WHITEPAPER

COMPARISON OF COPPER CROSS SECTION AND TRANSMISSION LOSSES FOR CABLES IN AC AND DC SYSTEMS

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COMPARISON OF COPPER CROSS SECTION AND TRANSMISSION LOSSES FOR CABLES IN AC AND DC SYSTEMS

CONTENTS

1. INTRODUCTION

One of the key objectives of the European Union is to establish a sustainable and efficient energy economy. Particularly in industrial plants, around 70% of the electricity demand is accounted for by electrically driven systems[1]. As there is a high potential for saving electrical energy in such cases, there has been a minimum requirement for the energy efficiency of electric motors stipulated by the European Union since 2011. With the efficiency classes for motors, only the electromechanical components and their contribution to the energy efficiency of machines and systems have been considered so far in standards and legislation.

Improvement of energy efficiency has been supported by the IEC 61800-9 series of standards since 2017. In it, energy analyses and loss value assessments are carried out across the entire adjusting and load range of the whole electric drive system when supplied from an AC grid.

Further increases in energy efficiency can be achieved when supplying speed-controlled drives and motors in a DC grid[2]. These considerations are not part of IEC 61800-9, but are the focus of this document. The basis is supplying a speed-controlled motor (frequency f_{var}) from an AC grid with a B6 bridge rectifier, DC link and inverter (case 1) and a DC grid with intermediate circuit and inverter (case 2). This is shown in Figure 1.

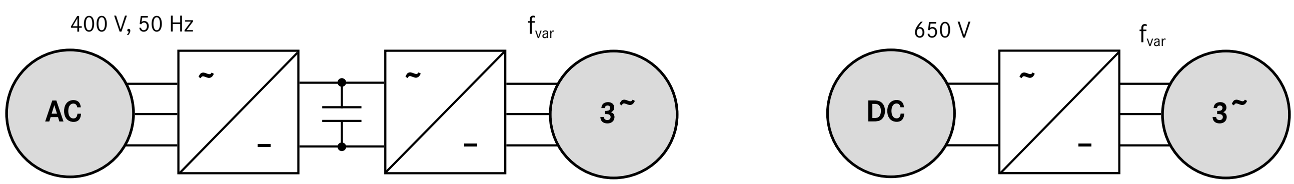


Figure 1: Representation of the supply of a speed-controlled motor from an AC grid (left, case 1) and DC grid (right, case 2)

1 T. Kuhlmann, E. Fosselmann et al.: "Benefits of industrial DC grids", World Sustainable Energy Days, 28/02–03/03/2023, Wels, Austria
2 ZVEI & consortium DC Industry 2: system concept DC Industry 2, available online at: https://dc-industrie.zvei.org/publikationen/systemkonzept-fuer-dc-industrie 2; last accessed 24/02/2023

The following shows how the DC supply can be used to achieve a reduction in the copper cross-section and lower losses in the transmission/distribution of energy. The power factor plays a major role, which in the AC system greatly depends on the type and use of mains filters or chokes. The power factor λ takes into account the phase shift between current and voltage at 50 Hz as well as distortion due to harmonics.

This document first explores the relevant foundations for subsequent considerations:

- **Method of generating the DC voltage**
- **Measures to reduce harmonics: Mains chokes and filters**
- **Power factor and power calculation**

2. BASICS

2.1 Generating the DC voltage

Central feed-in rectifier and mains voltage in DC system
Controlled feeds with AIC (active infeed inverter, i.e. feed with filter technology) are widely used in industrial environments. These AC/DC converters can only generate a DC voltage that is above the rectified AC voltage (= peak value of the phase-to-phase AC voltage). If the DC voltage falls below this value, the AIC loses its controllability.

When connected to a three-phase system with 400 V, DC voltages can be generated in a voltage range of 600–750 V. The limits of this voltage range depend on the supplier topology and the supplying AC grid. This range enables the load flow control of the power sources (especially in grid installations with more than one supply) via a characteristic-based regulation. A value of 650 V is determined as the nominal voltage and used for subsequent calculations. These assumptions are from the DC Industry 2 project[3].

3 ZVEI & consortium DC Industry 2: system concept DC Industry 2, available online at: https://dc-industrie.zvei.org/publikationen/systemkonzept-fuer-dc-industrie 2; last accessed 24/02/2023

Uncontrolled supply devices (e.g. B6 bridge rectifier)
Due to a good efficiency level and lower costs, most industrial frequency converters are uncontrolled rectifiers. They generate a DC voltage corresponding to the rectified value and is usually $1.35 \cdot U_{AC}$ at nominal load.

For example, the control of speed-controlled motors from the AC grid consists of a rectifier, intermediate circuit and inverter (see figure 1, left, case 1). Three-phase rectifiers in the form of bridge circuits and a pulse count of six are often used for the rectifiers. The pulse count indicates how many rectifier branches become conductive within a period. The differences in the momentary positive and negative line conductor voltages result in a pulsating direct voltage. In contrast to AIC, uncontrolled supply devices generate harmonics in the upstream AC grid, which lead to distortion of the alternating current. Figure 2 shows an example of the signal sequences for a sinusoidal (undistorted) alternating current (λ = 1) and a typical distorted current shape with a power factor of λ = 0.63.

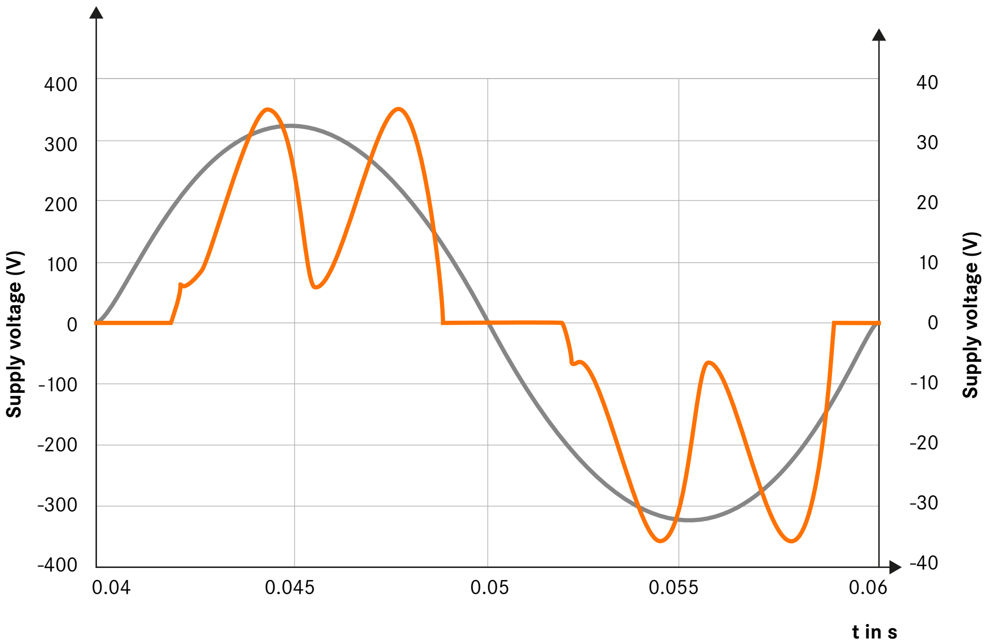


Figure 2: Sinusoidal and distorted alternating current in the upstream AC grid (grey: λ = 1, orange: λ = 0.63)

2.2 Measures to reduce harmonics

Harmonics not only lead to larger conductor cross-sections of cables (see section 3.3), but also cause additional losses and place a strain on the input circuits (especially the capacitors). They can also lead to faster ageing and premature failure of components.[4]

By using:

- **mains chokes**
- **active or passive mains filters**

harmonics in the current of the upstream AC grid are reduced and the grid current is smoothed to a sinusoidal waveform.

Mains chokes are low-impedance coils and are installed in the AC system in series between the supply and the consumer or in series at the input of a frequency converter. They can be used to dampen currents with different frequencies.

In addition, active or passive filters can be used, which are located between each phase and the ground between the AC supply and the consumer (see Figure 3). The filters reduce or compensate the current components with multiple frequency components greater than 50 Hz through counter-current components.

However, the proportion of harmonics is also influenced by the size of the intermediate circuit capacitor. According to IEC 61800-9-2, frequency converters with large capacity and smaller mains chokes cause a peaked input current waveform and a worse power factor. Smaller capacities in the intermediate circuit cause a block-shaped current. Overall, a high proportion of inductance can smooth the current through the use of mains chokes and produce an (optimised) power factor of around 0.9 in the upstream AC grid. Without mains chokes or other measures, this factor is approximately 0.6. This range of values is considered to be the basis for further considerations.

4 T. Kuhlmann, E. Fosselmann et al.: "Benefits of industrial DC grids", World Sustainable Energy Days, 28/02–03/03/2023, Wels, Austria

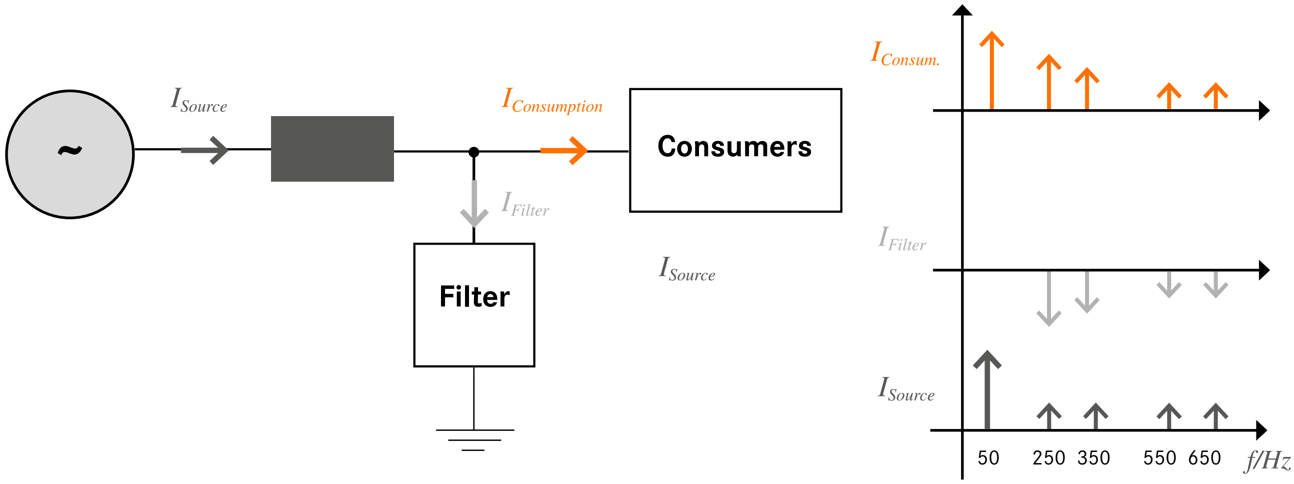


Figure 3: Arrangement and function of a grid filter in the AC grid to reduce harmonics[5]

3. CALCULATIONS FOR THE USE OF COPPER AND ENERGY EFFICIENCY FOR AC AND DC CABLES WITH EQUAL POWER CONVERSION

3.1 Procedure

The comparison of the complete material used for the inner conductors of AC and DC cables is based on the dimensioning of the cable cross-section depending on the operating current according to DIN VDE 0298-4 (current rating of cables and taking into account the laying type B2 (multi-core cable or multi-core sheathed installation line in an electrical installation pipe on a wall). Other designs with regard to voltage drop and short-circuit current are not taken into account here.

In low-voltage three-phase current systems, 4-core AC cables are mainly used to connect motors or drives. In low voltage, however, a distinction must also be made between grid topologies with five conductors (3 phase, 1 neutral and 1 protective earth). Regardless, there are three current-carrying conductors.

In low-voltage DC systems, grid topologies are mainly constructed with two current-carrying phases (L+ and L-) and a protection earth (PE). Depending on the grounding, another midpoint conductor can be routed as well. There is generally one less current-carrying conductor than in the three-phase system.

5 IHKS specialist journal: Harmonics, Chapter 5: Filter techniques for harmonics, URL: https://www.ihks-fachjournal.de/kapitel-5-6-themen-um-oberschwingungen-und-netzqualitaet-in-stromversorgungsnetzen/, accessed on 06/06/2023

In the first step, the currents in the AC and DC grid are calculated as a function of the power factor and a ratio is derived (see section 3.2). The corresponding cross-section can be read from DIN VDE 0298-4 based on the calculated current. The number of current-carrying conductors (AC: 3, DC: 2) must be taken into account.

The currents in the AC and DC grid are then calculated as a function of the power factor and a ratio of the currents between DC and AC is derived (see section 3.2). On the basis of these currents, a cross-section is read from the standard DIN VDE 0298-4 and multiplied by the number N of the respective sub-conductors to form a total cross-section. In the last step, the ratio of both total cross-sections is formed and evaluated[6].

3.2. Basics of calculating current intensity in AC and DC systems

The respective operating current (phase current) is calculated on the basis of the associated power equation. In AC systems, a basic distinction must be made as to whether it is a single-phase AC system or a three-phase system. The following considerations for drives in industrial grids are based on a three-phase system for which the following applies:

$$P = \sqrt{3} \cdot U_{AC} \cdot I_L \cdot \eta \cdot \lambda \qquad (3\text{-}1)$$

The conversion according to the phase current yields the expression:

$$I_L = \frac{P}{\sqrt{3} \cdot U_{AC} \cdot \eta \cdot \lambda} \qquad (3\text{-}2)$$

The following applies to sinusoidal (harmonic) variables: $\lambda = \cos\varphi$

The following applies to non-sinusoidal variables: $\lambda = \frac{\cos\varphi}{\sqrt{1 + THD^2}}$ (3-3)

LEGEND

- P - effective power [W]
- U_{AC} - nominal voltage (phase-to-phase voltage) in the AC system [V]
- I_L - conductor current [A]
- η - Efficiency [-]
- $\lambda = \frac{P}{S}$ - power factor [-]

LEGEND

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

6 U.I. Lapp GmbH: "Calculation and selection of the cross-section for cables in AC and DC systems", whitepaper, April 2023

Since no reactive power is transmitted in DC systems nor do measurable distortions occur in current and voltage, the power factor can be set to $\lambda \sim 1$.

The following applies to the power equation:

$$P = U_{DC} \cdot I_L \cdot \eta \qquad (3\text{-}4)$$

The conversion according to the phase current results in:

$$I_L = \frac{P}{U_{DC} \cdot \eta} \qquad (3\text{-}5)$$

LEGEND

P - power [W]
U_{DC} - nominal voltage DC system [V]
I_L - conductor current [A]
η - efficiency[-]

3.3. Calculation and comparison of copper usage

In the following considerations, a 400 V three-phase system (AC) is compared with a 650 V system (DC) with the same power consumption. Based on the formulas for calculating the current intensity shown in section 3.2, the ratio I_{DC}/I_{AC} is formed and the respective operating voltage is used:

$$\frac{I_{DC}}{I_{AC}} = \frac{\sqrt{3} \cdot U_{AC} \cdot \lambda_{AC}}{U_{DC}} \qquad (3\text{-}6)$$

A power factor of $\lambda_1 = 0.63$ results in a ratio of $\frac{I_{DC}}{I_{AC}} = 0.67$, for $\lambda_2 = 0.9$ a ratio of 0.95.

In the following considerations, the currents specified in DIN VDE 0298 for systems with two and three current-carrying conductors for the same or different cross-sections are compared until the ratios calculated above are approximately reached and not undershot. Table 1 (for λ_1) serves as an illustration. The result shows that the ratio of the currents I_{DC}/I_{AC} for a cross-section of 2.5 mm² in the AC system and 1.5 mm² in the DC system comes closest to the ratio calculated above and does not undershoot it.

Table 1: Comparison of the conductor cross-sections for AC and DC systems

A in mm²	I in A for 2 loaded cores (= DC)	I in A for 3 loaded cores (= AC)	I_{DC}/I_{AC}
1.5 mm²	16.5 A	15 A	1.1
2.5 mm²		20 A	**0.83**
4 mm²		27 A	0.61

This procedure is continued for the other cross-sections up to 300 mm². Figure 4 shows how the AC and DC cross-sections differ. The AC cross-section is shown as a reference. On the y axis, the difference to the DC cross-section is shown as an integer. For example, a difference of -1 means that the next smaller cross-section can be used for DC.

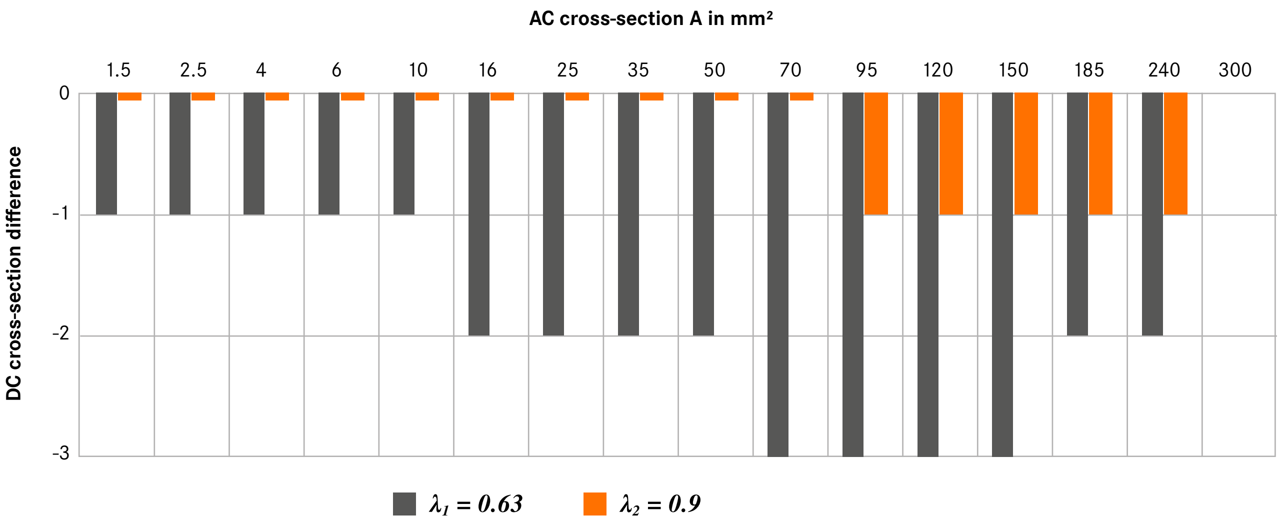


Figure 4: Differences in conductor cross-sections for AC and DC systems

The results show a significant influence of the power factor on the ratio of the cross-sections between AC and DC. However, other differences can also occur due to the type of installation, so this should only be considered as an example.

The copper saving is shown below. The total cross-section for AC and DC systems with different numbers of conductors is calculated and compared. A distinction is made between AC systems with four and five conductors and DC systems with three and four (see **Fig. 3** and **4**).

The copper savings considered here, which are typical for many DC systems, generally result from a smaller conductor current, which can be attributed to a higher DC voltage (see section 2.1) and the absence of reactive power in the DC system. The results show that for a high power factor of $\lambda = 0.9$, there are fewer copper savings compared to a poorer power factor (due to a larger cross-section). In addition, the number of cores plays a key role in the comparison. The highest saving is obtained when comparing a DC cable with three conductors versus an AC cable with five conductors for cross-sections up to 70 mm² if the AC system is highly harmonic (low power factor). In contrast, there is no savings potential for AC and DC cables with the same amount of cores for cross-sections up to 70 mm² if the AC grid is almost harmonic-free (high power factor).

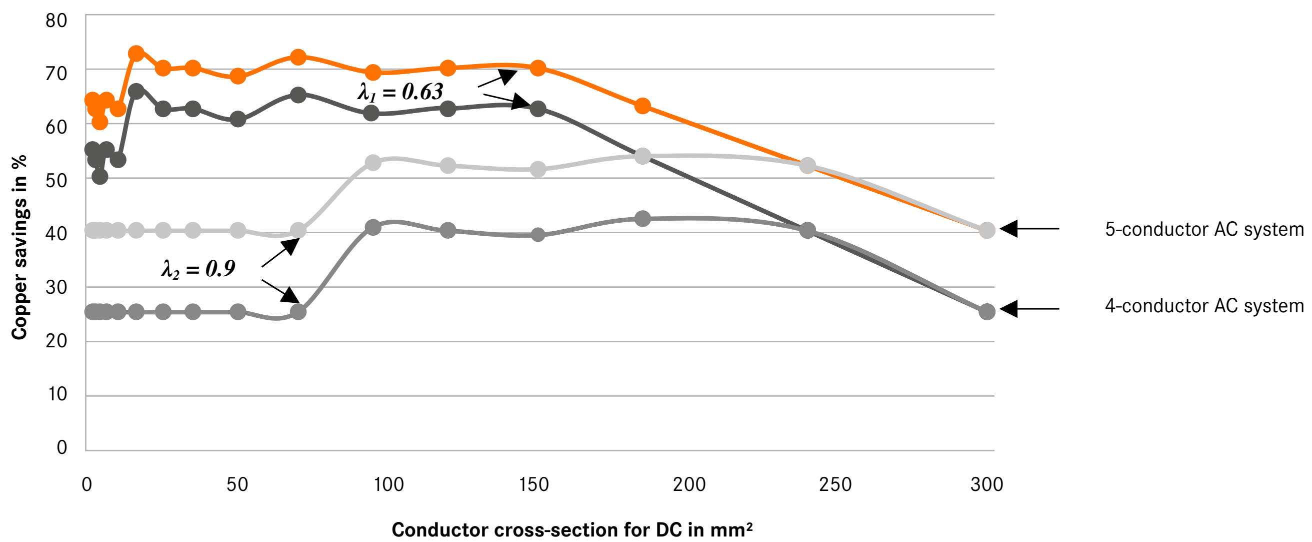


Figure 3: Comparison of a 3-conductor DC system with 4- and 5-conductor AC system

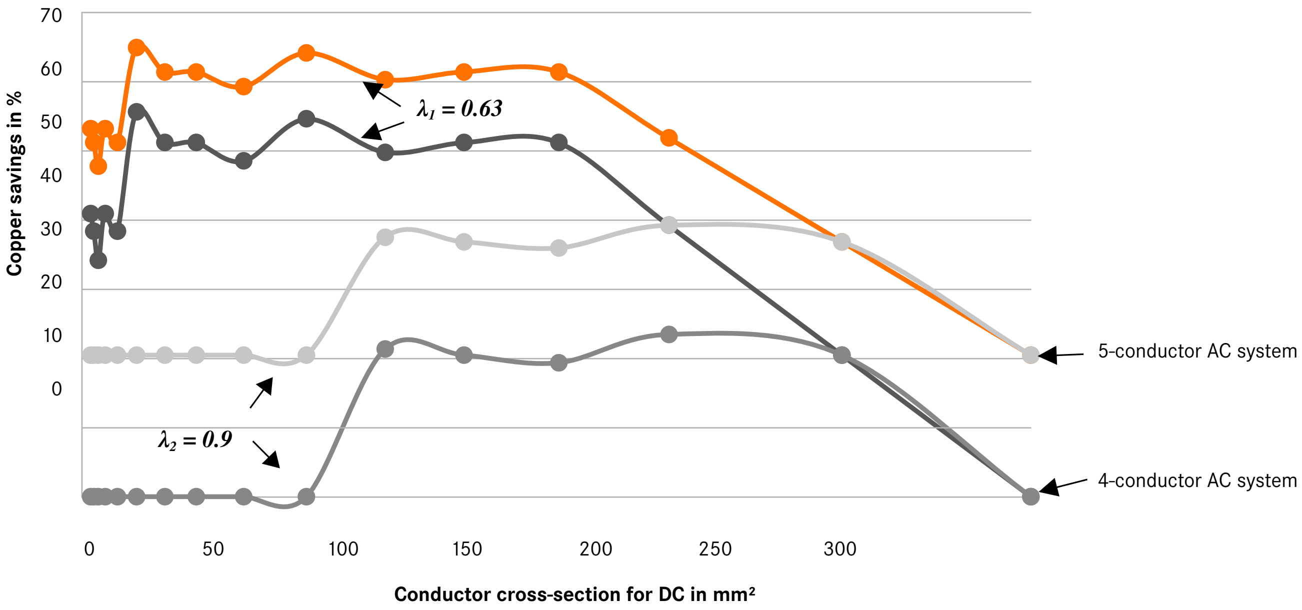


Figure 4: Comparison of a 4-conductor DC system with 4- and 5-conductor AC system

3.5. Calculation and comparison of transmission losses

While a DC system offers the technical requirements for a smaller conductor cross-section compared to an AC system due to the higher voltage, a larger conductor cross-section $\boldsymbol{A}$ is more advantageous for reducing transmission losses. The calculations in this chapter compare the transmission losses (as power loss $\boldsymbol{P_V}$ in $\boldsymbol{W}$) in the AC and DC system. These can be calculated as follows using the number $\boldsymbol{N}$ of current-carrying conductors (N = 2 for DC, N = 3 for AC), the conductor resistance $\boldsymbol{R}$ and the conductor current $\boldsymbol{I}$:

$$P_V = N \cdot R \cdot I^2 \tag{3-7}$$

It is often customary to represent the power loss in relation to the length $\boldsymbol{l}$. With the calculation rule for the conductor resistance

$$R = \rho \cdot \frac{l}{A} \tag{3-8}$$

the result is:

$$P'_V = \frac{P_V}{l} = N \cdot \frac{\rho}{A} \cdot I^2 \tag{3-9}$$

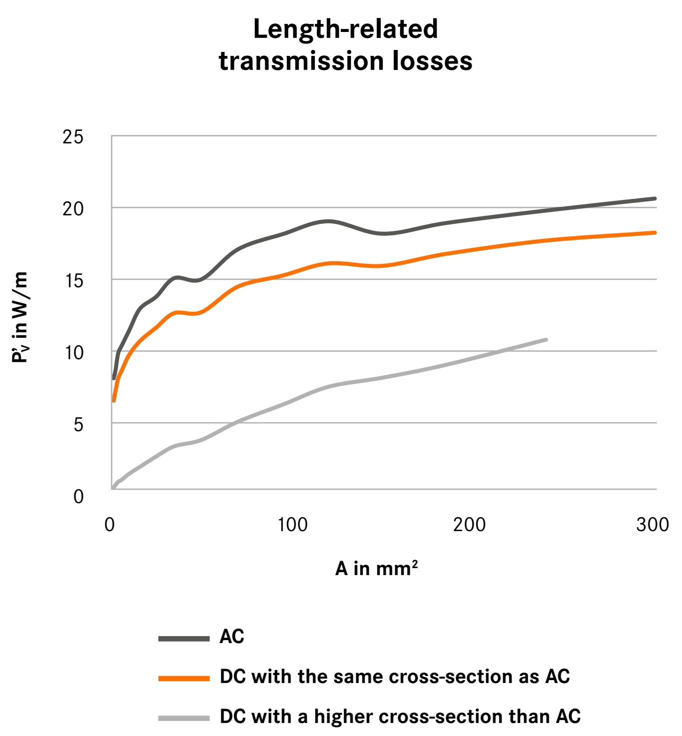
LEGEND

- P_V - power loss [W]
- P'_V - length-related power loss [W/m]
- I - conductor current [A]
- ρ - specific electrical resistivity (of copper) [Ω mm²/m]
- N - number of current-carrying conductors
- A - conductor cross-section [mm²]
- l - transmission length [m]

ρ is the specific electrical resistance of copper and is used for the calculations with $0.018\ \Omega\ mm^2/m$.

Based on the cross-sections and currents given in Figure 5, the length-related transmission power losses P'_V in W/m are calculated and presented for the same and different cross-sections for AC and DC.

The results show that, depending on the cross-section, the length-related transmission power loss through a DC cable with two current-carrying conductors is reduced by 12–20% compared to an AC cable with three current-carrying conductors. A further significant reduction of more than 50% of the transmission losses results if the next larger conductor cross-section is selected in the DC system for the same current. This aspect contradicts the copper savings and the associated material costs in section 3.3. With regard to the energy efficiency of technical systems and the constantly rising energy costs, this aspect is becoming increasingly important.



A in mm²	DC: I in A	AC: I in A
1.5	17.5	15.5
2.5	24	21
4	32	28
6	41	36
10	57	50
16	76	68
25	101	89
35	125	110
50	151	134
70	192	171
95	232	207
120	269	239
150	300	262
185	341	296
240	400	346
300	458	394

Figure 5: Length-related transmission losses for AC and DC cables (left) and currents based on DIN VDE 0298-4 (right)

4. CALCULATION EXAMPLES FOR INDUSTRIAL GRIDS

This chapter shows an example of how to dimension the conductor cross-sections for the supply of a motor with a fixed speed from the three-phase system (case 1) and a speed-controlled motor from the three-phase system via converters (B6 rectifier without mains choke, intermediate circuit and inverter) (case 2) and from the DC system with DC link and inverter (case 3) (see Figure 6). The ambient temperature is assumed to be 30 °C. The feed lines considered are each 5 m.

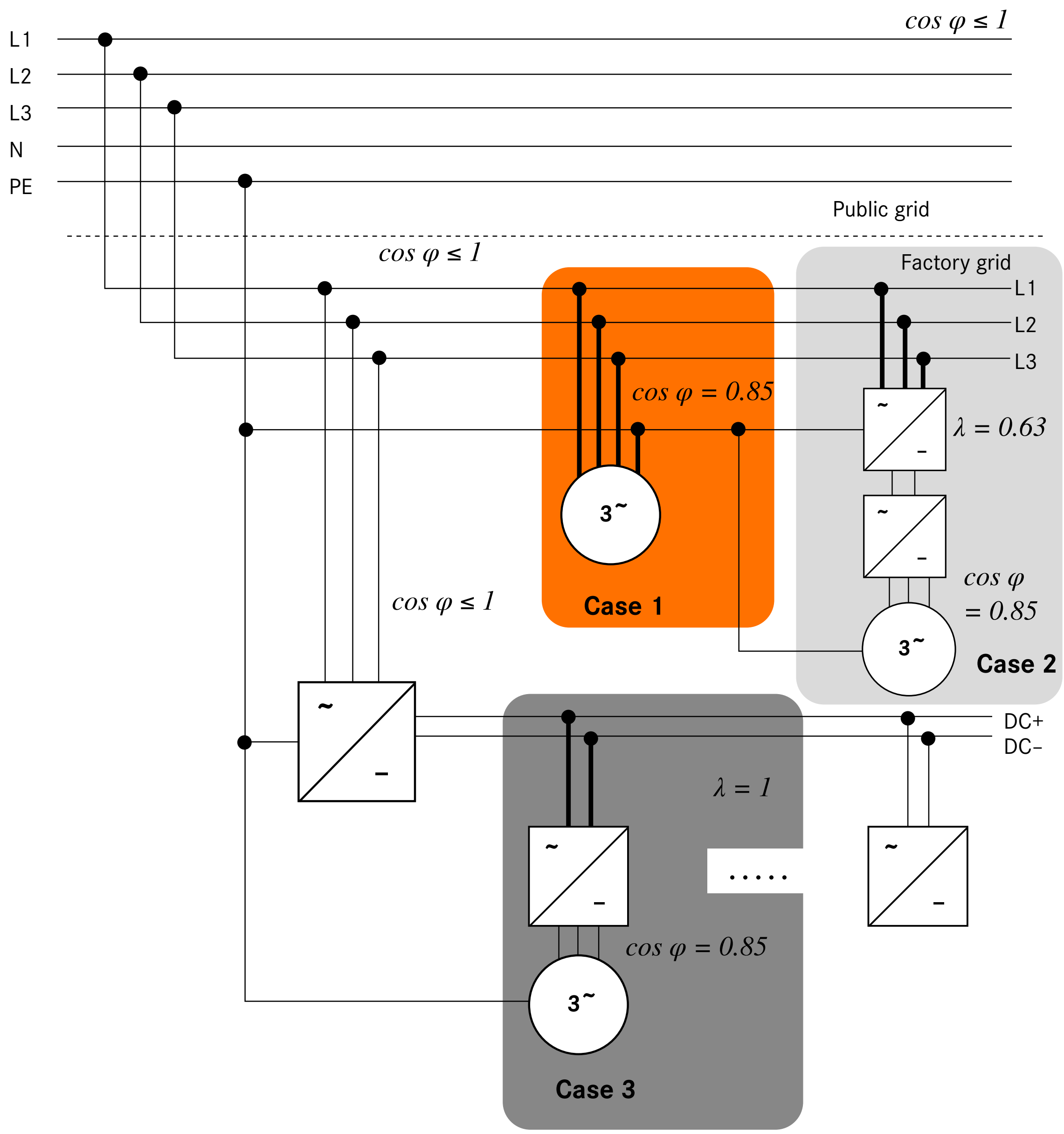


Figure 6: Supply of a motor with a fixed speed from the three-phase system (case 1) and a speed-controlled motor from the three-phase system (case 2) and direct current system (case 3)
Specified motor variables: $P_{Motor} = 7.5\ kW$, $\cos \varphi = 0.85$, $\eta = 0.887$
Specified variables of the frequency converter (B6 bridge rectifier): $\eta = 0.97$

Case 1: Motor in a three-phase system without frequency converter (power in the motor cable)

Assumption: no distortions, so $\lambda = \cos \varphi = 0.85$

$$P_{motor} = \sqrt{3} \cdot U_n \cdot I_L \cdot \eta \cdot \lambda$$

$$I_L = \frac{P_{Motor}}{\sqrt{3} \cdot U_n \cdot \eta \cdot \lambda} = \frac{7500\ W}{\sqrt{3} \cdot 400V \cdot 0.887 \cdot 0.85} = 14.35\ A$$

Case 2: Power to AC supply line of frequency converter for speed-controlled motor

Case 2.1

Assumption: $\lambda = 0.63$ (B6 rectifier without mains choke)

$$I_L = \frac{P_{Motor}}{\sqrt{3} \cdot U_n \cdot \eta \cdot \lambda} = \frac{7500\ W}{\sqrt{3} \cdot 400V \cdot 0.887 \cdot 0.97 \cdot 0.63} = 20.31\ A$$

Case 2.2

Assumption: $\lambda = 0.9$ (B6 rectifier with mains choke)

$$I_L = \frac{P_{Motor}}{\sqrt{3} \cdot U_n \cdot \eta \cdot \lambda} = \frac{7500\ W}{\sqrt{3} \cdot 400V \cdot 0.887 \cdot 0.97 \cdot 0.9} = 14\ A$$

Case 3: Power to DC supply line of frequency converter for speed-controlled motor

Assumptions: $\lambda = 1,\ U = 650\ V$

$$I_L = \frac{P_{Motor}}{U_n \cdot \eta} = \frac{7500\ W}{650V \cdot 0.887 \cdot 0.97} = 14.25\ A$$

Table 4: Selection of conductor cross-sections for different types of motor supply

	Case 1	Case 2.1	Case 2.2	Case 3
Conductor current I_L	14.35 A	20.31 A	14 A	14.25 A
Cable cross-section according to DIN VDE 0298-4	1.5 mm²	2.5 mm²	1.5 mm²	1.5 mm²

Assumption: Routing type B1 – routing in installation pipes

Due to the short connection length, the dimensioning of the cable cross-section according to the occurring voltage drop is omitted here. Similar to the previous considerations, the example comparison shows that an AC grid by harmonics requires a larger cable cross-section.