

# WHITEPAPER

CALCULATION AND SELECTION  
OF THE CROSS-SECTION FOR  
CABLES IN AC AND DC SYSTEMS

# CALCULATION AND SELECTION OF THE CROSS-SECTION FOR CABLES IN AC AND DC SYSTEMS



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## 1. INTRODUCTION

Depending on their length and cross-section, cables (note: hereinafter referred to as cables for the sake of simplicity) have different electrical resistances, which lead to heating of the electrical conductors during the flow of current. In accordance with the insulating material used and its heat resistance (class of insulating material), this temperature must not exceed a permissible value. This is 70 °C for PVC, as an example. Exceeding the limit temperature means a significant reduction in the service life of the cables used or even the risk of a disruptive charge or a short circuit. By choosing the right cable cross section, cables and the connected devices can be protected against overload and short circuits. This is also a key requirement from DIN VDE 0100 "Erection of low-voltage installations"<sup>1</sup>, which applies up to and including 1,000 V AC and 1,500 V DC.

The chosen conductor cross-section must therefore be "sufficiently large". The starting point for the selection of the cross-section is the determination of the operating current (known as the conductor current). The maximum current rating and current type, ambient temperature, routing type, piles, mechanical strength, type of cable, short-circuit current rating and the permissible voltage drop along the cable must be taken into account.

The associated procedure as well as the rules and tables required for the design are shown in IEC 60364, Part 5-52 "Selection and erection of electrical equipment - Wiring systems"<sup>2</sup>, which was implemented in Germany with DIN VDE 0100-520. DIN VDE 0100-520 refers to DIN VDE 0298-43 in the "Current rating" chapter, excerpts of which can be found in LAPP Technical Table T12 "Load\_capacity\_Basic\_table\_Reduction\_factors".

This document explains how the conductor current for AC and DC systems is calculated and how the conductor cross-section to be selected is derived from this. The steps are presented in shortened form and with reference to the individual sections as follows:

<sup>1</sup> <https://www.dke.de/de/arbeitsfelder/core-safety/din-vde-0100-normenreihe-sicherheit-schutz-elektroinstallation>

<sup>2</sup> <https://www.dke.de/de/normen-standards/dokument?id=4018246&type=dke|dokument>

<sup>3</sup> <https://www.dke.de/de/normen-standards/dokument?id=4018246&type=dke|dokument>

- **Section 2 calculates the operating current (phase current  $I_L$ ) for alternating and direct current systems with a known power and applied nominal voltage. For AC, an effective value of the 50 Hertz fundamental wave is initially assumed for  $I_L$ , which is purely sinusoidal and undistorted. With DC,  $I_L$  is almost smoothed and undistorted. The determined value  $I_L$  represents a theoretical assessment basis.**
- **In Section 3, the influence of a different ambient temperature, piled cable routing, the number of all loaded cores (including other consumers) and the effect of harmonics (only for AC) are shown by the respective reduction factors.**
- **In section 4, the cross-section is determined taking into account the cable length and a maximum permissible voltage drop. If the calculated cross-sections are present in accordance with points 2, 3 and 4, the larger value for the required line should be used after a comparison.**
- **The short-circuit current rating is not explored in this document.**

The procedure shown here for dimensioning the conductor cross-section is a practically oriented recommendation. For insurance and legal reasons, LAPP cannot provide any guarantee for the specific planning of an electrical system, despite this recommendation.

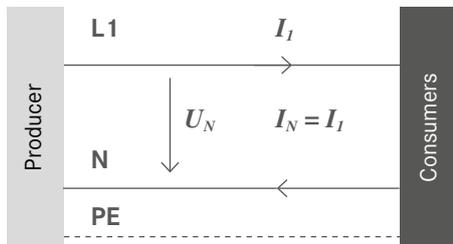
## 2. CALCULATION OF THE OPERATING CURRENT FOR AC AND DC SYSTEMS

### 2.1 Calculating in the case of AC systems

The respective operating current (phase current  $I_L$ ) is calculated on the basis of the associated power (see formula 2-1). In AC systems, a basic distinction must be made as to whether it is a single-phase AC system or a three-phase system (see Figure 2.1). In industrial applications, single-phase AC systems are typical for lighting circuits or small drives. Large drives (symmetrical consumers), on the other hand, are three-phase consumers that often do not require a neutral conductor.

#### Single-phase alternating current (AC) system:

$$I_L = I_I$$



#### Three-phase system (TPS):

$$I_L = I_I = I_2 = I_3 \text{ (symmetr. load)}$$

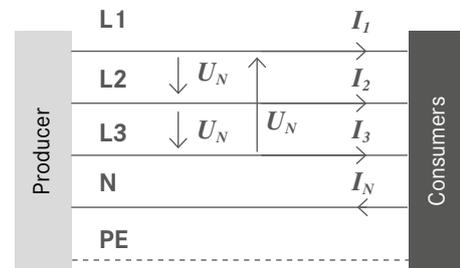


Figure 2.1: Conductor sizes in single-phase and three-phase systems

In a single-phase alternating current system (index AC with suffix "1P"), the equation is:

$$S = P_{AC,1P} = U_N \cdot I_L \cdot \eta \cdot \lambda \tag{2-1}$$

The calculated conductor current  $I_L$  is an apparent current. This must always be used as a basis for the design of the conductor cross-sections of L1, L2 and L3 (known as the line conductors), since the proportion of reactive currents also leads to effective conductor losses and thus to stress and heating of the line. In most cases, the same dimensions should be used for the cross-section of the neutral conductor N (if it is necessary for the connection of the respective consumer) as for the line conductors L1, L2 and L3.

The equation conversion (2-1) according to the phase current yields the expression:

$$I_L = \frac{S}{U_L \cdot \eta \cdot \lambda} \tag{2-2}$$

The neutral conductor also carries the phase current (as a return conductor).



#### LEGEND

- $P$  - power [W]
- $S$  - apparent power [W]
- $U_N$  - nominal voltage  
(effective value of the phase-to-phase voltage) [V]
- $I_L$  - effective value of the phase current (= apparent current) [A]
- $I_N$  - neutral conductor current [A]
- $\eta$  - efficiency [-]
- $\lambda = \frac{P}{S}$  - power factor [-]

In a three-phase system (index AC with the suffix "3P"), the above expression must be expanded by the chaining factor  $\sqrt{3}$  if the specified operating voltage is a nominal voltage (phase-to-phase voltage):

$$S = P_{AC,3P} = \sqrt{3} \cdot U_N \cdot I_L \cdot \eta \cdot \lambda \quad (2-3)$$

As above, the conversion according to the phase current yields the expression:

$$I_L = \frac{S}{\sqrt{3} \cdot U_L \cdot \eta \cdot \lambda} \quad (2-4)$$

The power factor  $\lambda$  takes into account the phase shift due to reactive power at 50 Hz due to the effective factor  $\cos \varphi$  and distortions of the total current due to harmonics. The following relationships generally apply

- For sinusoidal (harmonic) variables  $\lambda = \cos \varphi$
- For non-sinusoidal variables:  $\lambda = \frac{\cos \varphi}{\sqrt{1 + THD^2}}$

The harmonic currents have an influence on the current in the neutral conductor and, due to the resulting heating, on the dimensioning of the cross-sections of all conductors. The influence of the harmonics can generally be calculated using the power factor  $\lambda$ . A reduction factor  $k$  is introduced in DIN VDE 0298-4, which specifically takes into account the proportion of the 3rd harmonic (see Chapter 3.2).

### 2.2 Calculating in the case of DC systems

Since no reactive power is transmitted in DC systems (index "DC") nor do measurable distortions occur in current and voltage, the power factor can be set to  $\lambda \sim 1$ . The following therefore applies to the power equation:

$$P = P_{DC} = U_{DC} \cdot I_L \cdot \eta \quad (2-5)$$

The conversion according to the phase current results in:

$$I_L = \frac{P}{U_{DC} \cdot \eta} \quad (2-6)$$



#### LEGEND

- $\cos \varphi$  - effective factor (of the power factor) [-]
- THD - Total harmonic distortion [-]



#### LEGEND

- $P$  - power [W]
- $U_{DC}$  - nominal voltage [V]
- $I_L$  - conductor current (= active current) [A]
- $\eta$  - efficiency [normalised]

Figure 2.2 shows the associated nominal voltage and phase current in the DC system.

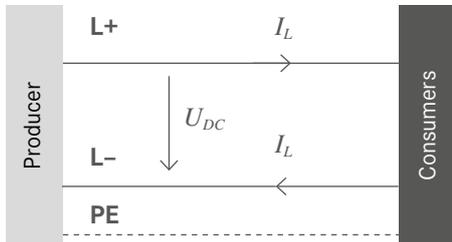


Figure 2.2: Representation of the nominal voltage and the phase current in the DC system

### 2.3 Determination of the conductor cross-section

If the operating current  $I_L$  is known or calculated according to the equations in 2.1 or 2.2, the conductor cross-section is determined depending on the type of routing. Categories according to DIN VDE 0298-4:2013-063, Tables 3 and 4 or excerpts in T12 Table 12-1 (LAPP) were defined for this. In addition, T12 Table 12-10 should be used for welding cables and T12 Table 12-9 for rubber-sheathed cables. The procedure for applying these values is identical for AC and DC systems.

<b>A1</b>	Single cores in the electrical installation pipe in a thermally insulated wall
<b>A2</b>	Multi-core cable or multi-core sheathed installation line in an electrical installation pipe in a thermally insulated wall
<b>B1</b>	Single cores in the electrical installation pipe on a wall
<b>B2</b>	Multi-core cable or multi-core sheathed installation line in an electrical installation pipe on a wall
<b>C</b>	Single-core or multi-core cable or single-core or multi-core sheathed installation line
<b>D</b>	Multi-core cable in an electrical installation pipe or cable duct in the ground
<b>E</b>	Multi-core cable with a distance of at least $0.3 \text{ diameter } D$ to the wall
<b>F</b>	Single-core, touching cables at a distance of at least $1 \text{ diameter } D$ from the wall
<b>G</b>	Single-core cables spaced at a distance $D$ at least $1 \text{ diameter } D$ from the wall

### 3. INFLUENCE OF REDUCTION FACTORS ON THE PERMISSIBLE OPERATING CURRENT

#### 3.1 Reduction factors

If the ambient temperature deviates from 30 °C, if cables are routed in piles, if there are large numbers of current-carrying cores or if there are harmonics in the grid, the cable will heat up more. This leads to a lower current rating of the line conductors L1, L2 and L3. The reduction is taken into account by the following influencing factors  $f_1$  to  $f_4$ :

$$I_Z = I_L \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_4 \quad (3-1)$$

The influencing factors, also called reduction factors, are:

- $f_1$  - ambient temperature deviating from 30 °C  
(according to DIN VDE 0298-4:2013-06, Table 17 or excerpts in T12 Table 12-2 (LAPP))
- $f_2$  - piled cable routing  
(according to DIN VDE 0298-4:2013-06, Table 22 or excerpts in T12, Tables 12-6 to 12-8 (LAPP))
- $f_3$  - number of all loaded cores (including other consumers)  
(number of cores (phases) that carry current: three in a symmetrically loaded three-phase system or two in a single-phase AC system; according to DIN VDE 0298-4:2013-06, Table 26 or excerpts in T12 Table 12-3)
- $f_4$  - effects of harmonics (in the non-symmetrical AC or three-phase system)

#### 3.2 Influence of harmonics in the AC system

Harmonics are integer multiples of the mains frequency. They are caused by non-linear loads such as discharge lamps (e.g. energy-saving lamps), overloaded transformers, power supply units with peak-value rectifiers or by using rectifiers to supply direct current consumers in a three-phase system<sup>4</sup>.

Harmonics blanket the current fundamental vibration of the prevailing mains frequency (e.g. 50 Hz) and result overall in a non-sinusoidal current in the respective line conductors. In addition, in a three-phase system, depending on the rectifier used, the currents of the third harmonic (and its multiples) from the individual line conductors can add up in the neutral conductor N. This results in impermissibly higher thermal stresses on the neutral conductor and the line conductor. The higher-frequency current flow with a frequency of  $n \cdot 150$  Hz ( $n = 1, 2, 3 \dots$ ) in the neutral conductor leads to undesirable higher-frequency magnetic fields that can interfere with electronic devices, for example. If a higher current intensity is expected in the neutral conductor than in the phase conductors, the cross-section of the cable must be calculated on the basis of the neutral conductor current.



#### LEGEND

$I_Z$  - Permissible phase current after considering the reduction factors (= current rating) [A]

<sup>4</sup> <https://www.tuvsud.com/de-de/indust-re/elektrotechnik-info/oberschwingungen2>  
(accessed 10/11/2022)

The problem of the neutral conductor current  $I_N$  can be illustrated on the basis of the nodal equation (based on Figure 2.1, right):

$$I_1 + I_2 + I_3 + I_N = 0 \quad (3-2)$$

Due to the prevailing phase shift of  $120^\circ$  between the phase currents, the sum of the instantaneous values is zero at all times for the fundamental vibration at 50 Hz and most of the harmonics (see Figure 3.1). Exceptions are harmonics with multiples of the 3rd order, i.e. also of the 6th, 9th, 12th ... order. In the case of the 3rd order harmonics, the phase shift of  $120^\circ$  is just as large as the period length resolved according to the angle. This geometric problem means that the harmonics are in phase in all three line conductors and the instantaneous values of the currents are interfered to three times the value in the neutral conductor (see example for 150 Hz in Figure 3.2).

In DIN VDE 0100-520<sup>5</sup>, a reduction factor  $k = f_4$  with a very fine gradation for the proportion of the 3rd harmonic in the total current is used. However, it must first be determined whether, depending on the converter used and the number of pulses, harmonics that can be divided by three are formed. For example, for a B6 bridge rectifier (typical for the control of a speed-controlled motor), current harmonics of the  $6n \pm 1$  orders form, i.e. 5th and 7th, 11th and 13th, 17th and 19th etc., so "pairs" with multiples of plus 6 and minus 1<sup>6</sup>. It is therefore better to always use the power factor for dimensioning.



## LEGEND

$I_z$  - Permissible phase current  
after considering the  
reduction factors  
(= current rating) [A]

<sup>5</sup> Submission version E DIN VDE 0100-520/A1 (VDE 0100-520/A1):2022-09 (as at: 22/07/2022)  
<sup>6</sup> <https://www.ihks-fachjournal.de/sechs-themen-um-oberschwingungen-und-netzqualitaet-in-stromversorgungsnetzen-2/> (accessed 11/11/2022)

The following applies to 50 Hz:

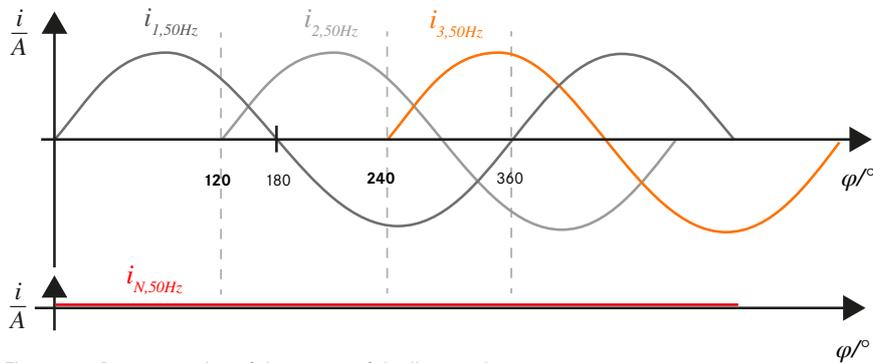


Figure 3.1: Representation of the curves of the line conductor currents and the neutral conductor current at 50 Hz over the phase position

The following applies to 150 Hz:

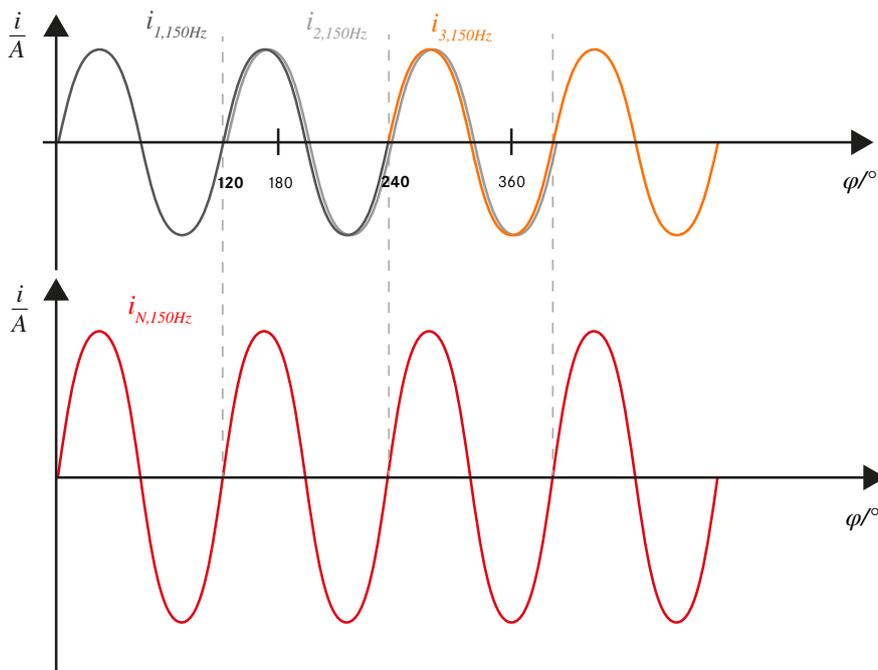


Figure 3.2: Representation of the curves of the line conductor currents and the neutral conductor current at 150 Hz over the phase position

The actual current load due to harmonics can be determined using suitable measuring devices such as true-RMS measuring devices. They are available from various companies.

**3.2 Current rating for cables with higher limit temperatures than 70 °C**

When designing the conductor cross-section, a limit temperature of 70 °C (permissible operating temperature of the insulating material) is normally assumed. For cables whose insulation is designed for a limit temperature higher than 70 °C, the current rating also increases

$$I_Z = I_1 \cdot 0.17 \cdot \sqrt{\vartheta_{L'} - \vartheta_u} \tag{3-3}$$



LEGEND

- $\vartheta_u$  - Ambient temperature [°C]
- $\vartheta_L$  - Limit temperature [°C]

The limit temperatures for various insulating materials are given as examples:

- PVC wiring cable NYFAW:  $\vartheta_L = 90 \text{ °C}$
- Rubber-core cable N4GA:  $\vartheta_L = 120 \text{ °C}$
- Silicone single-core cable H05SJ:  $\vartheta_L = 180 \text{ °C}$
- Special rubber-core cable NSGAÖU:  $\vartheta_L = 90 \text{ °C}$
- Rubber hose cable NSSHÖU:  $\vartheta_L = 90 \text{ °C}$
- Silicone hose cable:  $\vartheta_L = 180 \text{ °C}$

**4. CONSIDERATION OF THE CABLE LENGTH INTO (VOLTAGE DROP)**

After determining the cable cross-section, taking into account the current rating, the next step is to check how the length of the cable or affects the cross-section. In essence, the greater the length, the greater the resistance of the conductor and the larger the necessary cable cross-section. This behaviour is taken into account by the voltage drop, which increases with the length of the cable.

However, it should be ensured that the voltage drop  $\Delta U$  (in volts) depending on the nominal voltage  $U_n$  (in volts) does not exceed a permissible value  $\Delta u$  (in percent):

$$\Delta u = \frac{\Delta U}{U_n} \times \% \tag{4-1}$$

According to TAB 2019 (technical connection conditions)<sup>7</sup>, NAV (low-voltage connection ordinance)<sup>8</sup> and VDE-AR-N 4100<sup>9</sup>, a value of  $\Delta u \leq 0.5\%$  must not be exceeded between a domestic connection box and meter space. From the meter space to the last consumer  $\Delta u$  is  $\leq 3\%$  according to DIN 18015-1<sup>10</sup>. In contrast, DIN VDE 100 Part 520 Section 525<sup>11</sup> states that the voltage drop from the domestic connection box to the consumer should not exceed 4%. Exceptions are only made for loads with high starting currents such as motors. Further distinctions are shown in Table 3.1.

Figure 3.3 first gives an overview of the various maximum permissible voltage drops from the domestic connection box to the consumer.

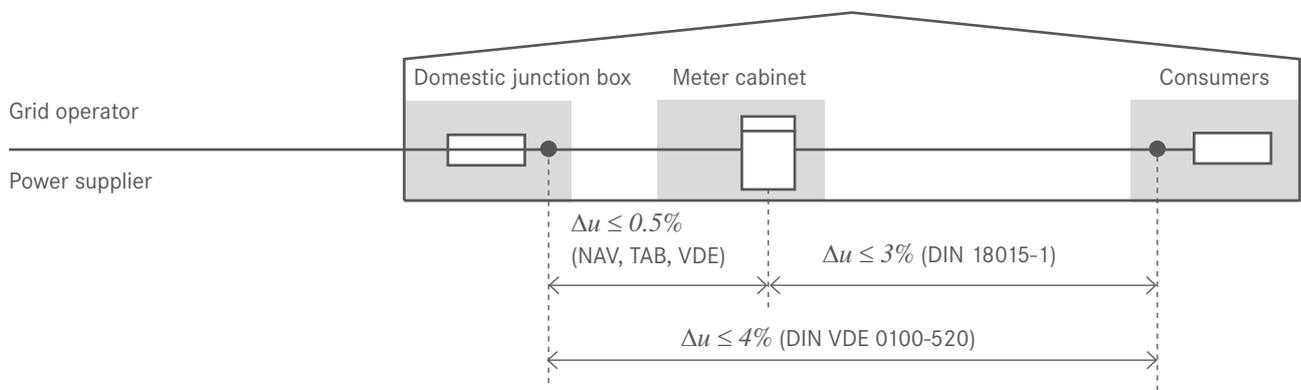


Figure 3.3: Representation of the permissible voltage drops from the domestic junction box to the consumer

Grid	Lighting circuits	Other consumers
Public supply grid	3%	5%
Private supply grid	6%	8%

Table 3.1: Voltage drops according to grid type and consumer type according to DIN VDE 100-520<sup>11</sup>

7 [https://www.sw-netz.de/wp-content/uploads/TAB\\_2019.pdf](https://www.sw-netz.de/wp-content/uploads/TAB_2019.pdf)  
 8 [https://www.gesetze-im-internet.de/nav/\\_13.html](https://www.gesetze-im-internet.de/nav/_13.html)  
 9 <https://www.vde.com/de/fnn/arbeitsgebiete/tar/tar-niederspannung/tar-niederspannung-vde-ar-n-4100>  
 10 <https://www.din.de/de/ueber-normen-und-standards/nutzen-fuer-den-verbraucher/verbraucherrat/ueber-uns/din-18015-1-elektrische-anlagen-in-wohngebaeuden-teil-1-planungsgrundlagen-mit-ausgabedatum-mai-2020-veroeffentlicht-711662>  
 11 <https://www.vde-verlag.de/normen/0100170/din-vde-0100-520-vde-0100-520-2013-06.html>

The conductor cross-section  $A$  is calculated depending on the system used:

- **Single-phase alternating current:**

$$A = \frac{2 \cdot l \cdot I \cdot \cos \varphi}{\gamma \cdot \Delta U}$$

- **Three-phase alternating current (three-phase system):**

$$A = \frac{\sqrt{3} \cdot l \cdot I \cdot \cos \varphi}{\gamma \cdot \Delta U}$$

- **Direct current:**

$$A = \frac{2 \cdot l \cdot I}{\gamma \cdot \Delta U}$$

According to the calculations of the cross-sections according to points 2, 3 and 4, the larger cross-section should be used for the required line.



#### LEGEND

$A$	- Conductor cross-section [mm <sup>2</sup> ]
$l$	- Cable length [m]
$\Delta U$	- Absolute voltage drop [V]
$I$	- Nominal current [A]
$\cos \varphi$	- Power factor [-]
$\varphi$	- Phase shift between current and voltage [°]
$\gamma$	- Electrical conductivity of the conductor material [S/m] (for copper: 58 S/m)

## 5. CALCULATION EXAMPLE: CONNECTING CABLES FOR HEATERS

Four heaters must be routed on a wall with an ambient temperature of up to 45 °C using 3 m long connecting cables (sheathed cables, NYM). Each of the heaters (three-phase consumers) draws an operating current of 10 A. How should the cross-section be measured?

1. Required current rating  $I_Z = 10 \text{ A}$
2. Consideration of the reduction factors  $f_1$   
(deviating ambient temperature and  $f_2$  (piled cables))

$$I_Z = I_L \cdot f_1 \cdot f_2$$

$$I_L = \frac{I_Z}{f_1 \cdot f_2}; f_1 = 0.79; f_2 = 0.65$$

$$I_L = 19.47 \text{ A}$$

3. Table 9.2: Routing type group C (routing on a wall)  
→ read cross-section: 2.5 mm<sup>2</sup> per conductor
4. Voltage drop

$$\Delta u = \frac{\Delta U}{U_n} = 3\%$$

$$\Delta u = 0.03 \cdot 400 \text{ V} = 12 \text{ V}$$

$$A = \frac{\sqrt{3} \cdot l \cdot I \cdot \cos \varphi}{\gamma \cdot \Delta U} = \frac{\sqrt{3} \cdot 3 \text{ m} \cdot 10 \text{ A}}{58 \frac{\text{S}}{\text{m}} \cdot 12 \text{ V}} = 0.075 \text{ mm}^2$$

The cross-section calculated according to the maximum permissible voltage drop is smaller than the cross-section calculated in point 3 depending on the current rating. Therefore, the cross-section of 2.5 mm<sup>2</sup> from point 3 should be used.

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