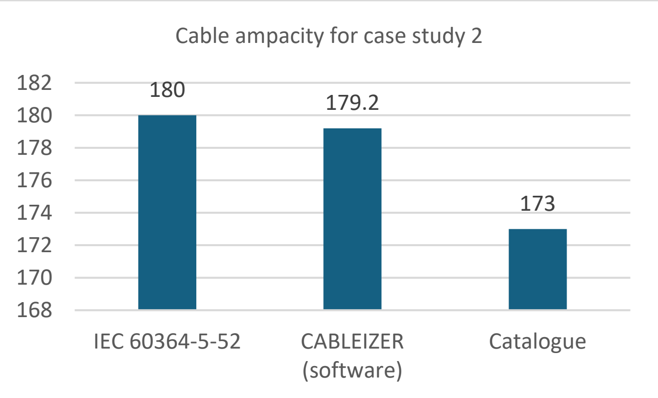

Figure 7 The cable ampacity for Case study 2

It can be observed that the highest ampacity is given by the IEC standard, which is up to 4% higher than the values provided by the manufacturer's user guide and the software results, which are very similar (difference of 0.5%).
In this case study, DIN VDE 0276-603 is excluded, as it assumes a cable-to-cable spacing of 7 cm.

4.1 Analysis of cable ampacity regarding software modeling for various environmental and load conditions

Case studies are analyzed as follows:

1. Case study 3: same as case study 1, but for load factor 0.5;
2. Case study 4: same as case study 1, but for soil thermal resistivity of 2 Km/W.

For direct-buried cables, a load factor is applicable. In Case Study 3, a load factor of 0.5 is used (compared to a load factor of 1 in Case Study 1). This load factor is common for many types of loads, including power converters used in solar power plants.
The results for Case Study 3 are presented in Table 13.

Table 13 Results of case study 3

Source of data	Load factor=1	Load factor=0.5	Diff.(%)
CABLEIZER	140.2	206	46.9

It can be observed that, when the load factor is reduced to 0.5 (where applicable) for direct-buried cables, cable ampacity in this case study increases by 46.9%. This is valid for a wide range of loads, including motors, power converters, and similar equipment. In the software, this load factor is based on the IEC M-factor. The concept of the load factor is introduced in [15].
For direct-buried cables, different soil thermal resistivity values are applicable. In Case Study 4, a soil thermal resistivity of 2 Km/W is used (compared to 2.5 Km/W in Case Study 1). A soil thermal resistivity of 2 Km/W is more common in the Herzegovina region and in regions with regular rainfall.

The results for Case Study 4 are presented in Table 14.

Table 14 Results of case study 3

Source of data	2 Km/W	2.5 Km/W	Diff.(%)
CABLEIZER	154.8	140.2	10.4

If soil thermal resistivity is set to 2 Km/W instead of 2.5 Km/W, which is more common in real-world case studies, cable ampacity can be increased by more than 10%.

5 Conclusion

In this paper, the ampacity of direct-buried low-voltage cables was investigated. For direct-buried cables, ampacity generally depends on:

- Burial depth;
- Ambient temperature;
- Soil thermal resistivity;
- Number of parallel laid cables.

In this paper, a comparison of low-voltage cable ampacity across various case studies was conducted. This comparison was between software (numerical) ampacity calculations and analytical calculations (standards and manufacturer datasheets).
For Case Study 1, five direct-buried cables with a cable-to-cable spacing of 7 cm were analyzed. The highest ampacity is given by the manufacturer's user guide, which is up to 3.4% higher than the values

provided by the DIN standard, IEC standard, and the software model. When comparing the standards with the software results, the differences are below 3%.
For Case Study 2, three direct-buried cables with a cable-to-cable spacing of 12.5 cm were analyzed. The highest ampacity specified by the IEC standard is up to 4% higher than the manufacturer's user guide and software results, which are very similar (0.5% difference).

In Case Study 3, ampacity calculations were performed using the software (numerical) with load factors of 1 and 0.5 (dynamic loading). A load factor of 0.5 is often applicable for renewable generators, such as power converters used in photovoltaic (PV) plants. Using a load factor of 0.5 where applicable, ampacity can be increased by 46.9% in this case study.
For Case Study 4, ampacity calculations were performed using the software assuming soil thermal resistivities of 2 Km/W and 2.5 Km/W. In our region and in regions with regular rainfall, a soil thermal resistivity of 2 Km/W is typically more appropriate than the standard default of 2.5 Km/W (seldom-raining regions). In this case study, cable ampacity is increased by 10.4% for a soil thermal resistivity of 2 Km/W.
Future work will focus on investigating the ampacity of medium-voltage cables.
The contribution of this paper is as follows:

- For direct-buried low-voltage cables, ampacity values from the presented standards and manufacturer user guides (analytical calculations) were compared with those obtained from modeling in the commercial software Cableizer (numerical calculations). Across all case studies, cable ampacity values from standards, manufacturer data, and software results differ by no more than 4%. This is due to software (numerical) modeling of all heat paths and mutual effects explicitly, instead of using generalized derating factors.
- The impact of different load factors on cable ampacity was analyzed numerically. Applying appropriate load factors can increase direct-buried cable ampacity and reduce CAPEX in cable system budgeting. This can yield substantial savings in cabling when the dynamic cabling concept is adopted, where applicable.
- Considering soil thermal resistivity, cable ampacity can be increased if the actual soil thermal resistivity is measured or properly assumed. This factor can also contribute to reducing CAPEX in cable system planning (financial savings).

Regarding the importance of cable systems, the authors argue that numerical and analytical analyses should be performed in cabling design. The lowest-ampacity scenario should be adopted for safety. For various load factors, the advice is to use numerical calculations for the dynamic cabling concept where applicable.

Conflicts of Interest: The author(s) report there are no competing interests to declare;

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