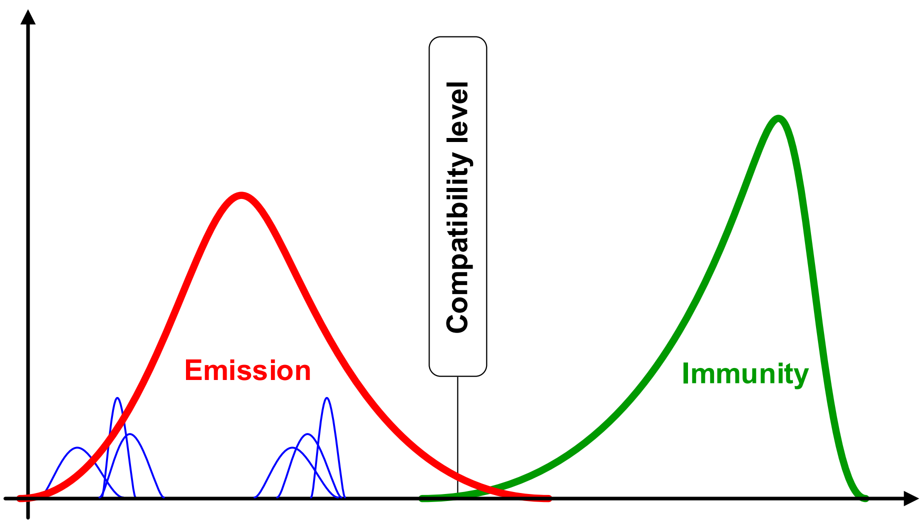
Technical Rules for the assessment of network disturbances

(Technische Regeln für die Beurteilung von Netzrückwirkungen)

Part A: Fundamentals



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Special thanks are due to those persons whose work on previous editions contributed significantly to the development of these Technical Rules.

Content

Foreword

The increasing usage of power electronics in electrical appliances and installations as well as the widespread use of distributed generation and flexible loads place growing emphasis on the issue of disturbances of the supply system and their assessment. For the first time, VDEW (Association of German Electricity Grid Operators) published the document “Grundsätze für die Beurteilung von Netzrückwirkungen” (Principles for the Assessment of Network Disturbances) in 1976 and VEÖ (Association of Austrian Electricity Companies) published the document “Empfehlung für die Beurteilung von Netzrückwirkungen” (Recommendation for the Assessment of Network Disturbances) in 1980. Technical development as well as international and European standardization required new editions of both documents in the following years. The VEÖ recommendation was adopted by VSE (Swiss Electricity Industry Association) in 1995 and the VDEW principles was adopted by CSRES (Czech Association of the Regulated Power Supply Companies) in 1997.

Based on the VEÖ and VSE recommendations, a working group D-A-CH-CZ of the four holding associations together with university representatives published the 1st edition of “Technical Rules for the Assessment of Network Disturbances” in 2004, which replaced the previous documents. After the revision, the 2nd edition followed in 2007. Upon the recommendation of the users, a “Supplementary Document for the Assessment of Installations Connected to High-voltage networks” (Ergänzungsdokument zur Beurteilung von Anlagen für den Anschluss an Hochspannungsnetze) was prepared by the D-A-CH-CZ working group and published in 2012.

In this 3rd edition, the basic document and the supplementary document have been combined, taking into account the technical progress of the subject and the harmonisation with modified and new standards.

During the preparation of this edition of the Technical Rules, a large number of technologies, systems and strategies have been developed with the objective of making better use of distribution networks and promoting their evolution and market penetration. Depending on the utilization or optimization objective, positive influences on the power quality can result. On the other hand, the economic pressure on the distribution network operators (DSOs) will cause a higher loading of networks, with the consequence that the power quality characteristics will become more evident in the future. The specific influences of individual technologies on the performance of the distribution networks have not yet been comprehensively analysed. Customer installations with a non-linear characteristic of the appliances, such as inverters of generating installations, affect the frequency-dependent network impedance and can cause undesired resonances in the network. Decentralized control in the distribution network, aimed at local voltage stability, can impair the dynamic network stability. Even in the case of “network-friendly” or “network-serving” measures, important issues for the network operation, such as the procedure in the event of failure of these technologies, have not yet been sufficiently investigated.

It is deemed to be difficult by the working group to consider these aspects in a general manner during the EMC coordination. The Technical Rules should therefore be applied with caution if, for example, there is an excessive amount of installations that strongly affect individual disturbance phenomena due to their technology and operating schemes.

Network operators who use so-called Smart Grid technologies in their distribution networks are recommended to carry out more detailed analyses for the coordination of customer connections. State-of-the-art network calculation tools, taking into account the specific network conditions, can be used to justify to what extent the recommendations in this document may (in case of positive effects) or shall (in case of negative effects) be deviated from.

As of this edition, no distinction is made between consuming and generating installations. Irrespective of the direction of the active power flow, solely the term customer installation (installation of the network user) is used. This fundamental change in philosophy already accounts for the expected use of distributed storage installations.

In addition to editorial improvements, a new structure is introduced for the consolidation of the two documents currently in force. Therefore, this edition comprises three parts:

- Part A “Fundamentals” contains basic information (objectives, specifications, short-circuit power and terms) as well as all necessary explanatory information. This part is intended to support the user to understand the corresponding specifications for the individual disturbance phenomena. Technical contexts and mathematical methods are described in a comprehensible way, so that the derivation of the individual reference and limit values can be understood. The document structure corresponds to the same order of the various phenomena as chosen in the 2nd edition.
- Part B “Requirements and Assessment” comprises all the equations and tables required for the application of the Technical Rules. For the benefit of the user, this part is divided into three individual sections applicable for the network levels LV, MV and HV.
- Part C “Examples” summarises relevant calculation examples, again classified according to phenomena and network levels.

In addition, the working group will publish other official documents comprising further explanations of the methods used and assumptions made in the derivation of calculation equations and the specification of corresponding parameters. This allows DSOs even more flexibility in adjusting the calculation methods to individual conditions.

References to standards that are implemented in all four countries are provided with reference to the respective European (EN, HD) or International Standards (e.g. IEC). Otherwise, their designation begins with the following letters:

D: DIN, VDE
A: OVE / ÖNORM
CH: SN
CZ: CSN, PNE

All standards are referenced in the list of standards at the end of the document. In the text, the standard is given in square brackets to improve legibility.

The mentioned associations would like to thank their experts, who prepared these transnational Technical Rules with great commitment.

Aarau, Berlin, Prague, Vienna September 2021

Abbreviated terms

CENELEC	European Committee for Electrotechnical Standardisation
EHV	Extra high voltage
EMC	electromagnetic compatibility
EN	European standard
EURELECTRIC	Union of the Electricity Industry
HV	high voltage
IEC	International Electrotechnical Commission
IEV	International Electrotechnical Vocabulary
LV	low voltage
MV	medium voltage
PV	photovoltaics
AFRC	Audio frequency ripple-control
UIE	International Union for Electroheat
UNIPEDE	International Union of Producers and Distributors of Electric Energy

1. Terms and definitions

If one of the terms defined is originated from the International Electrotechnical Vocabulary (IEV) [IEC 60050], the corresponding reference number is given in brackets. If no IEV term is available, the definition was taken from IEC standards or an appropriate definition was introduced.

(agreed) power of the customer installation S_A

value of the apparent power of the customer installation on which the customer and the system operator agree

Note:
The agreed power S_A usually corresponds to the contracted power, which is requested by the planner of the installation and is determined in coordination with the DSO.

commutation notch (IEV 161-08-12)

voltage change, with a duration much shorter than the AC period which may appear on an AC voltage due to the commutation process in a converter

compatibility level (IEV 161-03-10)

the specified electromagnetic disturbance level used as a reference level for coordination in the setting of emission and immunity limits

Note 1:
By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. However electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that, at each location, the disturbance level resulting from the cumulative emissions is lower than the immunity level for each device, equipment and system situated at this same location.
Note 2:
The compatibility level may be phenomenon, time or location dependent.

consumption capacity factor k_C

ratio of the maximum possible installation power of all consuming installations to a reference power of the network S_N

customer installation

total equipment used for generation, consumption or storage of electrical energy and owned by a customer (network user)

Installation of the network user or network user installation are equivalent terms for customer installation.

declared supply voltage U_c

typically, equal to the nominal voltage U_n of the electrical network

If, due to an agreement between the DSO and the customer (network user), a voltage is specified that differs from the nominal voltage of the electrical network, then this is the declared supply voltage U_c.

Note:
In low-voltage systems, the declared supply voltage U_c is generally the nominal voltage U_n. In medium-voltage systems, the level of the supply voltage is defined by the declared supply voltage U_c.

emission limit

the maximum emission level of a given electromagnetic disturbance allocated to a customer installation

The objective of EMC coordination is to ensure that the compatibility levels and planning levels are maintained when the system is fully utilized with customer installations emitting at their allocated limits.

These values are determined based on applicable national and international standards.

flicker (IEV 161-08-13)

impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

Flicker is the subjective impression of fluctuating luminance.

Note:
Fluctuating luminance can be caused by voltage fluctuations, interharmonics and phase shifts. Above a certain threshold flicker becomes annoying. The annoyance grows very rapidly with the amplitude of the fluctuation. At certain repetition rates even very small amplitudes can be annoying [EN 50160].

flicker impression time t_f

value with a time dimension which describes the flicker impression of a voltage change characteristic [EN 61000-3-3]

Note:
The flicker impression time represents the physiological perceiving and forgetting it again.

flicker severity

intensity of flicker annoyance defined by the UIE-IEC flicker measuring method [EN 61000-4-15] and evaluated by the following quantities:

- short-term flicker severity P_{st}, measured over a period of 10 min
- long-term flicker severity P_{lt}, calculated from a sequence of 12 $P_{st\,i}$ values over a two-hour interval

flicker-related phase angle φ_f

phase angle in the considered load condition which is relevant for the flicker behaviour

Note:
For motor start-up, this is the phase difference during start-up; for resistance welding machines, this is the phase difference of maximum welding power.

generation capacity factor k_G

ratio of the maximum possible installation power of all generating installations to a reference power of the network S_N

harmonic component (IEV 103-07-25)

sinusoidal component of the Fourier series of a periodic quantity, the harmonic order of which is an integer number greater than one

Note:
The fundamental frequency is the power frequency.
The harmonic of order 1 is usually referred to as the fundamental component.

impedance angle factor k_{XR}

factor related to the influence of the X/R ratio of the short-circuit impedance on the extrapolation accuracy of the frequency-dependent network impedance

impedance at ripple-control frequency Z_s

impedance of the customer installation at ripple-control frequency f_s

impedance factor ε

ratio of the impedance at ripple-control frequency Z_S to the installation impedance Z_A

installation current I_A

current derived from the agreed power S_A and the nominal voltage U_n or the declared supply voltage U_C of the customer installation

installation impedance Z_A

impedance derived from the agreed power S_A and the nominal voltage U_n or the declared supply voltage U_C of the customer installation

interharmonic component (IEV 103-07-27, modified)

sinusoidal component of the Fourier series of a periodic quantity the harmonic order of which is a non-integer rational number

Note:
The fundamental frequency is the power frequency.

load change (apparent power change) ΔS_A

apparent power change of a device or installation (active power and reactive power change) relevant for the assessment of network disturbances

maximum voltage change ΔU_{max}

difference between maximum and minimum value of the r.m.s. voltage within a voltage change characteristic or voltage fluctuation [EN 61000-3-3]

planning level

level of a particular disturbance in the MV, HV or EHV system adopted as a reference value for setting emission limits for customer installations and which is very likely not to be exceeded by the disturbance levels in the respective network

power quality

characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters [EN 61000-4-30]

Note:
Power quality distinguishes voltage quality and current quality.

reference power of the network S_N

sum of the rated powers of all transformers which connect the considered network to the upstream network (voltage level) during normal operation

relative rapid voltage change d

difference between the r.m.s. values of successive half-cycles of the supply voltage, related to the supply voltage before the event occurred

Note:
Measurements according to [IEC 61000-4-30] are based on a slightly different definition.

relative supply voltage variation d

difference between e.g. two 10 min average values of the supply voltage or difference of the supply voltages before and after a load variation, related to the supply voltage before the load variation

increase or decrease of the r.m.s. voltage normally due to variations of the total load in a distribution network or part of a distribution network

relative voltage deviation Δu

slow voltage change determined from the deviation of a 10 min average value of the supply voltage from the nominal voltage U_n or the declared supply voltage U_c related to the nominal voltage U_n or the declared supply voltage U_c [EN 50160]

repetition rate *r* of load or voltage change

number of voltage changes (frequency of occurrence) N within the observation period T, in minutes, which should usually cover 10 operating cycles of a device or at least 2 h

Note:
Ramp-shaped voltage change characteristics with a rise or fall time above 1 s are not considered when determining the repetition rate.

resonance factor k_h

ratio of the actual harmonic impedance Z_h to the impedance $h \cdot Z_{sc}$ which is approximated from the short-circuit impedance at the relevant point in the network (extrapolated impedance line)

Note:
Resonance factor and quality factor g are not identical.

sharing factor k_N

factor indicating the share of a network level in the compatibility level for a disturbance

Note:
The sharing factor k_N is dependent on location and disturbance phenomenon.

short-circuit impedance at point of common coupling $Z_{sc\ PCC}$

impedance at power frequency effective at the point of common coupling in case of a three-phase short circuit

Note:
The short-circuit impedance $Z_{sc\ PCC}$ is the total impedance of the network components in the shorted circuit without connected devices or installations. It is the basis for the assessment of voltage changes, flicker, unbalance, harmonic components and commutation notches of a customer installation.

short-circuit power S_{sc}

three-phase short-circuit power provided by the DSO which is relevant for the assessment of network disturbances

The calculation shall take into account the network configuration under normal operating conditions, which results in the minimum value.

short-circuit ratio R_{sc}

ratio of short-circuit power S_{sc} to agreed power of the customer installation S_A

starting current I_a (IEV 411-48-18)

steady-state r.m.s. current taken from the line over the starting period from zero speed to load speed with rated voltage and frequency applied

Note:
This is the maximum current taken from the motor, including any starting devices, during the start-up without considering transient processes. In case of motor start-up of asynchronous machines, this is between 3 and 8 times the rated current of the motor without additional starting support measures. The starting current is different from the locked-rotor current and is not a standardized term; it is often understood differently.

storage capacity factor k_S

ratio of the maximum possible installation power of all storage installations to the reference power of the network S_N

supply voltage (operating voltage) U

r.m.s. voltage at a given time, measured over a given interval

supraharmonic component

(higher frequency) emission in the frequency range from 2 kHz to 150 kHz

total harmonic distortion THD

ratio of the r.m.s. value of the sum of all harmonic components (U_h or I_h, respectively) up to a specified order to the r.m.s. value of the fundamental component (U_1 or I_1, respectively)
[IEC 61000-3-6]

THD can be specified for both voltage (THD_u) and current (THD_i).

Note:
According to [EN 61000-2-2], THD considers harmonic components for orders up to 50. In other standards (e.g. [EN 50160]), harmonic components for orders up to 40 are taken into account. The additional contribution of harmonic components with order 41 to 50 is small, except in case of resonance phenomena.

voltage at point of common coupling U_{PCC}

supply voltage to be used for the assessment of network disturbances at the point of common coupling PCC

Note:
For simplification purposes, in the planning stage the nominal voltage U_n or the declared supply voltage U_c of the network in which the PCC is located is commonly used for the voltage U_{PCC}.

voltage at point of connection U_{POC}

supply voltage to be used for the calculation of network disturbances at the point of connection POC

Note:
For simplification purposes, in the planning stage the nominal voltage U_n or the declared supply voltage U_c of the network in which the POC is located is commonly used for the voltage U_{POC}.

voltage change ΔU (IEV 161-08-01)

variation of the r.m.s. or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations

Note:
Whether r.m.s. or peak value is chosen depends upon the application, and which is used should be specified.
A distinction is made between slow and rapid voltage changes.

voltage change characteristic $\Delta U(t)$

time characteristic of the relative r.m.s. voltage change evaluated as a single value for each successive half-cycle between zero-crossings of the source voltage during time intervals in which the voltage is in a steady-state condition for at least 1 s [EN 61000-3-3]

Note:
Since this property is only used for assessments based on calculations, the voltage in steady state is assumed to be constant within the measurement accuracy.
For the purpose of this definition the supply voltage is the source voltage.

voltage fluctuation (IEV 161-08-05)

a series of voltage changes or a continuous variation of the r.m.s. or peak value of the voltage

Note:
Whether r.m.s. or peak value is chosen depends upon the application, and which is used should be specified.

voltage unbalance (IEV 161-08-09)

in a polyphase system, a condition in which the r.m.s. values of the phase voltages (fundamental component) or the phase angles between consecutive phases are not all equal

unbalance factor k

in a three-phase system, degree of unbalance expressed by the ratio of the r.m.s. values of the negative sequence component to the positive sequence component of the fundamental component of voltage or current

2. Introduction

2.1 Voltage quality

The quality of the supply voltage in three-phase systems is identified by the following characteristics

- magnitude,
- phase angle,
- frequency,
- waveform,
- symmetry,
- DC component,

expressed by a set of parameters or reference values, respectively. Deviations of these parameters from their ideal values quantifying the level of network disturbances, which can have adverse effects on other electrical appliances and installations connected to the network.

The following interferences must be distinguished:

- malfunction,
- functional failure,
- indirect or direct damages, including any consequential damages.

Examples for interferences are:

- brightness variations in lighting installations,
- interference of telecommunications, telecontrol and electronic data processing systems, protection and measurement equipment or consumer electronic devices,
- excessive heating of motors, capacitors, blocking circuits, blocking chokes or transformers, oscillating torques on machines,
- malfunctions of ripple-control installations and systems for mains signalling via network.

Interferences depend on

- the amplitude,
- the frequency of occurrence,
- the duration,

of these network disturbances taking into account temporal superpositions of these effects (simultaneity factors) and their local distribution.

The Technical Rules specify permissible values for the following quality parameters at the point of common coupling, which form the basis for the assessment of customer installations:

- Slow and rapid voltage changes,
- Flicker,
- Voltage unbalance,
- Harmonics,
- Interharmonics,
- Supraharmonics (Emission in the frequency range 2 kHz – 150 kHz),
- Commutation notches,
- Mains signalling voltages.

For DC components informative explanations including internationally recommended limit values are given.

2.2 Electromagnetic compatibility

An appliance or customer installation shall function as intended in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other appliances or customer installations. To ensure the ability to function satisfactorily, the compatibility level has been introduced in the relevant standards. It is defined for LV and MV networks and may only be exceeded with a low probability by the disturbance levels in the network.

The ambiguous term "satisfactorily" emphasizes the difficulty of making suitable specifications, be it in the legal, regulatory or normative area. However, such specifications are necessary to enable objective measurements and assessments in connection with product and service quality as well as product liability.

The Technical Rules cover electromagnetic compatibility in the field of conducted disturbances.

2.3 Coordination of electromagnetic compatibility

The compatibility level is used to coordinate immunity and emission and thus to ensure electromagnetic compatibility. The compatibility coordination is carried out in a probabilistic manner (Fig. 2-1). The Technical Rules exclusively concern the specification of emission limits.

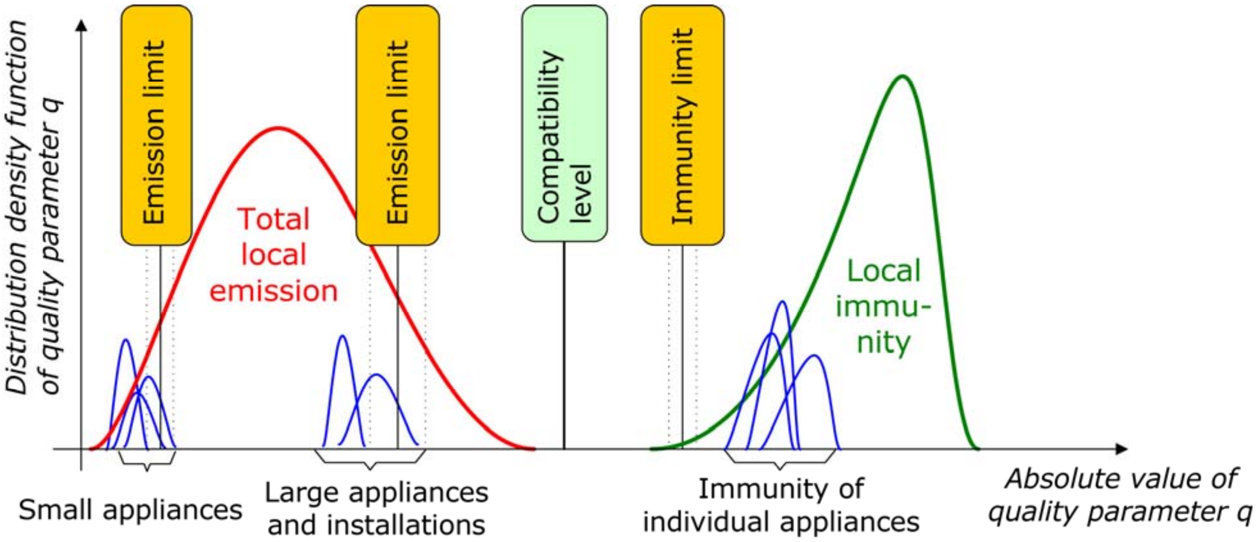


Fig. 2-1: Model of compatibility coordination

Compatibility coordination is intended to allocate emissions to the individual customer installations in such a way that it is unlikely that their cumulative effect exceeds the specified disturbance levels.

The disturbance level in a respective network level should not exceed the planning levels. The planning level in LV networks usually corresponds to the compatibility level. The level of the global contribution of an individual network level to the total emission shall be coordinated with the corresponding global contributions of all other network levels (Fig. 2-2). The global contributions do not correspond to the compatibility level or planning levels and shall be lower than these.

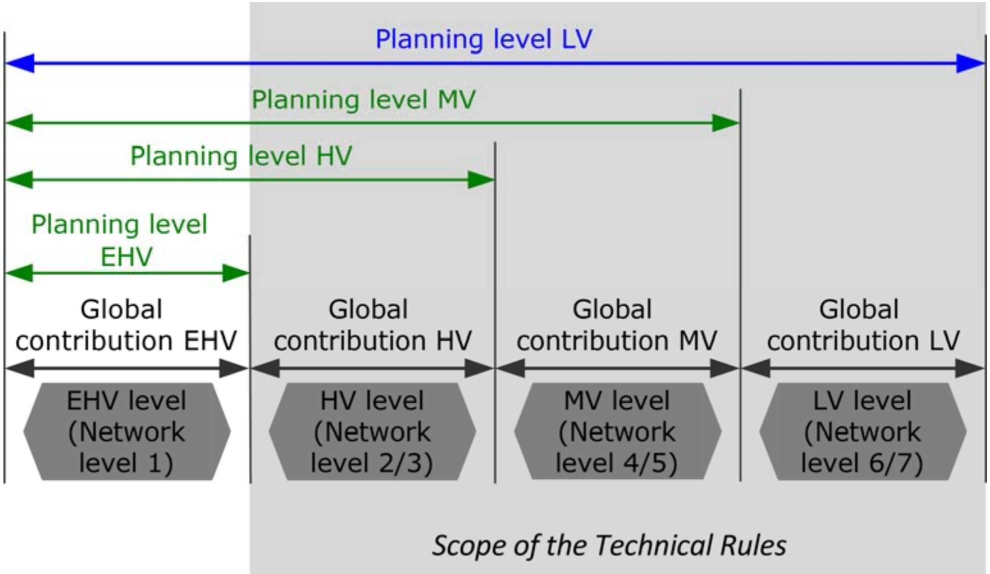


Fig. 2-2: Principle of coordination of the total emission between network levels

Within a network level, the determination of emission limits for the individual customer installations is based on a division of the global contribution of this network level proportional to its agreed power. **Thus, an individual customer installation may only claim a share of the global contribution.**

With regard to an appropriate division of the resulting responsibility for ensuring electromagnetic compatibility, the following aspects can be considered:

- appropriate planning and operational measures in the networks taking into account the objective quality requirements and economic viability,
- adapted specification of the requirements for the emission of electrical appliances and equipment in relevant EMC standards and compliance with them,
- stipulations by DSO for the implementation of technical measures to reduce network disturbances.

2.4 Scope

The Technical Rules are intended to define limit values for large appliances and customer installations subject to approval with an agreed power of more than 52 kVA. In the LV network, this corresponds to a rated current of an appliance or an installation current of 75 A. For appliances with a CE mark, electromagnetic compatibility is assumed due to the compliance with emission limits specified in respective standards required by the EMC Directive (Fig. 2-3). Therefore, it is not intended to assess these appliances or customer installations with a current lower than 75 A according to the Technical Rules. However, the DSO can require this under certain circumstances. In particular, an assessment is required in the event of an accumulation of similar appliances within a customer installation and for appliances without CE marking.

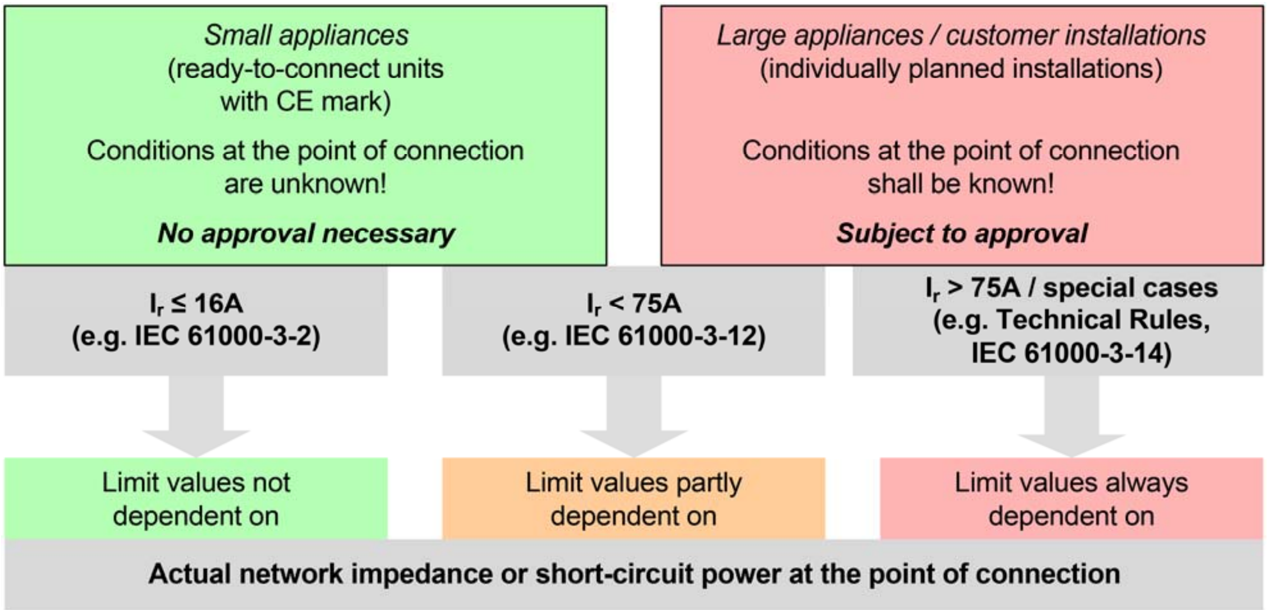


Fig. 2-3: Scope of the Technical Rules

The Technical Rules apply to the connection of customer installations to the LV, MV and HV network of a DSO. HV is limited in this Technical Rules to 110-kV-systems. They do only apply to systems with synchronous connection to an interconnected system, but not to islanded systems.

A customer installation can be a consuming installation, generating installation or storage installation. These are treated equally in terms of emission limits according to the principle of non-discrimination and simplest possible application.

For specific phenomena (e.g. voltage rise), generating and storage installations can have a different influence than consuming installations. If, due to physical-technical interactions, an individual approach to the assessment of a specific phenomenon is mandatory, this shall be taken into account correspondingly.

2.5 Location for calculation and assessment

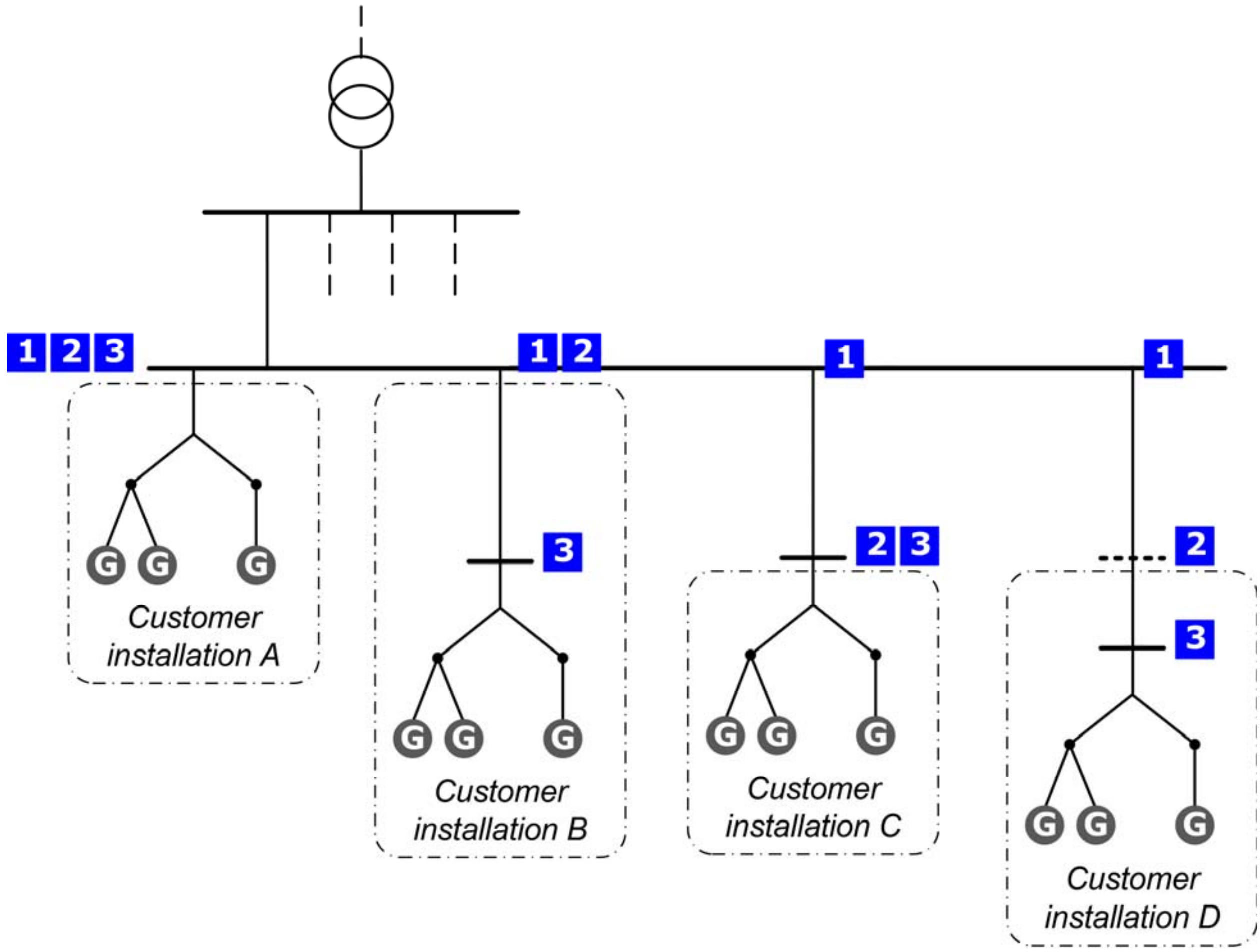
A distinction must be made between the locations point of connection (POC), point of common coupling (PCC) and point of supply (POS) (Fig. 2-4). It should be noted that in addition to the above-mentioned points, other locations such as the appliance connection point, the point of metering or the point of evaluation are defined in various standards and guidelines. They are not relevant to the aspects dealt with here and are therefore not discussed further.

The POC is of technical relevance. It is a location in a supply network where the customer installation is connected.

The PCC also is of technical relevance. It is a location in the network of the DSO to which a certain customer installation is electrically closest and to which other customers are also connected or can be connected. It is specified by the DSO.

The POS is of legal relevance. It is a location in an electrical network designated as such and contractually fixed, at which electric energy is exchanged between contractual partners (i.e. the customer and the DSO).

At the POC, the emission limits will be calculated. At the PCC, the network disturbances will be assessed. At the POS, the quality of electricity as a product will be assessed, among other things.



1 – Point of Common Coupling (PCC)
2 – Point of Supply (POS)
3 – Point of Connection (POC)
G – Appliance

The dot-dash line represents the property boundary.

Fig. 2-4: Possible arrangements of the locations

According to their definition, the POC and the PCC are relevant for the purposes of calculating emission limits and assessing a customer installation. As determined by the DSO, the PCC can also be the POS.

In many cases, the POC and the PCC practically coincide in terms of location (with regard to absolute value and angle of short-circuit power). If the POC and the PCC do not coincide, phenomena-specific conversions are necessary. These are described in the respective section.

2.6 Sign conventions

There are two different sign conventions called the load (consumer) convention and the generator convention. Both sign conventions can be applied to loads as well as generators.

In the Technical Rules, the load convention, as usually used for network calculations, is applied.

The voltage and current phasors on a network element point in the same direction. This results in the following relationships:

- An ohmic resistance absorbs active power (positive active power).
- An inductive reactance absorbs reactive power (inductive reactive power).
- A capacitive reactance supplies reactive power (capacitive reactive power).

In the load convention, an overexcited synchronous generator supplies (generates) active power and reactive power. Active and reactive power therefore have negative signs.

The angle φ (phase displacement between current and voltage) is obtained by moving counter-clockwise (mathematical positive direction) from the current phasor to the voltage phasor. Possible angular ranges for φ are shown in Fig. 2-5.

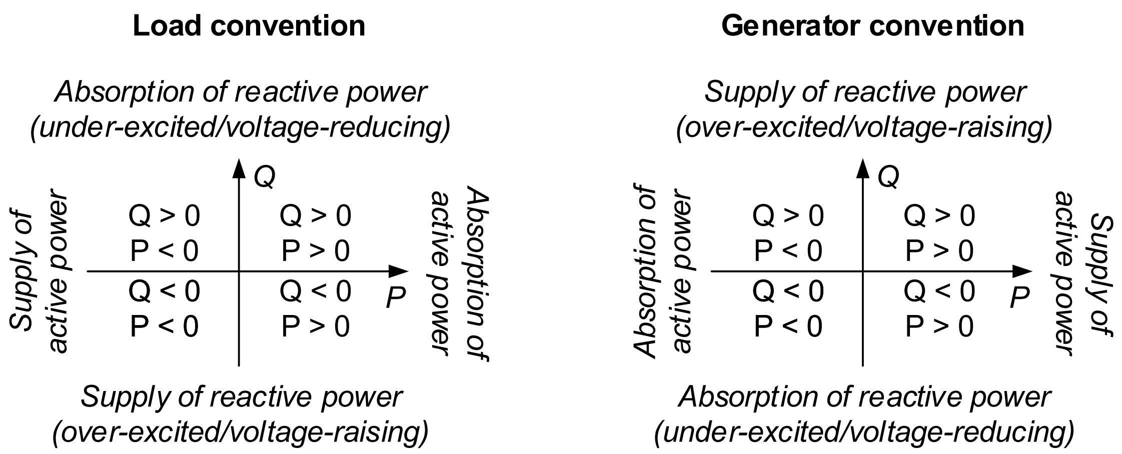


Fig. 2-5: Signs for active and reactive power

2.7 Assessment procedure

The assessment scheme follows a two stage approach (Fig. 2-6).

Stage 1 represents a simplified assessment based on a power ratio. If the assessment in stage 1 shows that the connection is not permitted, a detailed assessment must be carried out according to stage 2. This involves an assessment based on refined input data of the customer installation as well as the calculation of emission limits. If, according to the assessment in stage 2, only a conditional acceptance is possible, respective mitigation measures may be necessary.

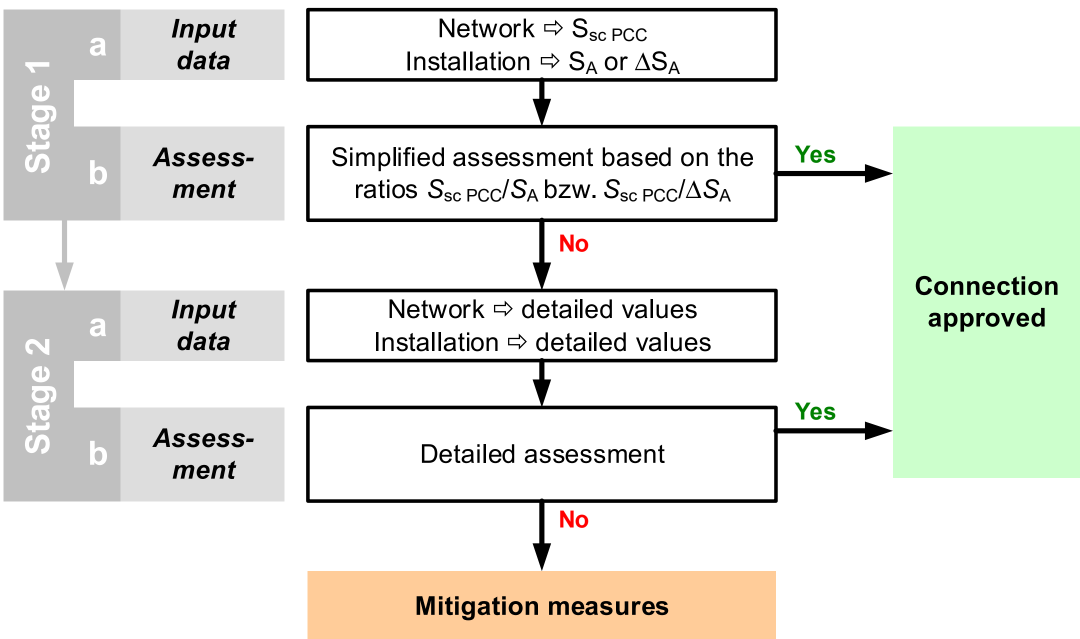


Fig. 2-6: Assessment scheme

The assessment procedure only represents a tool to estimate the need for mitigation measures in a simple way. Since numerous details relevant to network disturbances, such as emission of individual appliances and customer installations, interaction with other equipment and the network, performance and operating times are usually not known at the planning stage, a more exact result cannot generally be expected with a more elaborate calculation.

An assessment procedure that is intended to provide reasonable results that are not unnecessarily conservative, shall not be expected to ensure that every customer installation that has been found to be "approved" actually complies with the emission limits. It is therefore recommended that emission limits are always provided to the customer as part of the connection assessment. It cannot be ruled out that, in individual cases, the customer may still have to subsequently implement measures to reduce the network disturbances so that the emission limits are complied with.

Special situations, such as unusual customer and network configurations and accumulation of similar simultaneous operating appliances and installations, should be subject to a special study.

The assessment must be carried out individually for each disturbance phenomenon that can be expected from a customer installation. For motors with power electronic front end, for example, an individual assessment must be made for voltage changes and flicker as well as harmonics, interharmonics and supraharmonics.

2.8 Mitigation measures

In principle, a distinction is made between mitigation measures on the installation side and on the network side. Measures on the installation side depend on the disturbance phenomenon and are described in the corresponding section concerning the respective network disturbance.

Measures on the network side are, in most cases, independent of the disturbance phenomenon and concern the increase of the short-circuit power at the PCC. The following measures, among others, can be taken for this purpose:

- reduction of the effective line impedance from the transformer busbar to the PCC by adding parallel cables or replacing of cables with a higher cross-section;
- use of a transformer with lower short-circuit voltage or higher rated power (efficiency of the measure decreases with increasing distance of the PCC from the transformer busbar);
- relocation of the PCC in the direction of the transformer busbar;
- relocation of the PCC to the upstream network level.

For disturbance phenomena concerning higher frequencies (e.g. supraharmonics), the aforementioned measures on the network side may have little or practically no effect, since the effective impedance at higher frequencies is in most cases dominated by neighbouring customer installations or neighbouring appliances and not by the network.

If an emission limit for a disturbance phenomenon is specified as a current value (e.g. unbalance) during planning and this is exceeded during operation of the customer installation, it is recommended to assess the actual contribution of the customer installation to the corresponding voltage of the disturbance phenomenon before deciding on suitable measures. If, based on such an assessment, mitigation measures are deferred in their implementation, a periodic monitoring of the contribution is recommended, as the characteristics of the network and/or the customer installation can change over time.

2.9 Measurements

It is recommended to support the connection of the customer installation by associated measurements. The measurements should be carried out before and after the connection of the installation. All possible operating conditions of normal operation of the customer installation are to be taken into account. If the emission limits are exceeded during operation of the customer installation, a phenomena-specific assessment of the influence on the voltage is recommended before actual mitigation measures are agreed.

For measurements to verify compliance with specified emission limits, in principle, a power quality instrument complying with [IEC 61000-4-30] Class A shall be applied. If no measurement method is defined in [IEC 61000-4-30], it will be described in the corresponding section in Part A. The corresponding assessment of the measured values is also described there.

In LV networks, the phase-to-neutral voltages will be assessed. In MV and HV networks, the phase-to-phase voltages will be assessed, which may have to be derived from the phase-to-ground voltages.

2.10 Resonance behaviour

All distribution networks are resonant systems. The number, type and position of points of resonance are subject to a wide variety of influencing factors and can have significant impact on distortion levels in the distribution network. Resonances can be taken into account in the relevant assessment methods. However, this requires that the exact value of the frequency-dependent network impedance is known. For cases where this value is not known, guidance for its estimation is given in the Technical Rules.

2.11 Normative references

The assessment methods and limit values given in the Technical Rules are based on concepts regarding the probabilistic coordination of electromagnetic compatibility. This is described in the IEC 61000 standard series and refers to the PCC. Compatibility levels for public LV and MV distribution networks are defined in [EN 61000-2-2] and [EN 61000-2-12], respectively. Recommendations for planning levels for harmonics, flicker and unbalance are provided in the Technical Reports [IEC 61000-3-6], [IEC 61000-3-7] and [IEC 61000-3-13]. Emission limits for harmonics and voltage changes/flicker for individual appliances with a rated current up to 16 A or within the range of 16 A to 75 A are given in [EN 61000-3-2] or [EN 61000-3-3] as well as in [EN 61000-3-11] and [EN 61000-3-12]. Measurement methods are specified in [EN 61000-4-30] as well as in [EN 61000-4-7] and [EN 61000-4-15].

Other methods for calculating emission limits and assessing compliance of customer installations can be found in the IEC documents listed in Tab. 2-1. These documents have the status of Technical Reports (TR) and their application is therefore not mandatory. Hence, several other country-specific rules and guidelines exist with particular respect to the assessment of customer installations with higher agreed power.

Tab. 2-1: Overview of the IEC documents on the assessment of customer installations

<table>
<tr><th></th><th>Low voltage</th><th>Medium voltage</th><th>High voltage</th></tr>
<tr><td>Voltage fluctuations and flicker</td><td rowspan="3">IEC 61000-3-14
IEC 61000-3-15</td><td colspan="2">IEC 61000-3-7</td></tr>
<tr><td>Unbalance</td><td colspan="2">IEC 61000-3-13</td></tr>
<tr><td>Harmonics</td><td colspan="2">IEC 61000-3-6</td></tr>
</table>

Compatibility levels for the frequency range from 2 kHz to 150 kHz are defined in [EN 61000-2-2]. At the time of publication of these Technical Rules, emission limits were still under development.

[EN 50160] describes electricity as a product in terms of its quality at the POS. Therefore, it is not a basis for considerations on electromagnetic compatibility. If, however, the relevant standards and rules for electromagnetic compatibility are applied consistently, there is also a high probability of compliance with the reference values according to [EN 50160].

3. Short-circuit power

3.1 General

The short-circuit power represents the network impedance as seen from the relevant point in the network (short-circuit impedance). It is the calculation basis for the POC and the assessment basis for the PCC. Therefore, no specific location index is given in the following general equations.

The simplified procedure described in this section applies to radial, single-fed networks, such as those found primarily in LV and MV networks. This procedure is not applicable to meshed networks with one or multiple infeeds. For such situations, the short-circuit power is to be determined using network calculation packages.

When determining the short-circuit power, the normal operating conditions resulting in the minimum short-circuit power shall be assumed. Care shall be taken to select the switching state which represents the worst-case condition in normal operation, i.e. which results in the minimum short-circuit power. Special operational switching states are not taken into account.

Effects of connected devices and customer installations as well as shunt resistances and cable capacitances are neglected in the simplified procedure.

Within a customer installation, higher network disturbances can occur due to additional impedances (e.g. transformer(s), electric lines).

For the short-circuit power in three-phase systems, the following relationship applies for a relevant point in the network:

$$S_{sc} = \frac{U^2}{Z_{sc}} \tag{3-1}$$

where

S_{sc} *is the short-circuit power,*

U *is the phase-to-phase voltage,*

Z_{sc} *is the short-circuit impedance of the network.*

The short-circuit impedance primarily results from the impedances of the electric lines in the considered voltage level and the supply transformer. The impact of the impedances of the network elements of the upstream network is usually low, but may not be negligible.

3.2 Determination of impedances

3.2.1 Impedance of the upstream network

The impedance of the upstream network Z_{UN} is determined from the short-circuit power $S_{sc\ UN}$.

$$Z_{UN} = \frac{U_{UN}^2}{S_{sc\ UN}} \tag{3-2}$$

where

Z_{UN}	*is the impedance of the upstream network,*
U_{UN}	*is the phase-to-phase voltage in the upstream network,*
$S_{sc\ UN}$	*is the short-circuit power of the upstream network.*

For HV and EHV networks, the ohmic component of the impedance of the upstream network can be neglected, since the impedance angle is usually between 75° and 85°.

$$R_{UN} \approx 0$$

$$X_{UN} \approx Z_{UN}$$

Otherwise, the impedance components can be determined from the impedance angle of the network.

$$R_{UN} = Z_{UN} \cdot \cos(\psi_{UN}) \tag{3-3}$$

$$X_{UN} = Z_{UN} \cdot \sin(\psi_{UN}) \tag{3-4}$$

For a given X/R ratio, the impedance angle of the network is calculated using the following equation:

$$\psi_{UN} = \arctan\left(\frac{X_{UN}}{R_{UN}}\right) \tag{3-5}$$

where

R_{UN}	*is the resistance of the upstream network,*
X_{UN}	*is the reactance of the upstream network,*
ψ_{UN}	*is the impedance angle of the upstream network.*

3.2.2 Transformer impedance

R_T and X_T can be determined from the rating data of the transformer.

$$R_T = u_r \cdot \frac{U_{rT}^2}{S_{rT}} \tag{3-6}$$

$$X_T = u_x \cdot \frac{U_{rT}^2}{S_{rT}} \tag{3-7}$$

where

R_T	*is the resistance of the transformer on the low-voltage side,*
X_T	*is the reactance of the transformer on the low-voltage side,*
$U_{r\ T}$	*is the rated voltage of the transformer on the low-voltage side,*
$S_{r\ T}$	*is the rated apparent power of the transformer,*
u_r	*is the resistive component of the relative short-circuit voltage u_{sc},*
u_x	*is the reactive component of the relative short-circuit voltage u_{sc}.*

For u_r and u_x the following equations apply:

$$u_r = \frac{P_{sc}}{S_{rT}} \quad (3\text{-}8)$$

$$u_x = \sqrt{u_{sc}^2 - u_r^2} \quad (3\text{-}9)$$

where

P_{sc}	*are the short-circuit losses of the transformer,*
u_{sc}	*is the relative short-circuit voltage.*

3.2.3 Line impedance

If the values for length-related resistance and reactance are provided by the manufacturer, R_L and X_L are calculated using the following equations:

$$R_L = R_L' \cdot \ell \quad (3\text{-}10)$$

$$X_L = X_L' \cdot \ell \quad (3\text{-}11)$$

where

R_L	*is the resistance of the line,*
R'_L	*is the length-related resistance of the line,*
X_L	*is the reactance of the line,*
X'_L	*is the length-related reactance of the line,*
ℓ	*is the effective length of the line.*

The length-related resistance can be determined from geometric data.

$$R_L' = \frac{\rho}{A} \quad (3\text{-}12)$$

where

R'_L	*is the length-related resistance of the line,*
ρ	*is the resistivity of the line at 20 °C,*
	for copper ρ = 19 $\Omega mm^2/km$,
	for aluminium ρ = 29 $\Omega mm^2/km$,
A	*is the effective cross-section of the line.*

All the resistance values given above apply at a temperature of 20 °C. The resistance of the conductor material increases with temperature. This relationship can be taken into account in the calculations for aluminium and copper conductors with a temperature correction factor of 4 % per 10 K. The line impedances are determined at 70 °C.

3.3 Short-circuit impedance at the relevant point in the network

To calculate the resulting short-circuit impedance Z_{sc} at the relevant point in the network, the impedance components of all network elements shall be converted to the voltage at this relevant point.

This conversion is calculated by dividing the impedance components of each network element by the squared transformation ratios of all transformers which are located between the respective network element and the relevant point in the network.

The converted impedance components of a network element m are calculated using the following equations:

$$R_{m\text{con}} = R_m \cdot \frac{1}{K_{\text{T1}}^2} \cdot \frac{1}{K_{\text{T2}}^2} \cdot \ldots \cdot \frac{1}{K_{\text{T}n}^2} \tag{3-13}$$

$$X_{m\text{con}} = X_m \cdot \frac{1}{K_{\text{T1}}^2} \cdot \frac{1}{K_{\text{T2}}^2} \cdot \ldots \cdot \frac{1}{K_{\text{T}n}^2} \tag{3-14}$$

$$K_{\text{T}i} = \frac{U_{\text{r T}i\,\text{HV}}}{U_{\text{r T}i\,\text{LV}}} \tag{3-15}$$

where

$R_{m\,con}$	*is the converted resistance of the network element m,*
R_m	*is the resistance of the network element m,*
$X_{m\,con}$	*is the converted reactance of the network element m,*
X_m	*is the reactance of the network element m,*
$K_{T\,i}$	*is the transformation ratio of transformer i (i = 1 to n),*
$U_{r\,T\,i\,HV}$	*is the rated voltage on the high-voltage side of transformer i,*
$U_{r\,T\,i\,LV}$	*is the rated voltage on the low-voltage side of transformer i,*
m	*is the network element:*
	UN upstream network,
	T transformer,
	L line.

For estimations or in case of small deviations of the transformation ratios of the transformers from the ratios based on the voltage levels, the conversion can be calculated by dividing the impedance components of the network element m by the squared transformation ratio of its voltage level U_{m} to the voltage level U at the relevant point in the network. Thus, the converted impedance components of a network element m are simplified as follows:

$$R_{m\,\text{con}} = R_m \left(\frac{U}{U_m} \right)^2 \tag{3-16}$$

$$X_{m\,\text{con}} = X_m \left(\frac{U}{U_m} \right)^2 \tag{3-17}$$

where

$R_{m\,con}$	*is the converted resistance of the network element m,*
R_m	*is the resistance of the network element m,*
$X_{m\,con}$	*is the converted reactance of the network element m,*
X_m	*is the reactance of the network element m,*
U_m	*is the declared phase-to-phase supply voltage of the network element m,*
U	*is the declared phase-to-phase supply voltage or the nominal voltage at the relevant point in the network,*
m	*is the network element:*
	UN upstream network,
	T transformer,
	L line.

The converted impedance components m = 1 .. M have to be added and the resulting short-circuit impedance Z_{sc} is calculated as follows:

$$Z_{sc} = \sqrt{\left(\sum_m R_{m\ con}\right)^2 + \left(\sum_m X_{m\ con}\right)^2} = \sqrt{R_{sc}^2 + X_{sc}^2} \quad (3\text{-}18)$$

$$\psi_{sc} = \arctan\frac{X_{sc}}{R_{sc}} \quad (3\text{-}19)$$

$$Z_{sc} = R_{sc} + jX_{sc} = Z_{sc}\cdot e^{j\psi_{sc}} = Z_{sc}\cdot\cos\psi_{sc} + jZ_{sc}\cdot\sin\psi_{sc} \quad (3\text{-}20)$$

where

R_{sc} *is the resulting network resistance,*

X_{sc} *is the resulting network reactance,*

Z_{sc} *is the resulting absolute value of network impedance (short-circuit impedance),*

ψ_{sc} *is the resulting network impedance angle (short-circuit impedance).*

If the relevant point in the network is located in the LV network, it is often sufficient to combine the impedances of all network elements upstream to the MV/LV transformer and to determine estimated values with the transformation ratio according to equation (3-16) or (3-17) at a conductor temperature of 70 °C.

In LV networks, the short-circuit power can be determined in a simplified manner from the rated power and the short-circuit voltage of the MV/LV transformer as well as from the impedance of the lines between the LV side of the MV/LV transformer and the relevant point in the network according to the nomogram in Annex A.

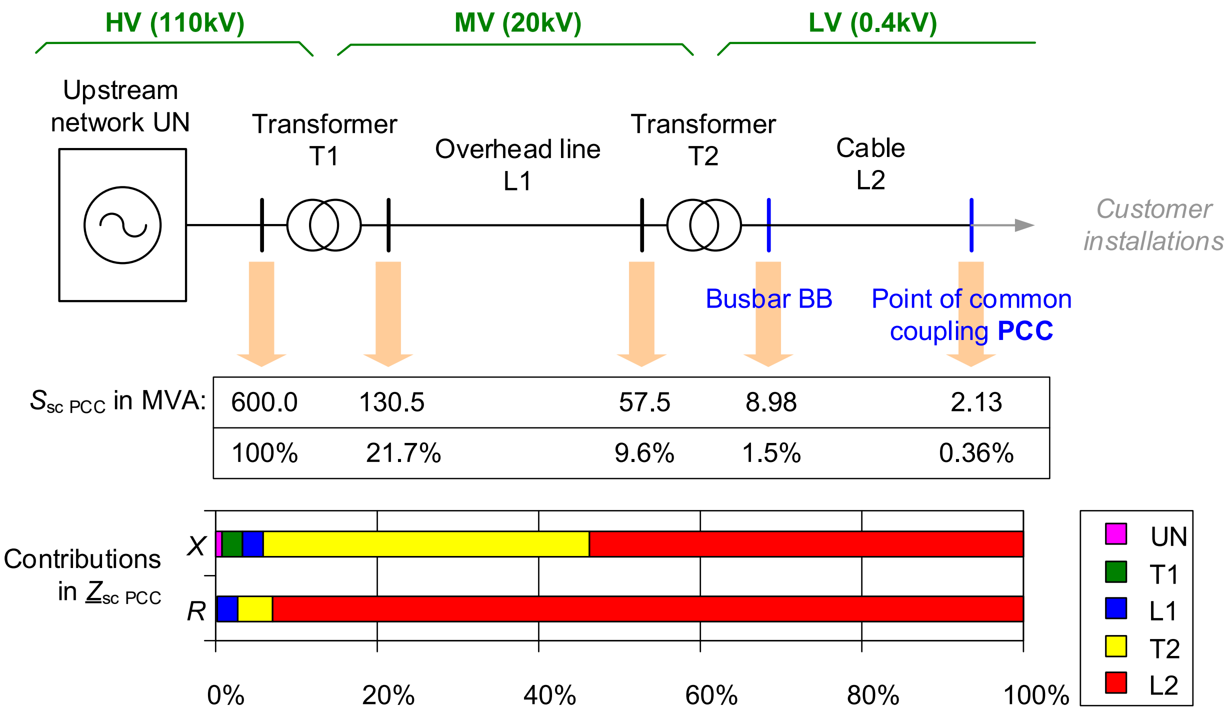


Fig. 3-1: Range of the short-circuit powers und contribution of the individual network elements

Fig. 3-1 shows the contributions of the impedances of the network elements as seen from a point in the LV network (PCC of the customer installation). It is obvious that the short-circuit impedance on the low-voltage side of the MV/LV transformer is essentially determined by the short-circuit voltage u_{sc} of the transformer. The transformer impedance can account for up to 95 % of the total short-circuit impedance and the impedance is inductive. If the relevant point in the network is located at a distance of 200 m or more from the transformer substation, the short-circuit impedance is mainly due to the impedance of the LV line. The contribution of the line impedance to the total short-circuit impedance can exceed 80 % for these lengths of the lines. Due to the high resistive component, the angle of short-circuit impedance will then be relatively small.

In several European countries, the short-circuit impedance at the PCC was measured and statistically analysed. In the individual countries, a reference impedance was determined from the 95 % quantiles of the measured values and has been specified in [IEC 60725]:

$R_P = 0.24\ \Omega$ $X_P = 0.15\ \Omega$ (for phase conductors)

$R_N = 0.16\ \Omega$ $X_N = 0.10\ \Omega$ (for neutral conductors)

The short-circuit power under reference conditions is 565 kVA. The angle of the short-circuit impedance is 32°. Thus, in public LV networks, the short-circuit power at the PCC generally exceeds 565 kVA.

4. Voltage changes and flicker

In this section, the term "load" is used for consuming, generating and storage installations. The voltage change can result in an increased or a decreased voltage.

4.1 Voltage changes

Every change of state in the network (load change, switching operation) results in a transient phenomenon. This causes current and voltage changes. Depending on the type and duration of the voltage change characteristic, a distinction is made between slow, rapid and (high-frequency) oscillating changes. These transient oscillations, which usually cause overvoltages, are not considered in the assessment.

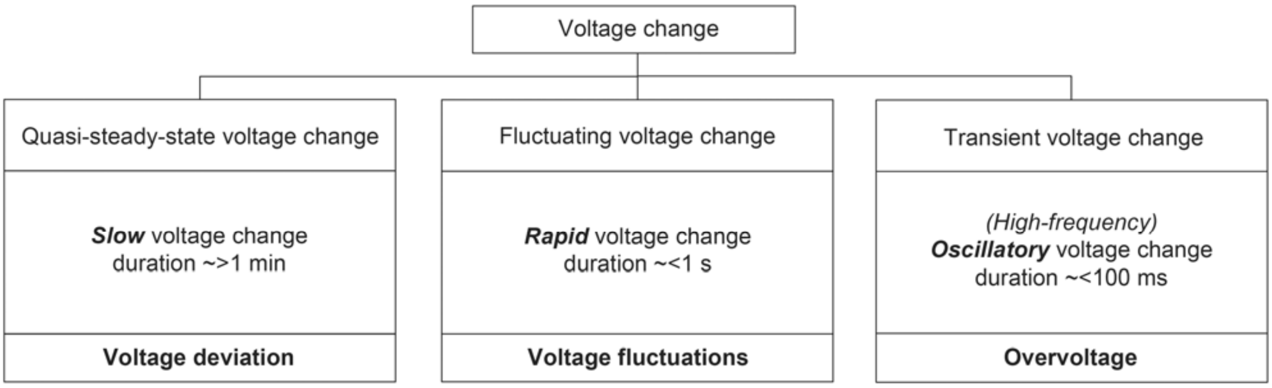


Fig. 4-1: Classification of voltage changes

All load changes result in a current change in the supply voltage and consequently in a voltage change ΔU.

Voltage changes can be caused e.g. by

- switching on high-power loads, e.g. motors, transformers, capacitors,
- high-power motors in load cycling mode,
- controlled loads (multicycle control, thermostat control, etc.),
- welding machines,
- variable generating units (e.g. wind turbine generator systems),
- electric furnaces,
- On-load-tap-changer (OLTC) transformers.

To prevent the interference of appliances and to avoid annoying flicker, voltage changes shall be limited.

Slow voltage changes are caused by the operating current of an installation. The sum of all slow voltage changes in a network represents a voltage profile. 10min average values of the r.m.s. voltage are to be used [EN 61000-4-30].

The voltage change in relation to the nominal voltage U_n or the declared supply voltage U_c or the voltage U_{PCC} at the PCC or the voltage U_{POC} at the POC is defined as "relative voltage change". The relative slow voltage change between two 10 min average values is calculated using equations (4-1) to (4-16) and for LV networks using additionally equation (4-17). If an equipment or customer installation is operated at rated power or agreed power respectively, replace ΔS_A by S_A to calculate the relative slow voltage change in equations (4-1) to (4-16) and also in equation (4-17) for LV networks. The angle φ of the load change (change of apparent power) corresponds to the phase angle φ_n under nominal operating conditions.

In practice, the relative deviation from a fixed voltage value (e.g. nominal voltage) Δu is also used for calculation (voltage deviation).

The **rapid voltage change** ΔU is to be measured as the difference of the r.m.s. values of successive half-cycles. The relative voltage change d refers to the supply voltage U before an event occurred. The voltage change characteristic results from the sequence of the individual half-cycle r.m.s. values of the supply voltage.

The interval between the end of a voltage change characteristic and the beginning of the next voltage change characteristic, in which the supply voltage is constant within a tolerance range, shall be at least 1 s. For the definition of the tolerance range, see [EN 61000-4-15, EN 61000-4-30].

The maximum voltage change ΔU_{max} is determined from the voltage fluctuation of successive voltage changes/voltage change characteristics or a periodic change of the envelope of the voltage curve. It is determined from the difference between the maximum and the minimum value of the r.m.s voltage within a voltage change characteristic.

The relative rapid voltage change d is calculated for balanced and unbalanced load changes (change of apparent power) using equations (4-1) to (4-16) and also using equation (4-17) for LV networks. The angle φ of the load change (change of apparent power) corresponds to the flicker-related phase angle φ_{f}.

The relative voltage change can be determined using complex calculations. If only the longitudinal voltage drop is considered, simple equations result. The resulting error can generally be neglected in the calculation of voltage changes. Only the equations for calculating approximate values are given below. They apply to both slow and rapid voltage changes.

For the purpose of this guideline, voltage changes that result in a voltage reduction are given a positive sign.

Using the following equations, the voltage changes at the POC can be calculated. If the PCC differs from the POC, the voltage changes shall be converted to the PCC according to Section 4.3 (upstream transfer).

4.1.1 Balanced load change

In the case of balanced load changes, all voltages of the three-phase system are subject to the same relative voltage change.

Absolute value of the voltage change:

$$\begin{aligned}\Delta U_{\text{POC}} &\approx \Delta U_{\text{longitudinal POC}} \\ &= \Delta I\left(R_{\text{sc POC}} \cdot \cos\varphi \mp X_{\text{sc POC}} \cdot \sin\varphi\right) \\ &= \frac{\Delta P_{\text{A}}}{U_{\text{POC}}} \cdot R_{\text{sc POC}} \mp \frac{\Delta Q_{\text{A}}}{U_{\text{POC}}} \cdot X_{\text{sc POC}}\end{aligned} \tag{4-1}$$

Relative voltage change:

$$d_{\text{POC}} = \frac{\Delta U_{\text{POC}}}{U_{\text{POC}}} \approx \frac{\Delta P_{\text{A}}}{U_{\text{POC}}^2} \cdot R_{\text{sc POC}} \mp \frac{\Delta Q_{\text{A}}}{U_{\text{AP}}^2} \cdot X_{\text{sc POC}} \tag{4-2}$$

negative sign: underexcited generator operation, resistive-capacitive load
positive sign: overexcited generator operation, resistive-inductive load

Using another notation:

$$d_{\text{POC}} = \frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}} \cdot \cos\left(\psi_{\text{sc POC}} \pm \varphi\right) \tag{4-3}$$

$$\psi_{\text{sc POC}} = \arctan\left(\frac{X_{\text{sc POC}}}{R_{\text{sc POC}}}\right) \tag{4-4}$$

positive sign: underexcited generator operation, resistive-capacitive load
negative sign: overexcited generator operation, resistive-inductive load

where

φ	*is the angle of the load change,*
d_{POC}	*is the relative voltage change,*
ΔU_{POC}	*is the voltage change,*
U_{POC}	*is the phase-to-phase voltage,*
ΔS_A	*is the load change (change of apparent power),*
$S_{sc\ POC}$	*is the short-circuit power,*
$\psi_{sc\ POC}$	*is the network impedance angle,*
ΔP_A	*is the change of the active power,*
ΔQ_A	*is the change of the reactive power,*
$X_{sc\ POC}$	*is the reactance of the network,*
$R_{sc\ POC}$	*is the resistance of the network.*

Note:
In the following explanations, the term "cos ($\psi_{sc\ POC}$ ± φ)" is abbreviated as "cos-term". If the angle of load change is unknown or the load angle is not defined, the "cos-term" shall be set to 1.

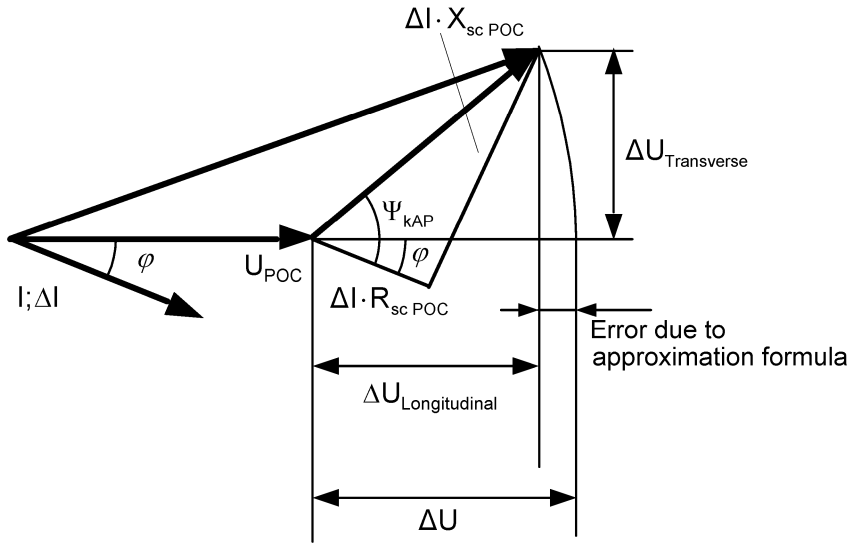


Fig. 4-2: Phasor diagram of the longitudinal and transverse voltage change due to a balanced load change

4.1.2 Unbalanced load change

A distinction is made between the connection between two phase conductors and the connection between phase conductor and neutral conductor in LV networks. The following equations apply to three-phase loads in partial load operation, if applicable. The maximum relative voltage change d_{max} depends on the type of load connection, e.g. balanced three-phase, two-phase or single-phase connection.

4.1.2.1 Load connected between two phase conductors

The following equations apply for a load connected between L1 and L2. If the load is connected between two other phase conductors, then the indices are to be swapped cyclically.

Relative voltage changes between two phase conductors:

$$d_{\text{L1-L2 POC}} = 2\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi\right) \tag{4-5}$$

$$d_{\text{L2-L3 POC}} = \frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi - 60^{0}\right) \tag{4-6}$$

$$d_{\text{L3-L1 POC}} = \frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi + 60^{0}\right) \tag{4-7}$$

Relative voltage changes between phase conductor and neutral conductor:

$$d_{\text{L1-N POC}} = \sqrt{3}\,\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi + 30^{0}\right) \tag{4-8}$$

$$d_{\text{L2-N POC}} = \sqrt{3}\,\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi - 30^{0}\right) \tag{4-9}$$

$$d_{\text{L3-N POC}} = 0 \tag{4-10}$$

positive sign: underexcited generator operation, resistive-capacitive load
negative sign: overexcited generator operation, resistive-inductive load

where

φ	*is the angle of the load change,*
d_{POC}	*is the relative voltage change,*
ΔS_A	*is the load change (change of the apparent power),*
$S_{sc\ POC}$	*is the short-circuit power,*
$\psi_{sc\ POC}$	*is the network impedance angle.*

When using three-phase transformers, equations (4-8) to (4-10) apply to the voltage change on the low voltage side and equations (4-11) to (4-16) apply to the voltage change on the high voltage side with the load connected on the low voltage side.

Star-star connection with index 0 (Yy0):

$$d_{\text{L1-L2 POC}} = 2\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi\right) \tag{4-11}$$

$$d_{\text{L2-L3 POC}} = \frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi - 60^{0}\right) \tag{4-12}$$

$$d_{\text{L3-L1 POC}} = \frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi + 60^{0}\right) \tag{4-13}$$

Delta-star connection or star-interconnected star connection with index 5 or 11 (e.g. Dy5 or Yz5):

$$d_{\text{L1-L2 POC}} = \sqrt{3}\,\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi + 30^{0}\right) \tag{4-14}$$

$$d_{\text{L2-L3 POC}} = \sqrt{3}\,\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi - 30^{0}\right) \tag{4-15}$$

$$d_{\text{L3-L1 POC}} = 0 \tag{4-16}$$

positive sign: underexcited generator operation, resistive-capacitive load
negative sign: overexcited generator operation, resistive-inductive load
where

φ	*is the angle of the load change,*
d_{POC}	*is the relative voltage change,*
ΔS_A	*is the load change (change of the apparent power),*
$S_{sc\ POC}$	*is the short-circuit power,*
$\psi_{sc\ POC}$	*is the network impedance angle.*

If necessary, the voltage changes that have been calculated by using the abovementioned equations shall be converted to the PCC by means of equation (4-38).

4.1.2.2 Load connected between phase conductor and neutral conductor (LV)

$$d_{\text{POC}} = 3\left(1+\alpha\right)\frac{\Delta S_{\text{A}}}{S_{\text{sc POC}}}\cos\left(\psi_{\text{sc POC}} \pm \varphi\right) \tag{4-17}$$

positive sign: underexcited generator operation, resistive-capacitive load
negative sign: overexcited generator operation, resistive-inductive load
where

φ	*is the angle of the load change,*
d_{POC}	*is the relative voltage change,*
ΔS_A	*is the load change (change of the apparent power),*
$S_{sc\ POC}$	*is the short-circuit power,*
$\psi_{sc\ POC}$	*is the network impedance angle,*
α	*is the ratio $Z_{neutral\ conductor} / Z_{phase\ conductor}$.*

Note:
($Z_{neutral\ conductor} = Z_{phase\ conductor}$) is assumed if the phase conductor and the neutral conductor have identical cross-sections and the impact of parallel earth return pathes of the neutral conductor on the impedance of the neutral conductor are low.
For the reference impedance according to IEC 60725, α is 0.6.
Where the load angle is unknown, the cos-term shall be set to 1.
In addition, generated active and/or reactive power results in a voltage change in the network. Some drive systems (e.g. in lift and cable car systems, CNC machines, cranes) feed power back into the network during regenerative braking (recuperation) and shall therefore also be taken into account when considering the voltage change in the network. It is recommended to request a respective statement from the customer.

4.1.3 Determination of specific load changes

4.1.3.1 Asynchronous machine

The relative rapid voltage change of asynchronous machines is calculated using equation (4-18). The applicable parameters for the relevant load condition are to be used. For the start-up, these are the apparent power and the phase angle during start-up operation; for load changes during operation, the operational load change and the phase angle at the nominal operating point are to be used. The applicable values can be requested from the manufacturer.

$$\Delta S_A = \sqrt{3} \cdot I_a \cdot U_r = \sqrt{3} \cdot k_i \cdot I_r \cdot U_r \tag{4-18}$$

where

I_a	*is the starting peak current,*
I_r	*is the rated motor current,*
U_r	*is the rated motor voltage,*
ΔS_A	*is the flicker-related load change (change of apparent power),*
k_i	*is the starting current ratio, also referred to as switched current factor.*

Tab. 4-1: Switched current factor

	$k_i = I_a / I_r$
Direct-on-line starting of the motor	5 .. 9
Star-delta starting of the motor	~ 3
Forced star-delta starting (crane-switch)	~ 4
Soft-start of the motor	3.5 .. 4.5
Frequency converter of the motor	1.2 .. 1.5
Generator start-up at 95 % to 105 % of the nominal speed	3 .. 5

Indicative values for the starting phase angle (angle of the load change) φ_s are in the range between 50° and 80°.

In case of star-delta starting, the load change ΔS_A shall be taken into account when changed over to delta connection. For starting with starting current limiter, the actual, reduced starting current shall be used.

If an asynchronous machine is connected without starting current limiter and with locked rotor, the starting current equals the locked-rotor current. To reduce the change of the apparent power ΔS_A, possible starting current limiters shall be provided depending on the machine power, if necessary.

The flicker-related phase angle during start-up can be calculated from the equivalent circuit diagram of the motor or requested from the manufacturer.

4.1.3.2 Welding machines

The change of apparent power ΔS_A during the maximum welding power and the repetition rate r (frequency of welding pulses per minute) as well as the welding current pulse pattern are essential parameters for the flicker assessment of resistance welding machines (resistance spot, projection, butt and seam welding). The maximum welding power and the displacement factor at the maximum welding power shall be requested from the manufacturer. If required, tests shall be performed. Usually, the rated power is considerably lower than the maximum welding power.

The welding current of arc welding equipment generally shows rectangular pulses and depends on the welding process and electrode parameters. The maximum change of apparent power $\Delta S_{A\,max}$ can be determined by testing.

4.2 Flicker

Flicker is a subjective impression of the unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Luminance changes are caused by:

- voltage fluctuations,
- interharmonics,
- phase jumps.

The basic tests for preparing an assessment method were performed with periodic voltage fluctuations on the 220 V/60 W incandescent lamp. The representation as amplitude-modulated time function in the frequency domain shows interharmonics. Hence, voltage interharmonics in the frequency range up to 100 Hz cause luminance changes, i.e. flicker. State-of-the-art light sources (LEDs, energy-saving lamps, fluorescent lamps, dimmed incandescent lamps, etc.) show a non-linear U-I characteristic. As a result, additional flicker-related sideband frequencies occur in addition to existing interharmonics and harmonics. Therefore, state-of-the-art types of light sources also respond to interharmonics above 100 Hz.

4.2.1 Determination of the flicker severity

The flicker is measured as the flicker severity which defines the flicker annoyance and is determined with the flickermeter [EN 61000-4-15].

A distinction is made between the short-term flicker severity P_{st} measured over an interval of 10 min and the long-term flicker severity P_{lt} measured over an interval of 2 h. For a flicker severity of $P_{st} \geq 1$, the luminance fluctuations caused by voltage fluctuations, interharmonics and phase jumps are perceived as annoying by 50 % of the subjects.

The flickermeter is based on a simulation of the lamp characteristics of a 60 W standard incandescent lamp as well as on eye sensitivity and brain response. The assessment method of flicker annoyance remains the same despite different types and usages of lighting sources. The objective of limiting the luminance changes due to various disturbances (voltage fluctuations, interharmonics, phase jumps) to levels induced in a 230 V/60 W incandescent lamp is achieved if no light source produces higher luminance changes than the reference incandescent lamp for any disturbances.

The DSOs define planning levels for the individual network levels in order to be able to coordinate emissions reliably. The planning levels are defined depending on the network configuration and the type of the network loads, among other things.

The amplitude of the flicker severity (99 % values) throughout the network should not exceed the planning levels. The emission limits are determined on the basis of the planning levels, taking into account common transfer coefficients.

The flicker severity can be determined using different methods:

- measurement with a flickermeter,
- determination by means of the reference curve,
- simulation,
- analytical method,
- virtual transfer of the POC of a customer installation.

4.2.1.1 Determination of the flicker severity of voltage fluctuations

The flicker severity is determined using the methods indicated in Section 4.2.1. At the planning stage, only calculation methods can be used. These are described in this section. The equations apply for any point in the network. When assessing the connection of a customer installation, a distinction must be made between the POC and the PCC.

Determination by means of the reference curve

In the case of repetitive rectangular voltage changes, the flicker severity of an individual appliance of the customer can be determined as follows using the flicker limiting curve for $P_{st\,ref} = 1$ according to Fig. 4-3 and Fig. 4-4 (reference curve) [2].

Short-term flicker severity at a given repetition rate r_i:

$$P_{st\,i} = \frac{d_i}{d_{ref}} P_{st\,ref} \tag{4-19}$$

Long-term flicker severity:

$$P_{lt\,i} = \sqrt[3]{\sum_{n=1}^{12} \frac{P_{st\,i\,n}^{\;3}}{12}} \tag{4-20}$$

where

d_i	*is the relative voltage change,*
d_{ref}	*is the relative voltage change according to the flicker limiting curve ($P_{st\,ref} = 1$),*
$P_{st\,i}$	*is the short-term flicker severity,*
$P_{st\,ref}$	*is the limiting value of flicker severity,*
$P_{lt\,i}$	*is the long-term flicker severity ($P_{lt\,ref} = 0{,}65$),*
i	*is the index for individual appliances or customer installations,*
n	*is the index of 10 min values within 2 h intervals.*

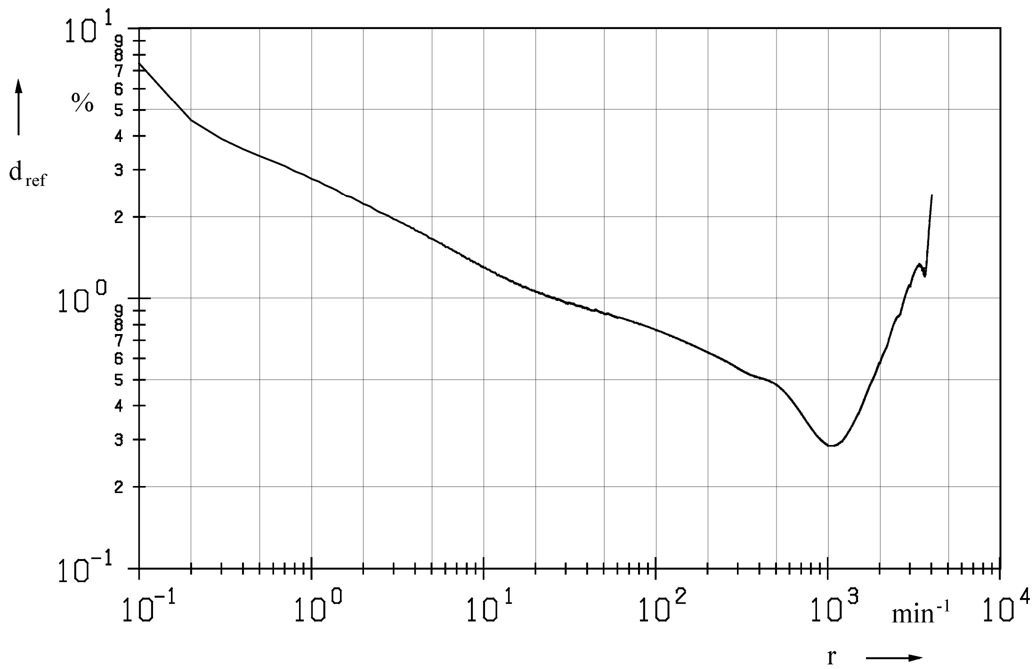


Fig. 4-3: Reference curve for $P_{st} = 1$ up to $f_F = 33$ Hz ($r = 4\,000$ min^{-1}) for rectangular voltage fluctuations [2]

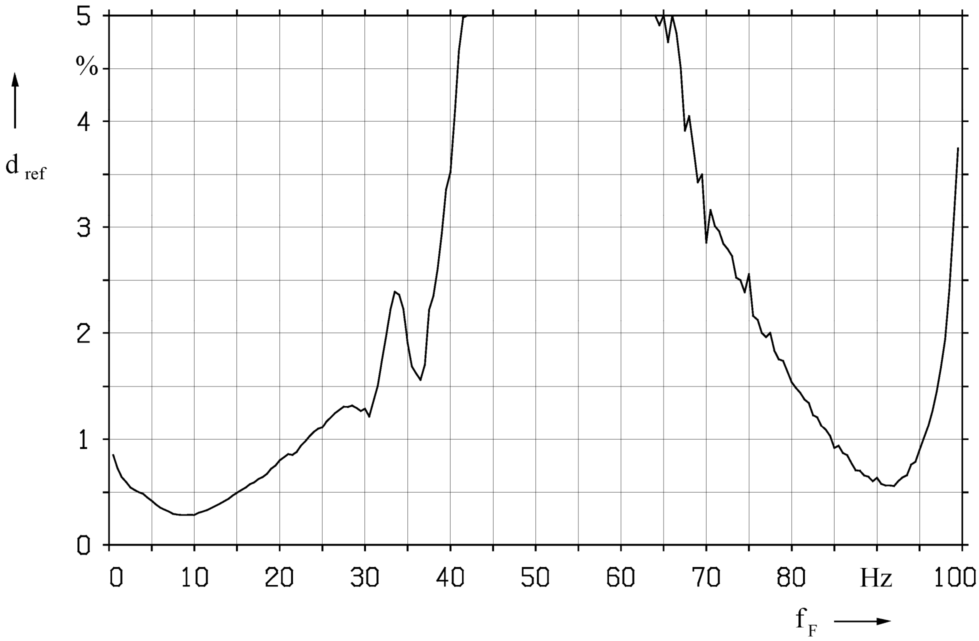


Fig. 4-4: Reference curve for P_{st} = 1 up to f_F = 100 Hz (r = 12 000 min^{-1}) for rectangular voltage fluctuations [2]

Using the following equation, the repetition rate r/min^{-1} is converted into the flicker frequency f_F/Hz:

$$f_F/\text{Hz} = \frac{r/\text{min}^{-1}}{120} \qquad (4\text{-}21)$$

Analytical method

As an approximation, the flicker severity can be calculated for given waveforms of the voltage change characteristic using the analytical method. The flicker severity is calculated using the following equation:

$$P_{st} = 0.365 \cdot F \cdot R \cdot |d/\%| \cdot \sqrt[3.2]{r/\text{min}^{-1}} \qquad (4\text{-}22)$$

where

d	*is the relative voltage change in %,*
F	*is the shape factor (Fig. 4-6),*
R	*is the correction factor, frequency factor (Fig. 4-5),*
r	*is the repetition rate in min^{-1},*
P_{st}	*is the flicker severity.*

Alternatively, the flicker severity can be determined using the flicker impression time according to the following modified equation [2]:

$$t_f/\text{s} = 2.4 \cdot |R \cdot F \cdot d/\%|^{3.2} \qquad (4\text{-}23)$$

where

t_f	*is the flicker impression time in s,*
d	*is the relative voltage change in %,*
F	*is the shape factor (Fig. 4-6),*
R	*is the correction factor, frequency factor (Fig. 4-5).*

Note:
Deviating from other standards and regulations, the coefficient 2.4 will be used. This provides higher accuracy.

The resulting flicker severity, related to the relevant observation period T_p, is calculated from the flicker impression time t_f.

$$P_{st} = \left(\frac{t_f}{T_p}\right)^{1/3.2} = \left(\frac{t_f}{T_p}\right)^{0.31} \tag{4-24}$$

where

t_f	*is the flicker impression time in s,*
T_p	*is the observation period in s,*
P_{st}	*is the flicker severity.*

Note:
The flicker impression time (also referred to as waiting time in previous standards) represents the physiological perceiving and forgetting it again.

The resulting flicker severity of several, mutually independent voltage change characteristics is obtained using the following equation:

$$P_{st\,g} = \left(\sum_i P_{st\,i}^{\alpha}\right)^{1/\alpha} = \left(\sum_i \left(\frac{t_{f\,i}}{T_p}\right)^{\alpha/3.2}\right)^{1/\alpha} \tag{4-25}$$

where

$P_{st\,g}$	*is the resulting flicker severity,*
$P_{st\,i}$	*is the flicker severity of the voltage change characteristic i,*
$t_{f\,i}$	*is the flicker impression time of the voltage change characteristic i,*
T_p	*is the observation period,*
α	*is the summation exponent,*
i	*is the index for voltage change characteristics.*

Using the shape factor F (see Fig. 4-6), specific waveforms (double steps, ramps, rectangular and triangular voltage changes, motor start-ups) of voltage change characteristics are converted into flicker-equivalent voltage steps [1].

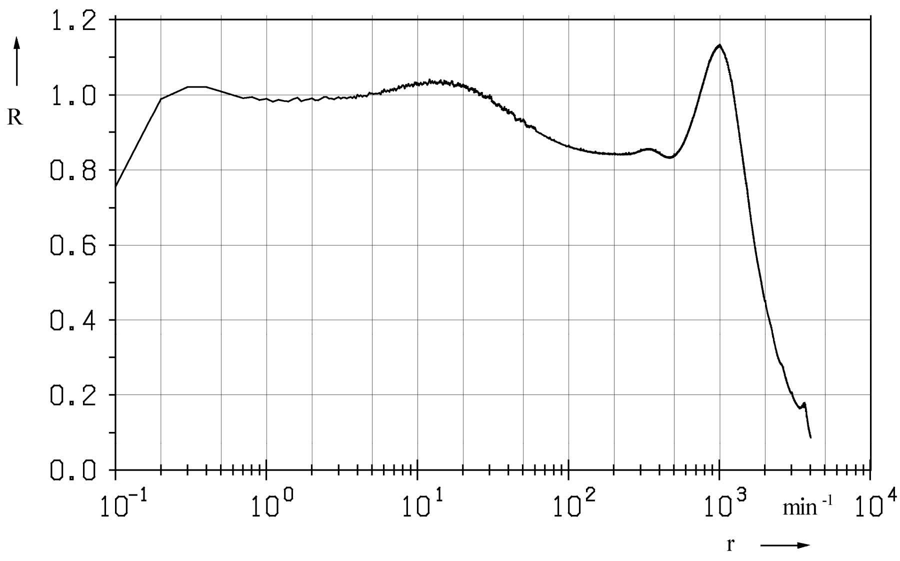


Fig. 4-5: Correction factor, frequency factor up to f_F = 33 Hz (r = 4,000 min^{-1}) [1]

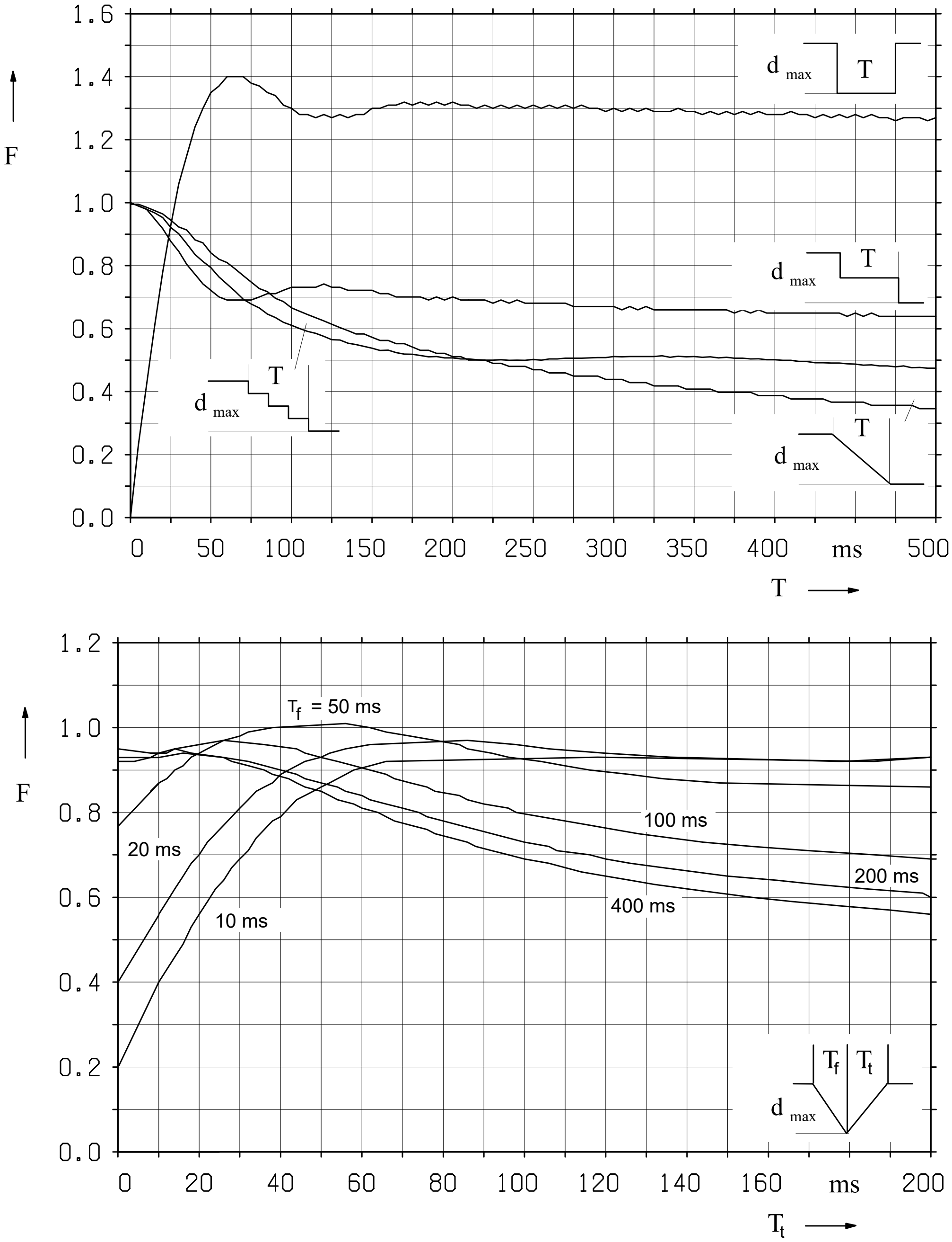


Fig. 4-6: Shape factor characteristics for staircase, ramped and step-wise voltage changes [1]

Note:

Shape factors of flicker can be determined by measurement for complex voltage change characteristics (refer to flicker step factor k_f for wind turbine generator systems, which is specified in the test report).

4.2.1.2 Determination of the flicker severity of interharmonics

A sinusoidal modulated time function

$$u(t) = \hat{u} \cdot \sin(\omega_N t)\left(1 + \frac{d}{2}\sin(\omega_F t)\right) \tag{4-26}$$

after multiplying by

$$\sin(\omega_N t) \cdot \sin(\omega_F t) = \frac{1}{2}\left[\cos(\omega_N t - \omega_F t) - \cos(\omega_N t + \omega_F t)\right] \tag{4-27}$$

where

d is the relative voltage change,

ω_N is the angular frequency of the network,

ω_F is the angular frequency of flicker,

gives the spectral representation of an amplitude-modulated time function with sidebands at a distance ω_F from the fundamental component ω_N. The relative voltage change is the relative fluctuation range of a sinusoidal amplitude-modulated time function.

Note:
For example, a sinusoidal amplitude-modulated time function with the flicker frequency f_F = 10 Hz results in a frequency spectrum with sidebands at a distance of 10 Hz from the power frequency. Contrary, an interharmonic with frequency f_i superimposed on the network voltage (frequency f_N) causes a flicker frequency $f_F = |f_N - f_i|$. Therefore, the approach in the frequency domain and in the time domain are equivalent. An interharmonic of 60 Hz at a power frequency of 50 Hz thus results in a modulation with a flicker frequency of 10 Hz.

The flicker severity can be determined using different methods:

- measurement with a flickermeter,
- determination by means of the reference curve,
- simulation.

The flicker severity is determined according to Fig. 4-7.

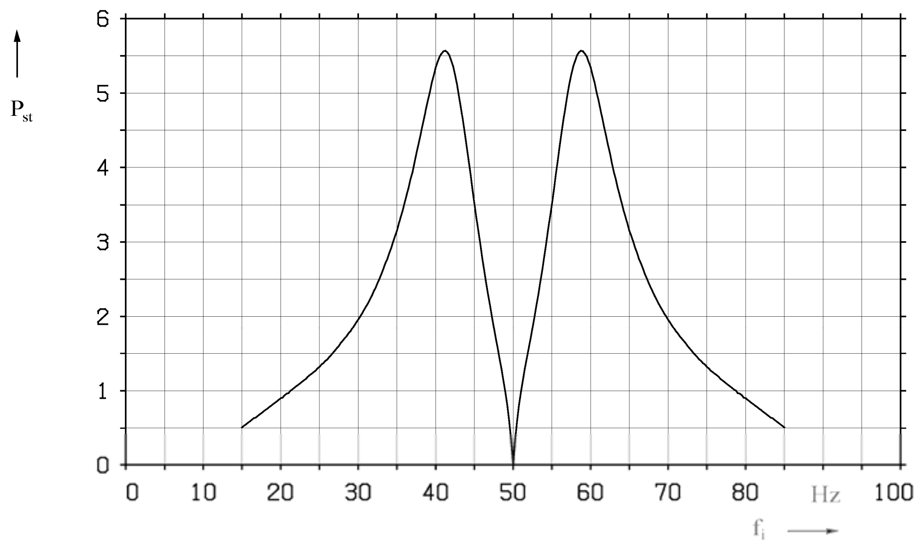


Fig. 4-7: Flicker severity P_{st} versus the frequency of the interharmonic f_i; relative amplitude of the interharmonic voltage: u_i = 1 % [3]

For the summation of the flicker severities of interharmonics, two cases have to be distinguished [3]:

- The interharmonics have different frequencies and are therefore mutually independent.

$$P_{\text{st}}^{\alpha} = \sum_{i=1}^{N} P_{\text{st}\,i}^{\alpha} \quad \text{with} \quad \alpha = 1.6\,..\,1.8 \tag{4-28}$$

where
P_{st} is the flicker severity,
$P_{st\,i}$ is the flicker severity of a single interharmonic i,
α is the summation exponent,
N is the number of interharmonics.

- The interharmonics have the same frequency with different amplitude ratios and phase relations or the interharmonics occur in pairs as sidebands to the fundamental component of the power frequency with different amplitude ratios and phase relations. The resulting P_{st} value for two interharmonics is calculated using the following equation:

$$P_{\text{st res}} = k_{\text{red}}(P_{\text{st 1}} + P_{\text{st 2}}) \tag{4-29}$$

where
$P_{st\,res}$ is the resulting flicker severity,
$P_{st\,1;2}$ is the flicker severity of interharmonics 1 and 2,
k_{red} is the reduction factor.

Fig. 4-8 shows the reduction factor for two interharmonics versus the relative phase shift of the interharmonics for different ratios u_{i2}/u_{i1}. The relevant parameter is the minimum ratio u_{i2}/u_{i1} or u_{i1}/u_{i2}, respectively

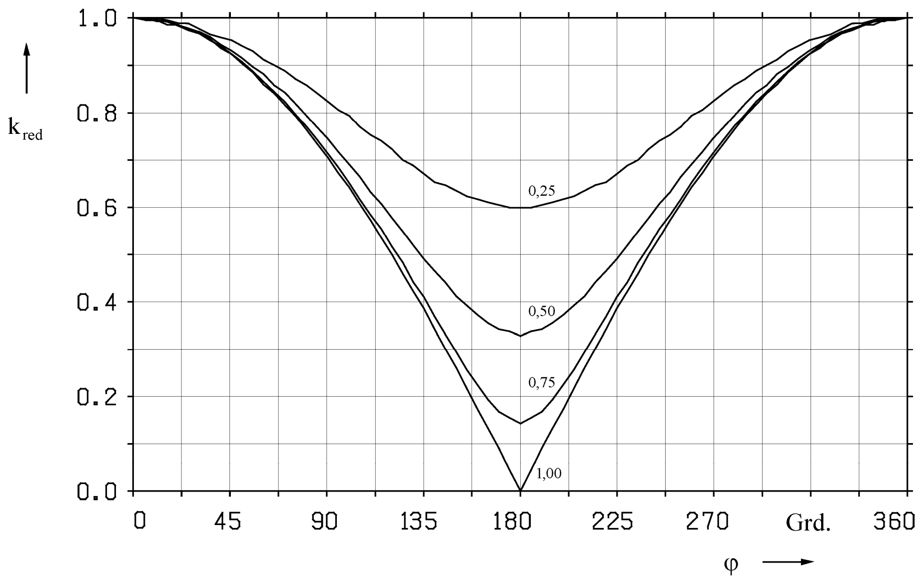


Fig. 4-8: Reduction factor k_{red} versus the relative phase shift φ of the interharmonics

4.2.1.3 Determination of the flicker severity of phase jumps

Phase jumps can be caused by

- abrupt load changes (e.g. when switching capacitors),
- alternating operating conditions (e.g. during the melting process in an arc furnace).

The outcome is a phase jump of the sinusoidal AC voltage and flicker occurs [4]. In addition, phase jumps are associated with voltage changes.

At time $t = t_1$, the phase angle of the supply voltage

$$u(t) = \sqrt{2}\,U \sin(2f_N\pi t + \beta_0^*) \tag{4-30}$$

changes by $\Delta\beta^*$ to

$$u(t) = \sqrt{2}\,U \sin(2f_N\pi t + \beta_0^* + \Delta\beta^*) \tag{4-31}$$

where

u(t)	*is the instantaneous value of the supply voltage,*
U	*is the r.m.s value of the supply voltage,*
f_N	*is the power frequency,*
t_1	*is the time of the phase jump,*
β_0^*	*is the phase angle at the time of the phase jump in rad,*
$\Delta\beta^*$	*is the amount of the phase jump in rad.*

Note:
Radians are converted in degrees according to $\beta = (180/\pi)\cdot\beta^*$.

$\beta_0 = 0^0$ implies that the phase jump occurs at the zero crossing of the voltage wave.

The flicker severity is

- independent of the supply voltage amplitude,
- a function comprising the parameters β_0 and $\Delta\beta$, which is mathematically expressed as $P_{st}\{\Phi(\beta_0, \Delta\beta)\}$.

For negative phase jumps $\Delta\beta^-$ and positive phase jumps $\Delta\beta^+$ in the range $-180° \le \Delta\beta \le 180°$, the following equations apply:

$$\begin{aligned} &P_{st}\left\{\Phi\left(\beta_0, \Delta\beta^+\right)\right\} = P_{st}\left\{\Phi\left(\beta_0, 180^0 - \left|\Delta\beta^-\right|\right)\right\} \\ &\text{e.g. } P_{st}\left\{\Phi\left(15^0, 100^0\right)\right\} = P_{st}\left\{\Phi\left(15^0, -80^0\right)\right\} \end{aligned} \tag{4-32}$$

and

$$\begin{aligned} &P_{st}\left\{\Phi\left(\beta_0, \Delta\beta^-\right)\right\} = P_{st}\left\{\Phi\left(\beta_0, \Delta\beta^+ - 180^0\right)\right\} \\ &\text{e.g. } P_{st}\left\{\Phi\left(30^0, -120^0\right)\right\} = P_{st}\left\{\Phi\left(30^0, 60^0\right)\right\} \end{aligned} \tag{4-33}$$

The flicker severity during phase jumps is calculated using the reference curves $\Phi(\beta_0, \Delta\beta)$ in Fig. 4-9.

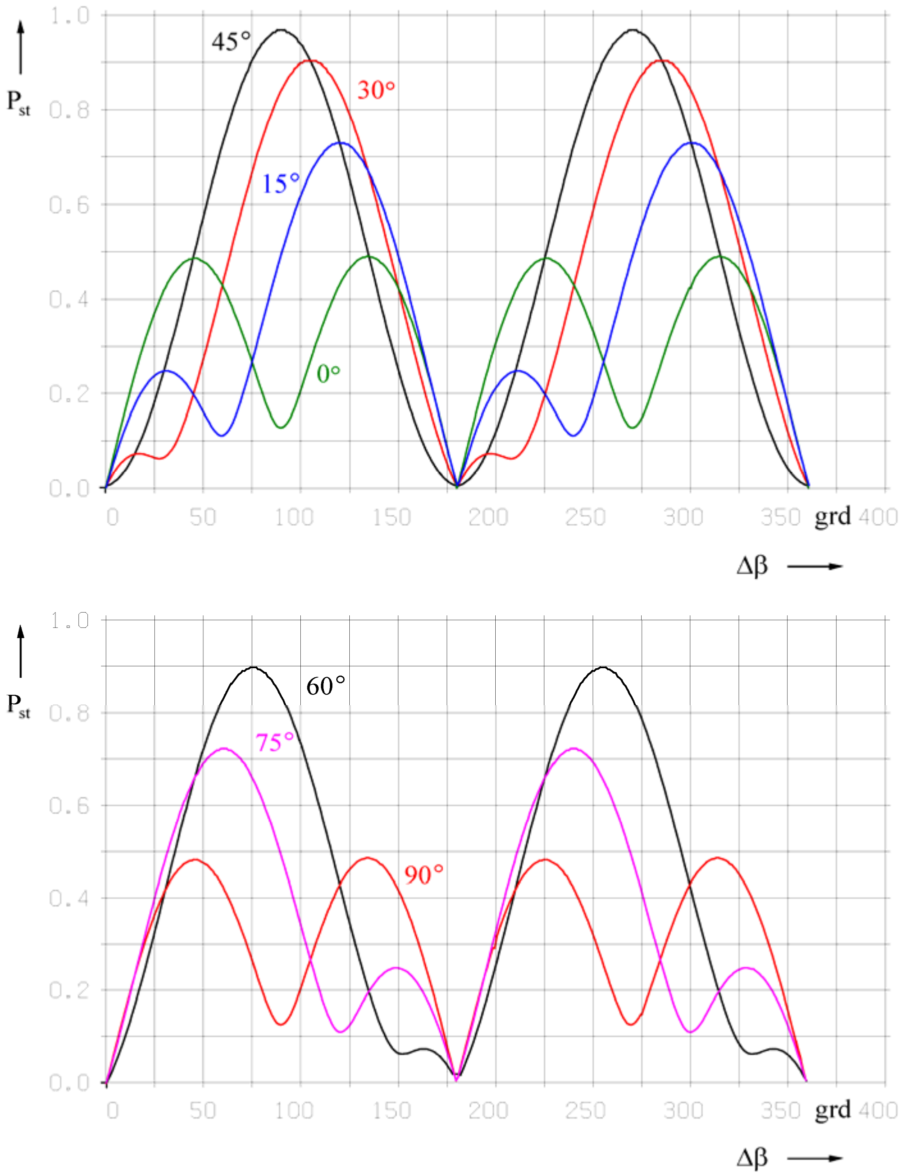


Fig. 4-9: Flicker severity versus Δβ including parameter β_0 [4]

4.2.2 Virtual transfer of the POC of a consuming installation

Knowing the flicker severity P_{st1} of a customer installation with S_{A1} and φ_{A1} at POC (1) and knowing the network data at the POC (1) with S_{sc1} and $\psi_{sc1,}$ the flicker severity that a customer installation with the same load response at POC (2) with S_{A2} and φ_{A2} and the network data at POC (2) with S_{sc2} and ψ_{sc2} would generate, can be calculated as follows (balanced load) [6]:

$$P_{\text{st 2}} = P_{\text{st 1}} \frac{S_{\text{sc 1}}}{S_{\text{A 1}}} \cdot \frac{1}{\cos(\psi_{\text{sc 1}} - \varphi_{\text{A 1}})} \cdot \frac{S_{\text{A 2}}}{S_{\text{sc 2}}} \cdot \cos(\psi_{\text{sc 2}} - \varphi_{\text{A 2}}) \qquad (4\text{-}34)$$

where

$P_{st\,1}$	*is the flicker severity of a customer installation at the POC (1),*
$P_{st\,2}$	*is the flicker severity of a customer installation at the POC (2),*
$S_{A\,1}$	*is the flicker-related power of a customer installation at the POC (1),*
$S_{A\,2}$	*is the flicker-related power of a customer installation at the POC (2),*
$\varphi_{A\,1}$	*is the angle of load change of the customer installation at the POC (1),*
$\varphi_{A\,2}$	*is the angle of load change of the customer installation at the POC (2),*
$S_{sc\,1}$	*is the short-circuit power at the POC (1),*
$S_{sc\,2}$	*is the short-circuit power at the POC (2),*
$\psi_{sc\,1}$	*is the network impedance angle at the POC (1),*
$\psi_{sc\,2}$	*is the network impedance angle at the POC (2).*

4.2.3 Flicker coefficient of generating installations

For generating installations, a flicker coefficient *c* is determined as a function of the network impedance angle (and, in the case of wind turbine generator systems, additionally as a function of the mean annual wind speed) and provided in tabular form in the test report. This allows the long-term flicker severity at the POC to be determined [6].

$$P_{\text{lt}} = c\left(\psi_{\text{sc POC}}, v_{\text{a}}\right) \frac{S_{\text{r G}}}{S_{\text{sc POC}}} \qquad (4\text{-}35)$$

where

$S_{r\,G}$	*is the rated power of the generating installation,*
$S_{sc\,POC}$	*is the short-circuit power,*
$c(\psi_{sc\,POC}, v_a)$	*is the flicker coefficient,*
$\psi_{sc\,POC}$	*is the network impedance angle,*
v_a	*is the mean annual wind speed.*

4.2.4 Superposition of flicker sources

The emission of an individual appliance or a customer installation is the short-term flicker severity $P_{st\,i}$, which is caused solely by its operation (i.e. by its load change) at the PCC.

The superposition law applies to the summation of the flicker emissions of several customer installations or several individual appliances.

$$P_{\text{st}} = \sqrt[\alpha]{\sum_{i=1}^{M} P_{\text{st}\,i}^{\alpha}} \qquad (4\text{-}36)$$

where

P_{st}	*is the flicker severity,*
$P_{st\,i}$	*is the flicker severity of an individual installation i,*
α	*is the summation exponent,*
M	*is the total number of installations.*

The exponent α depends on several parameters. A distinction shall be made whether the flicker is caused by continuous voltage fluctuations or by discrete load changes, e.g. switching operations.

For continuous voltage fluctuations, the following is recommended

- α = 2.0 for the summation,
- α = 3.0 for the subtraction (e.g. for elimination of background levels).

Note:
The emissions of an individual high-power customer installation can only be determined by flicker measurements at the POC. This procedure requires several steps:

1. *Measurement of the background level $P_{st\ Bg}$,*
2. *Measurement of the total flicker level $P_{st\ total}$ (background level $P_{st\ Bg}$ and emission of the customer installation $P_{st\ A}$),*
3. *Determination of the emission of the customer installation $P_{st\ A}$ from $P_{st\ total}$ by means of cubic subtraction of $P_{st\ Bg}$.*

For the long-term flicker severity, a summation exponent of α_{120} = 2.0 is recommended based on 120 min.

For independent discrete flicker events (time interval >1 s), α depends only on the number N_{10} of flicker-equivalent voltage steps during T_p = 10 min [5]. The flicker severity of the individual discrete flicker events can be determined either by measurement or by the analytical method.

The summation exponent can be determined in general using the following equation [5]:

$$\alpha = \frac{\ln(N_{10})}{0.31 \cdot \ln(N_{10}) + 0.281} \qquad (4\text{-}37)$$

where
α *is the summation exponent,*
N_{10} *is the number of flicker events during the observation period T_p =10 min.*

Tab. 4-2 shows the summation exponent α for a different number of flicker events.

Tab. 4-2: Summation exponent

N₁₀	α
2	1.4
3	1.8
4	1.9
5	2.0

For interdependent flicker events, α additionally depends on

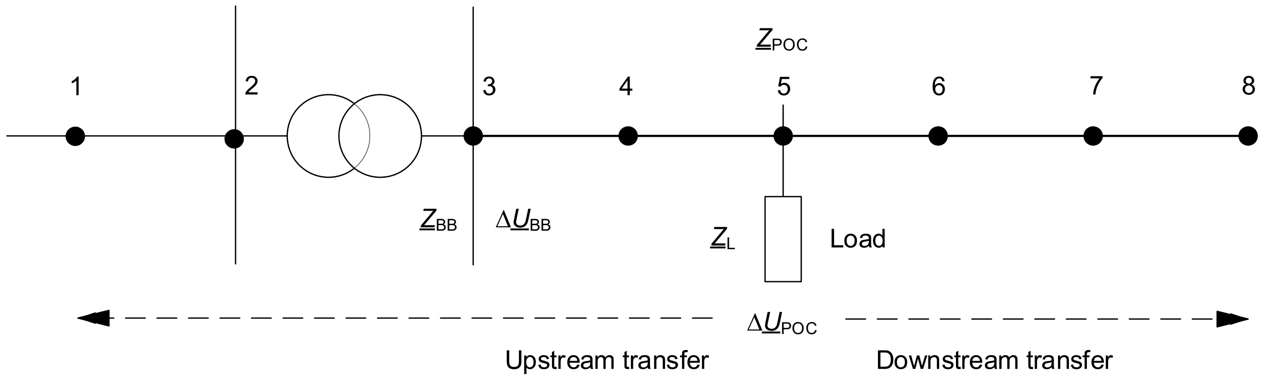
- the time interval of the voltage changes,
- the polarity of the voltage changes (same or alternating polarity).

For the exact calculation of the resulting flicker severity, a simulation program shall be used.

4.3 Conversion between POC and PCC

4.3.1 Voltage changes

Voltage changes induced by customer installations will propagate throughout the network.



$$\Delta U_{PCC1} < \Delta U_{PCC2} < \Delta U_{PCC3} < \Delta U_{PCC4} < \Delta U_{POC} = \Delta U_{PCC6} = \Delta U_{PCC7} = \Delta U_{PCC8}$$

Fig. 4-10: Propagation of voltage changes throughout radial networks

In radial networks, the voltage change from the POC of the disturbing installation towards the incoming supply of the network decreases according to the ratio of the short-circuit power $S_{\text{sc POC}}$ at the POC to the short-circuit power $S_{\text{sc PCC}\,i}$ at the relevant PCC$_i$ (upward transfer).

$$d_{\text{PCC}\,i} = \frac{S_{\text{sc POC}}}{S_{\text{sc PCC}\,i}} d_{\text{POC}} \qquad (4\text{-}38)$$

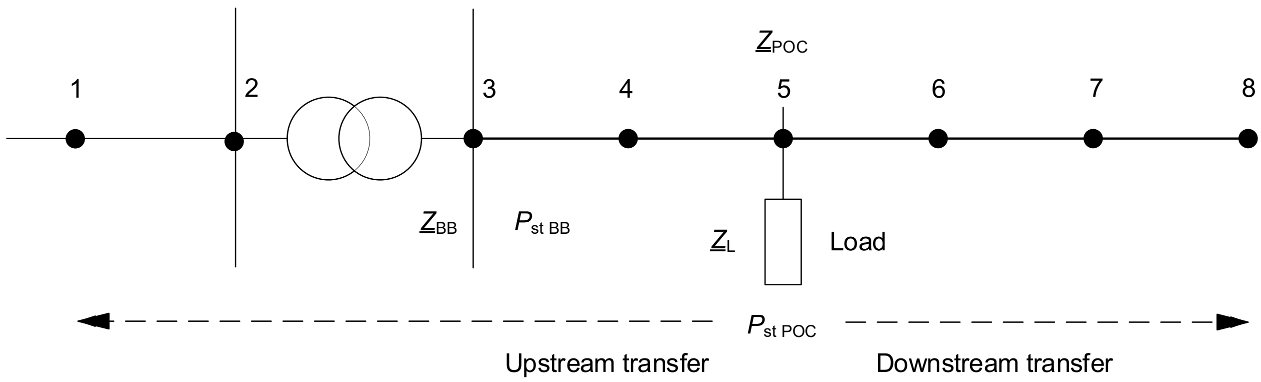
where

d_{POC}	*is the relative voltage change at the POC,*
$d_{PCC\,i}$	*is the relative voltage change at the relevant PCC$_i$,*
$S_{sc\,POC}$	*is the short-circuit power at the POC,*
$S_{sc\,PCC\,i}$	*is the short circuit power at the relevant PCC$_i$.*

In radial networks, the voltage change propagates from the point of the disturbing customer installation to downstream points without reduction (downstream transfer).

4.3.2 Flicker

Flicker induced by customer installations will propagate throughout the network.



$$P_{st,PCC1} < P_{st,PCC2} < P_{st,PCC3} < P_{st,PCC4} < P_{st,POC} = P_{st,PCC6} = P_{st,PCC7} = P_{st,PCC8}$$

Fig. 4-11: Propagation of flicker throughout radial networks

In radial networks, the flicker severity from the POC of the disturbing customer installation towards the incoming supply of the network decreases according to the ratio of the short-circuit power $S_{sc\ POC}$ at the POC to the short-circuit power $S_{sc\ PCC\ i}$ at the relevant PCC_i (upstream transfer).

$$P_{st\ PCC\ i} = \frac{S_{sc\ POC}}{S_{sc\ PCC\ i}} P_{st\ POC} \qquad (4\text{-}39)$$

where
$P_{st\ POC}$ *is the flicker severity at the POC,*
$P_{st\ PCC\ i}$ *is the flicker severity at the relevant PCC_i,*
$S_{sc\ POC}$ *is the short-circuit power at the POC,*
$S_{sc\ PCC\ i}$ *is the short-circuit power at the relevant PCC_i.*

In radial networks, the flicker severity propagates from the point of the disturbing installation to downstream points without reduction (downstream transfer).

4.4 Assessment parameters

4.4.1 Slow voltage change

Relative slow voltage changes are assessed using the difference between e.g. two 10 min average values of the supply voltage or the difference of the supply voltages before and after a load change, related to the supply voltage before the load change.

4.4.2 Rapid voltage change

Rapid voltage changes ΔU are determined as the difference of the r.m.s. values of successive half-cycles of the voltage. Rapid voltage changes are given either as absolute or relative value. The relative voltage change d refers to the supply voltage U before the event occurred. The voltage change characteristic results from the sequence of the individual r.m.s. values of the half-cycles of the supply voltage.

4.4.3 Flicker

The long-term flicker severity P_{lt} and the short-term flicker severity P_{st} are distinguished as the assessment parameters. The limit values specified in these Technical Rules are based on the flicker measurement and assessment methods according to [EN 61000-4-15]. If the flicker measurement method is changed, the limit values may have to be adjusted accordingly to ensure that the EMC objectives are met.

4.5 Mitigation measures

Detailed considerations can be found in [6].

Measures applicable on the network side:
Measures that are applicable on the network side to increase the short-circuit power are given in Section 2.8.

Measures applicable on the installation side:
Measures that are applicable on the installation side to reduce the flicker severity can be derived from the equation for calculating the flicker severity P_{st} and the known shape factors. Effective measures include:

- Limiting the amplitude of the maximum voltage change
  (e.g. dividing a load into a basic and an alternating load),
- Avoiding rapid voltage changes by flattening the rise time,
- Dividing individual voltage steps into partial steps
  (e.g. switching on heating resistors on electric heaters),
- Flywheel to compensate for load changes, spring couplings,
- Connecting an upstream series reactor,
- Connecting in parallel controlled reactive loads,
- Interlocks to prevent superposition effects
  (e.g. by stepwise connection of motors),
- Adjusting the repetition rate
  (However, it should be noted that as a result of $P_{st} \sim \sqrt[3]{r}$ the benefit is lower compared to adjusting $\Delta U/U$.),
- Avoiding of pulse-shaped voltage change characteristics of pulse duration T = 64 ms
  (e.g. avoiding current flow time during resistance welding of three full cycles),
- Balancing: A balanced three-phase load induces less voltage fluctuations than a two-phase load of the same power. Balancing of a two-phase resistive load is accomplished using the Steinmetz circuit. In the first step, this requires that the non-resistive two-phase loads have been compensated. In the second step, the balancing of the resistive load is carried out. After power-factor correction and balancing, the load behaves like a balanced resistive three-phase load. This has also an reducing impact on the unbalance factor (see Section 5 “Unbalance”),
- Dynamic compensation: In addition to adjusting the shape of voltage fluctuations (shape factor) and load balancing, dynamic flicker compensators are of significance.

In some cases, only a combination of several measures will achieve the desired outcome.

Further general information on the implementation of mitigation measures can be found in Section 2.8.

4.6 Measurement

4.6.1 Slow voltage change

The 10 min average values of the r.m.s. supply voltage are to be used [EN 61000-4-30]. The associated voltages shall be located within a specified tolerance range. Slow voltage changes are measured with a power quality instrument according to [EN 61000-4-30].

Supplementary specifications are given in the corresponding section of Part B (Requirements).

4.6.2 Rapid voltage changes

Rapid voltage changes are measured in the laboratory with a class F2 flickermeter; in the network, they are measured with a class F1 flickermeter with d-meter option [EN 61000-4-15] or with a power quality instrument according to [EN 61000-4-30].

4.6.3 Flicker severity

The flicker severity is measured with a flickermeter [EN 61000-4-15]. For measurements in the network, class F1 flickermeters are to be used. Flickermeters or power quality isntruments according to EN [EN 61000-4-30] measure voltage fluctuations as well as flicker due to interharmonics and phase shifts.

To check the compliance of individual customer installations or the total disturbance level caused by all customer installations, the 95 % quantiles of a one-week measurement period shall be assessed.

4.6.4 Accuracy of existing instrument transformers

Instrument transformers are used in the MV and HV networks. The transfer characteristics of instrument transformers existing in substations is generally satisfactory for accurate measurements.

5. Voltage unbalance

5.1 General

Unbalances are caused by unbalanced loading in terms of absolute value and phase of the three phase conductors of the three-phase system. Typical examples are single-phase or two-phase appliances where the connection is made between the phase and the neutral conductor or between two phase conductors, such as:

- inductive and capacitive heating appliances,
- different types of melting furnaces,
- resistance welding machines,
- single-phase connected charging rectifiers of electric vehicles,
- single-phase photovoltaic (PV) systems,
- single-phase battery storage systems,
- railway systems operating at power frequency of public networks,
- three-phase appliances in partial load operation (e.g. flow heaters).

The large number of low-power single-phase appliances with short operating times and rare simultaneous operation results in a contribution to unbalance, which is typically between 0.3 % and 1 % in LV networks. High-power appliances with longer operating times and higher probability of simultaneous operation can result in an additional increase in voltage unbalance. Fig. 5-1 shows the example of the unbalance factor of the voltage (unbalance of the negative-sequence component of the fundamental component) k_{U2} over the day according to equation (5-1) in an urban LV network with/without electric vehicles using single-phase charging.

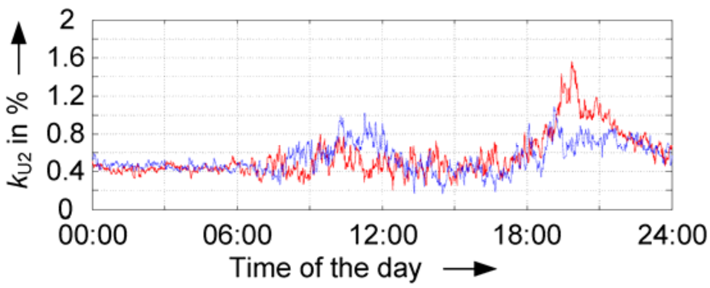


Fig. 5-1: Example of the unbalance factor of the voltage over the day in a network with (red)/without (blue) electric vehicles using single-phase charging [7]

Unbalances are not only caused by customer installations, but can also result from unbalances of network elements, e.g. in case of incomplete transposition of lines. As a result, the balanced systems are no longer fully decoupled.

Unbalances can cause the following:

- Increase in current load and losses in cables and transformers:
  For the same power, the phase currents can take two or three times the value, and the losses in the incoming lines can reach two to six times the value. Accordingly, cables and transformers can only be loaded to half or one third of their rated power.
- Losses in electrical machines:
  Unbalanced voltages cause unbalanced currents in electrical machines and increase the thermal stress, which can shorten service life.

- Vibration moments in electrical machines:
  The field induced by the negative-sequence component of unbalanced currents acts against the rotating direction of the rotor and causes increased mechanical stresses.
- Non-characteristic harmonic currents in line-commutated converters:
  Unbalanced voltages cause unbalanced current consumption in line-commutated converters, which result in additional, non-characteristic harmonic currents.

Three-phase connected appliances can also result in unbalanced currents during unbalanced operation. For such appliances, the maximum current flow during single-phase or two-phase operation shall be limited.

The unbalance in a three-phase system is fully described by the approach of sequence components (Fortescue transformation, sequence domain) in terms of absolute value and angle of the positive-sequence, negative-sequence and zero-sequence components. Unbalance is caused by different absolute values in the three phases and/or different angles between adjacent phases of voltages or currents in the abc-domain. The zero-sequence component represents the displacement of the rotating phasor system with respect to the earth potential. The negative-sequence component expresses the amplitude difference of the phase voltages and the deviation from the ideal phase shift of 120°. All standards and guidelines consider only the absolute value of the unbalance of the negative-sequence component at fundamental frequency. The unbalance of the zero-sequence component, which is also present and which, among other things, represents the loading of the neutral conductor, is not taken into account. For this reason, these Technical Rules only consider the absolute value of the unbalance of the negative-sequence component at fundamental frequency and use the simplified terms “unbalance factor of the current” and “unbalance factor of the voltage” and the following general calculation equations apply:

$$k_{\mathrm{U2}} = \frac{U_2}{U_1} \tag{5-1}$$

where
k_{U2} *is the unbalance factor of the voltage,*
U_2 *is the negative-sequence component of the voltage (fundamental frequency),*
U_1 *is the positive-sequence component of the voltage (fundamental frequency).*

$$k_{\mathrm{I2}} = \frac{I_2}{I_1} \tag{5-2}$$

where
k_{I2} *is the unbalance factor of the current,*
I_2 *is the negative-sequence component of the current (fundamental frequency),*
I_1 *is the positive-sequence component of the current (fundamental frequency).*

5.2 Calculations

5.2.1 Individual appliance connected between phase conductor and neutral conductor

Assuming a single-phase connected appliance with a constant impedance $\underline{Z}_A$ and a balanced supply voltage, the contribution to the unbalance factor of the voltage at the POC is calculated using the following equation:

$$k_{U2\,POC} = \frac{\left|\underline{Z}_{sc\,2\,POC}\right|}{\left|\underline{Z}_{sc\,0\,POC} + \underline{Z}_{sc\,2\,POC} + 3 \cdot \underline{Z}_A\right|} \qquad (5\text{-}3)$$

where

$k_{U2\,POC}$ *is the unbalance factor of the voltage of the appliance,*

$\underline{Z}_{sc\,2\,POC}$ *is the negative-sequence component of the short-circuit impedance,*

$\underline{Z}_{sc\,0\,POC}$ *is the zero-sequence component of the short-circuit impedance,*

$\underline{Z}_A$ *is the impedance of the appliance.*

Taking into account $|\underline{Z}_{sc\,0\,POC}| \ll |\underline{Z}_A|$, $|\underline{Z}_{sc\,2\,POC}| \ll |\underline{Z}_A|$ und $|\underline{Z}_{sc\,2\,POC}| \approx |\underline{Z}_{sc\,POC}|$, the following applies:

$$k_{U2\,POC} = \frac{Z_{sc\,POC}}{3 \cdot Z_A} \qquad (5\text{-}4)$$

where

$k_{U2\,POC}$ *is the unbalance factor of the voltage of the appliance,*

$Z_{sc\,POC}$ *is the short-circuit impedance,*

Z_A *is the impedance of the appliance.*

In relation with

$$Z_{sc\,POC} = \frac{U_{POC}^2}{S_{sc\,POC}} \quad \text{and} \quad Z_A = \frac{U_{POC}^2}{3 \cdot S_{A\,r}} \qquad (5\text{-}5), (5\text{-}6)$$

where

$Z_{sc\,POC}$ *is the short-circuit impedance,*

U_{POC} *is the phase-to-phase voltage,*

$S_{sc\,POC}$ *is the short-circuit power,*

Z_A *is the impedance of the appliance,*

$S_{A\,r}$ *is the rated apparent power of the appliance,*

the contribution to the unbalance factor of the voltage at the POC is determined using the following equation:

$$\mathrm{k}_{U2\,POC} = \frac{\mathrm{S}_{A\,r}}{\mathrm{S}_{sc\,POC}} \qquad (5\text{-}7)$$

where

$k_{U2\,POC}$ *is the unbalance factor of the voltage of the appliance,*

$S_{A\,r}$ *is the rated apparent power of the appliance,*

$S_{sc\,POC}$ *is the short-circuit power.*

5.2.2 Individual appliance connected between two phase conductors without connection to the neutral conductor

Assuming an appliance with constant impedance Z_A connected between two phase conductors and a balanced supply voltage, the contribution to the unbalance factor of the voltage at the POC is calculated using the following equation:

$$k_{U2\ POC} = \frac{|\underline{Z}_{sc\ 2\ POC}|}{|\underline{Z}_{sc\ 2\ POC} + \underline{Z}_A|} \qquad (5\text{-}8)$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*

$\underline{Z}_{sc\ 2\ POC}$ *is the negative-sequence component of the short-circuit impedance,*

$\underline{Z}_A$ *is the impedance of the appliance.*

Taking into account $|\underline{Z}_{sc\ 2\ POC}| \ll |\underline{Z}_A|$ und $|\underline{Z}_{sc\ 2\ POC}| \approx |\underline{Z}_{sc\ POC}|$, the following applies:

$$k_{U2\ POC} = \frac{Z_{sc\ POC}}{Z_A} \qquad (5\text{-}9)$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*

$Z_{sc\ POC}$ *is the short-circuit impedance,*

Z_A *is the impedance of the appliance.*

In relation with

$$Z_{sc\ POC} = \frac{U_{POC}^2}{S_{sc\ POC}} \quad \text{and} \quad Z_A = \frac{U_{POC}^2}{S_{A\ r}} \qquad (5\text{-}10), (5\text{-}11)$$

where

$Z_{sc\ POC}$ *is the short-circuit impedance,*

U_{POC} *is the phase-to-phase voltage,*

$S_{sc\ POC}$ *is the short-circuit power,*

Z_A *is the impedance of the appliance,*

$S_{A\ r}$ *is the rated apparent power of the appliance,*

the contribution to the unbalance factor of the voltage at the POC is determined using the following equation:

$$k_{U2\ POC} = \frac{S_{A\ r}}{S_{sc\ POC}} \qquad (5\text{-}12)$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*

$S_{A\ r}$ *is the rated apparent power of the appliance,*

$S_{sc\ POC}$ *is the short-circuit power.*

This equation equals that one for calculating the unbalance factor of the voltage of an appliance connected between phase conductor and neutral conductor according to Section 5.2.1.

5.2.3 Individual appliance connected between two phase conductors with connection to the neutral conductor

When connecting an appliance consisting of two identical loads with a constant impedance Z_A between two different phase conductors and the neutral conductor and a balanced supply voltage, the contribution to the unbalance factor of the voltage at the POC is calculated using the following equation:

$$k_{U2\ POC} = \frac{\left|\underline{Z}_{sc\ 2\ POC} \cdot \underline{Z}_{sc\ 0\ POC} + \underline{Z}_{sc\ 2\ POC} \cdot \underline{Z}_{A}\right|}{\left|\underline{Z}_{sc\ 2\ POC} \cdot \underline{Z}_{sc\ 0\ POC} + 2 \cdot \underline{Z}_{sc\ 2\ POC} \cdot \underline{Z}_{A} + 2 \cdot \underline{Z}_{sc\ 0\ POC} \cdot \underline{Z}_{A} + 3 \cdot \underline{Z}_{A}^{2}\right|} \tag{5-13}$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*
$\underline{Z}_{sc\ 2\ POC}$ *is the negative-sequence component of the short-circuit impedance,*
$\underline{Z}_{sc\ 0\ POC}$ *is the zero-sequence component of the short-circuit impedance,*
$\underline{Z}_{A}$ *is the impedance of each load.*

Taking into account $|\underline{Z}_{sc\ 0\ POC}| \ll |\underline{Z}_A|$, $|\underline{Z}_{sc\ 2\ POC}| \ll |\underline{Z}_A|$ und $|\underline{Z}_{sc\ 2\ POC}| \approx |\underline{Z}_{sc\ POC}|$, the following applies:

$$k_{U2\ POC} = \frac{Z_{sc\ POC}}{3 \cdot Z_A} \tag{5-14}$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*
$Z_{sc\ POC}$ *is the short-circuit impedance,*
Z_A *is the impedance of each load.*

In relation with

$$Z_{sc\ POC} = \frac{U_{POC}^2}{S_{sc\ POC}} \quad \text{and} \quad Z_A = \frac{2}{3} \cdot \frac{U_{POC}^2}{S_{A\ r}} \qquad (5\text{-}15), (5\text{-}16)$$

where

$Z_{sc\ POC}$ *is the short-circuit impedance,*
U_{POC} *is the phase-to-phase voltage,*
$S_{sc\ POC}$ *is the short-circuit power,*
Z_A *is the impedance of each load,*
$S_{A\ r}$ *is the rated apparent power of the appliance,*

the contribution to the unbalance factor of the voltage at the POC is determined using the following equation:

$$k_{U2\ POC} = \frac{S_{A\ r}}{S_{sc\ POC}} \tag{5-17}$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the appliance,*
$S_{A\ r}$ *is the rated apparent power of the appliance,*
$S_{sc\ POC}$ *is the short-circuit power.*

This equation equals that one for calculating the unbalance factor of the voltage of an individual appliance connected between phase conductor and neutral conductor according to Section 5.2.1.

5.2.4 Installation comprising several unbalanced individual appliances

If several appliances are unbalanced connected within a customer installation, it is not sufficient to exclusively consider the apparent powers of the individual appliances. Therefore, the unbalanced power $S_{\text{A un}}$ is introduced for general assessment [8]. It corresponds to that part of the apparent power of a customer installation which contributes to the negative-sequence component of the voltage and for which the following approximation applies:

$$S_{\text{A un}} \approx 3 \cdot U_{\text{LN POC}} \cdot I_{\text{2 POC}} = \sqrt{3} \cdot U_{\text{POC}} \cdot I_{\text{2 POC}} \tag{5-18}$$

where

$S_{A\,un}$	*is the unbalanced power,*
$U_{LN\,POC}$	*is the absolute value of the phase-to-neutral voltage,*
$I_{2\,POC}$	*is the negative-sequence component of the current,*
U_{POC}	*is the phase-to-phase voltage.*

Assuming balanced phase-to-neutral voltages, the unbalanced power $S_{\text{A un}}$ is calculated using the following equation:

$$S_{\text{A un}} = \left| \underline{S}_{\text{A L1}} + \underline{a}^2 \cdot \underline{S}_{\text{A L2}} + \underline{a} \cdot \underline{S}_{\text{A L3}} \right| \tag{5-19}$$

with

$$\underline{a} = e^{j \cdot \frac{2}{3} \cdot \pi} \tag{5-20}$$

where

$S_{A\,un}$	*is the unbalanced power of the customer installation,*
$S_{A\,L1}$	*is the complex power of the customer installation connected between phase L1 and the neutral conductor,*
$S_{A\,L2}$	*is the complex power of the customer installation connected between phase L2 and the neutral conductor,*
$S_{A\,L3}$	*is the complex power of the customer installation connected between phase L3 and the neutral conductor.*

Note:
The unbalanced power $S_{A\,un}$ is different from the power which is calculated in the sequence domain based on negative-sequence current and negative-sequence voltage.
If the rated apparent power and the displacement factor of the individual appliances as well as their phase distribution are known, they can be determined by phase-selective complex addition.
If the displacement factor of at least one appliance is unknown, only the rated apparent powers shall be used, but taking into account the respective direction of the power flow.
In case of two-phase appliances, their complex powers between phases shall first be converted into the equivalent complex powers per phase. The required equations are summarized in Tab. 5-1.

Tab. 5-1: Equations required for the conversion of powers between phases into powers per phase

Connection between L1 and L2	Connection between L2 and L3	Connection between L1 and L3
$\underline{S}_{\text{L1}} = \frac{1}{3} \cdot (1 - \underline{a}) \cdot \underline{S}_{\text{L1L2}}$	$\underline{S}_{\text{L1}} = 0$	$\underline{S}_{\text{L1}} = \frac{1}{3} \cdot (1 - \underline{a}^2) \cdot \underline{S}_{\text{L1L3}}$
$\underline{S}_{\text{L2}} = \frac{1}{3} \cdot (1 - \underline{a}^2) \cdot \underline{S}_{\text{L1L2}}$	$\underline{S}_{\text{L2}} = \frac{1}{3} \cdot (1 - \underline{a}) \cdot \underline{S}_{\text{L2L3}}$	$\underline{S}_{\text{L2}} = 0$
$\underline{S}_{\text{L3}} = 0$	$\underline{S}_{\text{L3}} = \frac{1}{3} \cdot (1 - \underline{a}^2) \cdot \underline{S}_{\text{L2L3}}$	$\underline{S}_{\text{L3}} = \frac{1}{3} \cdot (1 - \underline{a}) \cdot \underline{S}_{\text{L1L3}}$

All complex powers shall be given with a sign according to the load convention. Correspondingly, generators shall be given with a negative sign. For appliances with bidirectional power flow (e.g.

battery storages or electric vehicles with regenerative capability), the operating mode that produces the maximum unbalanced power shall be considered for the calculation. For example, if two electric vehicles with regenerative capability and a single-phase charger are each connected to two different phase conductors, the operating mode "charging" shall be assumed for the first electric vehicle and the operating mode "discharging" for the second electric vehicle (or vice versa).

The contribution to the unbalance factor of the voltage at the POC is calculated using the following equation:

$$k_{\mathrm{U2\ POC}} = \frac{S_{\mathrm{A\ un}}}{S_{\mathrm{sc\ POC}}} \tag{5-21}$$

where

$k_{U2\ POC}$ *is the unbalance factor of the voltage of the customer installation,*
$S_{A\ un}$ *is the unbalanced power,*
$S_{sc\ POC}$ *is the short-circuit power.*

5.3 Conversion between POC and PCC

The conversion between POC and PCC is performed using the ratio of the related short-circuit powers.

$$k_{\mathrm{U2\ PCC}} = \frac{S_{\mathrm{sc\ POC}}}{S_{\mathrm{sc\ PCC}}} \cdot k_{\mathrm{U2\ POC}} \tag{5-22}$$

where

$k_{U2\ PCC}$ *is the unbalance factor of the voltage of the customer installation at the PCC,*
$k_{U2\ POC}$ *is the unbalance factor of the voltage of the customer installation at the POC,*
$S_{sc\ POC}$ *is the short-circuit power at the POC,*
$S_{sc\ PCC}$ *is the short-circuit power at the PCC.*

For the absolute current values of the negative-sequence component the following approximation applies:

$$I_{2\ \mathrm{PCC}} \approx I_{2\ \mathrm{POC}} \tag{5-23}$$

where

$I_{2\ PCC}$ *is the current value of the negative-sequence component at the PCC,*
$I_{2\ POC}$ *is the current value of the negative-sequence component at the POC.*

5.4 Assessment parameters

The absolute current value of the negative-sequence component of a customer installation I_2 or the unbalanced power $S_{\mathrm{A\ un}}$ is used as the assessment parameter. Emission limits are specified as the absolute current value of the negative-sequence component of the customer installation $I_{2\ \mathrm{PCC}}$ at the PCC.

If the unbalance factor of the voltage of the customer installation at the PCC is to be assessed by measurement, the respective emission limit of the negative-sequence voltage is calculated from the emission limit of the negative-sequence current using the following equation:

$$k_{\mathrm{U2\ PCC}} = \sqrt{3} \cdot \frac{I_{\mathrm{2\ PCC}}}{S_{\mathrm{sc\ PCC}}} \cdot U_{\mathrm{PCC}} \qquad (5\text{-}24)$$

where
$k_{U2\ PCC}$ *is the emission limit of the unbalance factor of the voltage of the customer installation,*
$I_{2\ PCC}$ *is the emission limit of the negative-sequence current of the customer installation,*
$S_{sc\ PCC}$ *is the short-circuit power,*
U_{PCC} *is the phase-to-phase voltage.*

If the phase-to-phase voltage at the PCC is unknown, the nominal voltage or the declared supply voltage can be used instead.

5.5 Mitigation measures

Measures applicable on the network side:
Measures that are applicable on the network side to increase the short-circuit power are given in Section 2.8. In addition, single-phase series voltage regulators (SVR) can be used as network-side measure to reduce unbalances.

Measures applicable on the installation side:
Measures that are applicable on the installation side to reduce the contribution of a customer installation to the unbalance factor of voltage k_{U2} include:

- Equal sharing of single-phase loads among the phase conductors,
- Installation of power-factor correction systems for balancing by means of capacitors and reactors (Steinmetz circuit, controllable in case of variable loads), especially in case of high-power installations (see also Section 4, Voltage changes and flicker),
- Installation of active filters with balancing functions (see also Section 4, Voltage changes and flicker),
- Three-phase connection via converters,
- Connection of single-phase PV systems to the phase conductor with the minimum voltage,
- Use of automatic phase selectors when connecting single-phase charging rectifiers of electric vehicles.

Further general information on the implementation of mitigation measures can be found in Section 2.8.

Note:
Mitigation measures based solely on the measurement of the absolute value of the phase-to-neutral voltages in the individual conductors may lead to an increase in the unbalance factor of the voltage, depending on the absolute value and phase angle of the already existing unbalance factor of the voltage.

5.6 Measurement

5.6.1 Negative-sequence component of the current

The 95 % quantile of the measured 10 min average values of the negative-sequence component of the current at fundamental frequency I_2 of a one-week period or one operation cycle of the customer installation shall be lower than the calculated emission limit. In addition, the 99 % quantile of the 3 s average values of each day shall not exceed the emission limit multiplied by a factor in the range 1,25 .. 2; see also [IEC 61000-3-14] and [IEC 61000-3-13]. If no exact value is known, a default factor of 1,25 is recommended.

If only the unbalance factor of the current I_2/I_1 is measured by the measuring device, it is necessary to determine the absolute current values I_2 by multiplying each measured value by the corresponding positive-sequence current I_1 before the assessment.

5.6.2 Unbalanced power of the customer installation

Common measurement instruments cannot determine the unbalanced power of a customer installation at present. However, it can be determined from the absolute value of the negative-sequence current I_2 as follows:

$$S_{\mathrm{A\,un}} \approx \sqrt{3} \cdot U_{\mathrm{POC}} \cdot I_2 \tag{5-25}$$

where

$S_{\mathrm{A\,un}}$	*is the unbalanced power,*
U_{POC}	*is the phase-to-phase voltage at the POC,*
I_2	*is the negative-sequence component of the current (fundamental frequency).*

If the phase-to-phase voltage at the POC is unknown, the nominal voltage or the declared supply voltage can be used instead.

5.6.3 Accuracy of existing instrument transformers

Existing current and/or voltage transformers can falsify the measurement of the unbalance factor due to different measurement uncertainties within one accuracy class.

6. Harmonics, interharmonics and supraharmonics

6.1 General

The deviation of the supply voltage from sinusoidal waveform is called distortion and implies that additional, non-power-frequency components superimpose the voltage waveform at power frequency. In the context of this Technical Rules, the following types of distortion are distinguished:

- Harmonic components up to the order of 40,
- Interharmonic components up to the order of 40,
- Higher frequency emissions in the frequency range from 2 kHz to 150 kHz (referred to as supraharmonics in this document).

For interharmonics and supraharmonics, a further distinction shall be made between intentional emissions (e.g., ripple control or narrowband power line communication (PLC)) and nonintentional emissions. This section covers nonintentional emissions. Intentional emissions are discussed in Section 8.

Note:
In these Technical Rules, supraharmonic emission limits for nonintentional emissions are considered only in the frequency range from 2 kHz to 9 kHz. Intentional supraharmonic emissions in the frequency range from 2 kHz to 150 kHz are covered in Section 8.

Significant sources of harmonics are:

- power electronic appliances and installations, e.g. drive converters, rectifier systems, dimmers,
- mass-produced equipment using DC power supply, such as TV sets, compact fluorescent lamps with integrated electronic ballast, IT equipment,
- equipment with non-linear current-voltage characteristics, such as induction and arc furnaces, gas discharge lamps, motors, transformers and reactors with iron core.

Significant sources of interharmonics are:

- asynchronous machines,
- subsynchronous converter cascades,
- frequency converter drives,
- equipment using multicycle control,
- resistance welding machines,
- arc furnaces.

Significant sources of supraharmonics are:

- power electronic equipment using active power-factor correction, such as charging units for electric vehicles or switched-mode power supplies,
- self-commutated equipment, such as PV inverter or converter for storage devices,

Voltage distortions can cause interferences of both network operation and equipment (appliances and installations) at the customers.
Consequences of harmonic voltages can be:

- lifetime reduction of capacitors and motors due to additional thermal loading,
- acoustic noise in equipment containing electromagnetic circuits (reactors, transformers and motors),
- interference of communications and information-technology equipment,
- malfunctions of electronic equipment,

- failure of ripple-control receivers and protection equipment,
- impairment of earth-fault compensation in networks with resonant neutral earthing.

Consequences of interharmonic voltages can be:
- lifetime reduction of capacitors and motors due to additional thermal loading,
- acoustic noise in equipment containing electromagnetic circuits (reactors, transformers and motors),
- malfunction of ripple-control systems,
- flicker (see Section 4),
- malfunction of control systems, e.g. of PV inverters.

Consequences of supraharmonic voltages can be:
- malfunctions of equipment, especially when using capacitive touch controls,
- lifetime reduction of capacitors (e.g. in LED lamps) due to additional thermal loading,
- incorrect time display in clocks if the reading is derived from the zero crossings of the network voltage (e.g. certain clock radios),
- acoustic noise due to excitation of mechanical resonances.

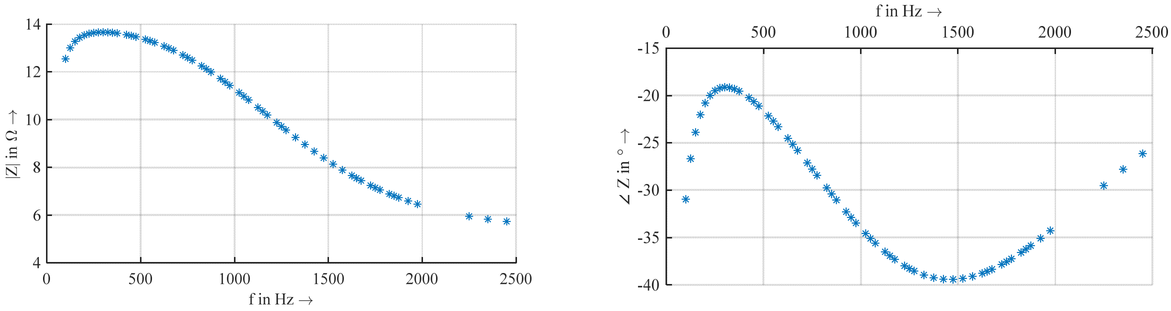
6.2 Frequency-dependent network impedance

The short-circuit impedance at the relevant point in the network Z_{sc} can only be used for calculating the power-frequency short-circuit power S_{sc} (see Section 3). Other values apply for the impedance at frequencies other than the power frequency. The prerequisite for calculating the current emission limits from associated voltage emission limits is the knowledge or assumption of the frequency-dependent network impedance.

The frequency-dependent network impedance usually has multiple resonances. The resonance frequency and the quality factor of the resonances strongly depend on the network configuration, the present switching state of the network, the type and operating point of the connected customer installations, as well as possibly on the switching state of the upstream network and the network loading. With increasing frequency, the series impedances of the network elements increase approximately linearly due to the direct influence of the frequency on the reactance, with a simultaneously increasing impedance angle. In addition, the frequency-dependent resistances of the network elements (skin effect, proximity effect) and the associated frequency-dependent inductances are relevant, but are not considered in the calculation of emission limits within the scope of these Technical Rules.

6.2.1 Low-voltage networks

Depending on the circuit topology, on input filter design and on the internal control circuits, the impact of appliances connected to the network on the frequency-dependent network impedance can be very different. Input capacitances of electrical appliances and non-detuned capacitor banks for power-factor correction in customer installations can influence the absolute value of the frequency-dependent network impedance in such a way that its phase angle decreases at higher frequencies and the resulting frequency-dependent network impedance can become capacitive over a wide frequency range. As the frequency increases, the frequency-dependent network impedance is determined more and more by the appliances connected in the customer installations and less by the network elements themselves. Fig. 6-1 shows an example of the characteristics of the absolute value and the phase angle of the input impedance of an electric vehicle with on-board charging rectifier with a dominant capacitive behaviour in the frequency range up to 2.5 kHz.



Absolute value   Phase angle

Fig. 6-1: Example of the characteristics of absolute value and phase angle of the frequency-dependent input impedance of a typical on-board charging rectifier for electric vehicles

Fig. 6-2 schematically shows the possible effects of appliances ($\underline{Z}_A$) on the frequency-dependent network impedance. One or more resonances can occur which can significantly interfere the frequency-dependent network impedance $\underline{Z}_M$ at point M. The characteristic of the frequency-dependent network impedance (absolute value and phase angle) is therefore highly dependent on location and time.

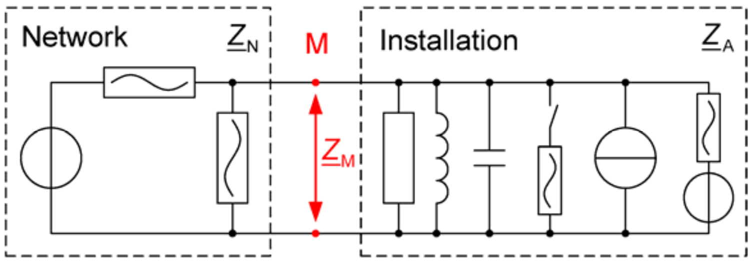


Fig. 6-2: Single-phase equivalent circuit diagram for determining the frequency-dependent network impedance at point M (parallel connection of network-side impedance and installation-side impedance)
($\underline{Z}_M$: Frequency-dependent network impedance; $\underline{Z}_N$: Network-side impedance; $\underline{Z}_A$: Installation-side impedance)

For LV networks, the standard [EN 61000-4-7] describes a characteristic of the frequency-dependent network impedance as a loop impedance up to 9 kHz, which takes into account the increasing influence of the connected appliances. Based on its application, this impedance is comparable with the reference impedance according to [IEC 60725] and is accordingly conservative, so that the actual frequency-dependent network impedance is lower at the most POCs. Fig. 6-3 shows measured values of the frequency-dependent network impedance (measured between phase and neutral) for selected representative points in public LV networks in Germany, Austria, Switzerland and the Czech Republic [9]. In most cases, they show at least one pronounced resonance and varies in the range of about two decades.

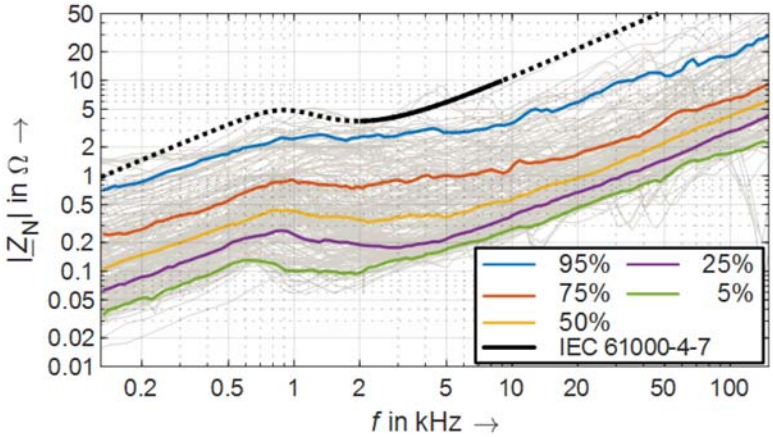
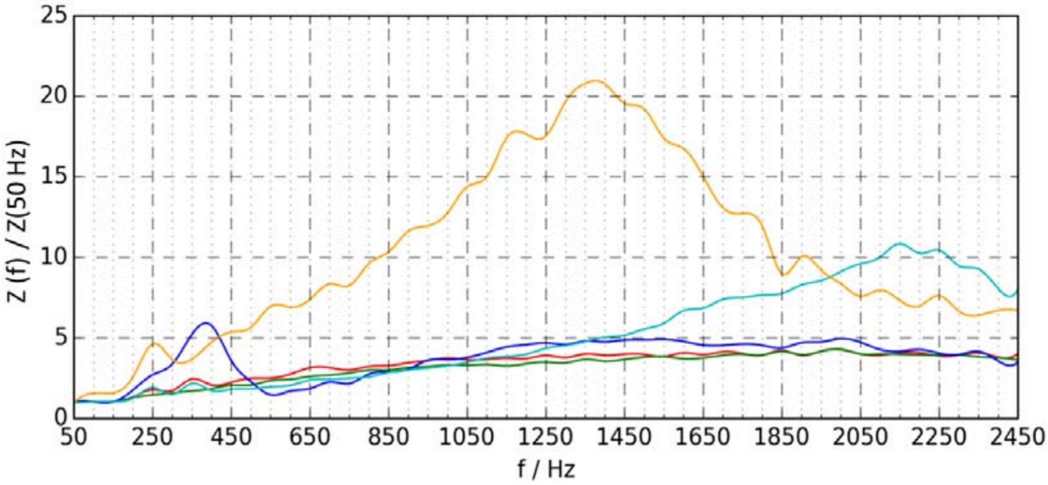


Fig. 6-3: Typical characteristics of the frequency-dependent network impedance (between phase and neutral) measured in public LV networks in Germany, Austria, Switzerland and the Czech Republic [9]

In LV networks, pronounced resonances are increasingly observed at frequencies in the range of a few hundred Hertz, which mainly results from the increasing number of filter capacitances in modern power electronic equipment. This is one of the reasons why a resonance factor is also introduced for the calculation of emission limits in LV networks.

Field measurements in LV networks at POCs with individual high-power converters or with numerous low-power converters show very clearly that the characteristic of the frequency-dependent network impedance can be significantly influenced by the rated power and the type of the converters (Fig. 6-4). This behaviour can be explained by the differences in circuit topology including the design of filter circuits and the implement control algorithms. If the appliances generate higher current harmonics at a resonance of the network impedance, considerable voltage distortions can occur, which in turn can interfere the behaviour of appliances of other customers. If oscillatory systems are excited in their resonance range, connected appliances can become unstable in case of low damping, which usually results in a disconnection from the network (tripping). Those converters whose power or current control react highly sensitive at resonances are particularly vulnerable.



red	Transformer substation
green	LV POC without inverter
blue	LV POC with type 1 and type 2 inverters
cyan	LV POC with type 3 inverter
yellow	LV POC with high-power converter

Fig. 6-4: Effect of converters on the characteristic of the frequency-dependent network impedance [10] (The types shown belong to different manufacturers.)

Based on studies in distribution networks with respect to distributed inverter-based installations [10], monitoring of current and voltage harmonics is recommended if:

- the ratio of short-circuit power to the total power of the connected installations is less than 50 and
- the ratio of short-circuit power to the rated power of an individual converter is less than 300.

For PV systems it is advantageous to use few inverters with high rated power instead of a high number of inverters of low power.

6.2.2 Medium- and high-voltage networks

Unlike in the LV level, the network configuration in the MV and HV level has a significant influence on the frequency-dependent network impedance. Especially in large cable networks, the first parallel resonance can already occur at low frequencies, which can e.g. cause controller resonances in generating installations. The inductances of the transformers connecting the downstream network level together with capacitances in the downstream network level (e.g. non-detuned capacitor banks) can result in pronounced series resonances.

Fig. 6-5 shows an example of a measurement of the frequency-dependent network impedance in an MV network at different switching states of a wind farm. The first parallel resonance is near the 5th harmonic, the second parallel resonance is at about 4 kHz. Fig. 6-6 shows the measurement of the frequency-dependent network impedance at different times of the day at the POC intended for connecting a traction power converter to an HV network. The characteristic also contains several resonances with considerably varying frequency of the second resonance depending on the time of the day.

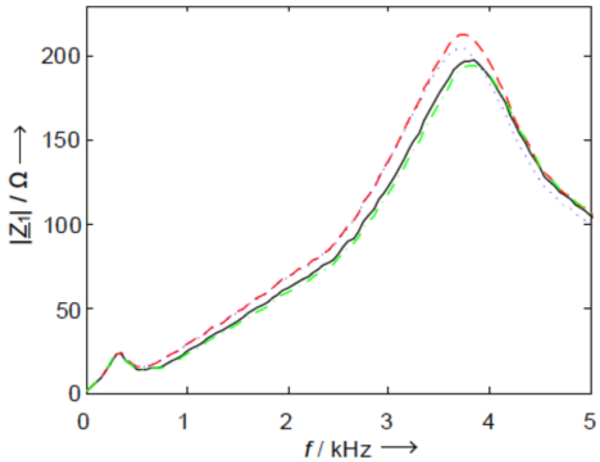


Fig. 6-5: *Characteristic of the frequency-dependent network impedance in a public MV network including a wind farm at several switching states [11]*

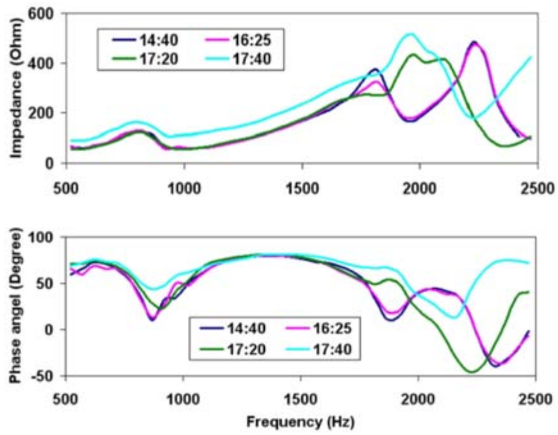


Fig. 6-6: *Characteristic of the frequency-dependent network impedance in an HV network [12]*

In general, in MV and HV networks, the following applies:

- The resonance frequency of the first parallel resonance in overhead line systems is higher than that in cable systems for a comparable network size.
- The resonance frequency of the first parallel resonance decreases with increasing size of the network for a comparable network configuration.
- A high network loading is attenuating the resonance rise.
- Usually, off-peak periods are the worst case in terms of resonance phenomena.

6.2.3 Determination

The reliable determination of resonances is complex and in practice only possible by detailed network studies with extensive simulations. Here, too, the results depend to a large extent on the availability and quality of the input data as well as on the models used for the network elements and customer installations.

For this reason, the frequency-dependent network impedance is in many cases extrapolated as a straight line based on the short-circuit impedance (impedance line). To allow resonances to be taken into account when calculating emission limits, a resonance factor *k* is introduced to represent the deviation of the actual characteristic of the frequency-dependent network impedance from the extrapolated impedance line. For harmonics and interharmonics in LV, MV and HV networks, the frequency-dependent network impedance is determined using the following equations:

Harmonics:

$$Z_{\nu} = k_{\nu} \cdot \nu \cdot Z_{sc} \tag{6-1}$$

Interharmonics:

$$Z_{\mu} = k_{\mu} \cdot (\mu + 0.5) \cdot Z_{\mathrm{sc}} \quad (6\text{-}2)$$

where

ν	*is the order of the harmonic subgroup (see note),*
μ	*is the order of the interharmonic subgroup (see note),*
k_{ν}	*is the resonance factor for the harmonic order* ν*,*
k_{μ}	*is the resonance factor for the interharmonic order* μ*,*
Z_{ν}	*is the approximated impedance for the harmonic order* ν*,*
Z_{μ}	*is the approximated impedance for the interharmonic order* μ*,*
Z_{sc}	*is the short-circuit impedance.*

Note:
The emission limits for harmonics and interharmonics apply for the respective subgroups according to [EN 61000-4-7]. For the sake of simplicity, these Technical Rules consider only the network impedance at the centre frequency of the relevant harmonic or interharmonic subgroup.

The physically exact definition of an interharmonic, as it is also used in various standards (e.g. [EN 61000-2-2]), is based on fractions of harmonic orders *m*:

$$Z_{m} = m \cdot Z_{\mathrm{sc}} \quad (6\text{-}3)$$

where

m	*is the interharmonic order,*
Z_m	*is the approximated impedance for the interharmonic order m,*
Z_{sc}	*is the short-circuit impedance.*

For supraharmonics in MV and HV networks, similar to harmonics and interharmonics, the following applies:

$$Z_{b} = k_{b} \cdot \frac{f_{b}}{f_{\mathrm{n}}} \cdot Z_{\mathrm{sc}} \quad (6\text{-}4)$$

where

f_b	*is the centre frequency of the supraharmonic band b,*
f_n	*is the nominal power frequency,*
k_b	*is the resonance factor for the supraharmonic with centre frequency* f_b*,*
Z_b	*is the approximated impedance for the supraharmonic with centre frequency* f_b*,*
Z_{sc}	*is the short-circuit impedance at power frequency.*

Based on a comprehensive measurement campaign (see [9] or Section 6.2.1), detailed knowledge of typical characteristics of the frequency-dependent network impedance is available for supraharmonics in LV networks. Therefore, a straight-line approximation based on the reference impedance $Z_{\mathrm{ref\,b}}$ proposed in the informative Annex B in [EN 61000-4-7] is applied in the frequency range from 2 kHz to 9 kHz (relevant frequency range for emission limits) in LV networks:

$$Z_b = k_b \cdot Z_{\mathrm{ref}\,b} \cdot \left(r + (1-r) \cdot \frac{S_{\mathrm{sc\,ref}}}{S_{\mathrm{sc}}} \right) \tag{6-5}$$

with

$$Z_{\mathrm{ref}\,b} = 10{,}25\,\Omega - \frac{(9\ \mathrm{kHz} - f_b)}{\mathrm{kHz}} \cdot \Omega \tag{6-6}$$

where

k_b	*is the resonance factor for the supraharmonic with centre frequency f_b,*
Z_b	*is the approximated impedance for the supraharmonic with centre frequency f_b,*
$Z_{ref\,b}$	*is the reference impedance for the supraharmonic with centre frequency f_b,*
r	*is the factor accounting for the influence of the short-circuit power,*
$S_{sc\,ref}$	*is the reference short-circuit power (= 570 kVA),*
S_{sc}	*is the short-circuit power at the relevant point.*

Note:
The emission limits for supraharmonics apply to a 200 Hz band according to [EN 61000-4-7] (see also definitions in Section 1). For this reason, only the network impedance at the centre frequency of the relevant 200 Hz band is considered for simplification.

The factor r takes into account that the frequency-dependent network impedance at frequencies above 2 kHz is increasingly influenced by the connected appliances and less by the short-circuit power or short-circuit impedance (see Section 6.2.1). It is in the range r = 0 .. 1, with r = 1 implying that the frequency-dependent network impedance is no longer influenced by the short-circuit power. Measurements have shown that the factor r tends to decrease with increasing short-circuit power. Further information can be found in [9].

Three options are available for determining the resonance factor $k_{\nu/\mu/b}$ and thus the frequency-dependent network impedance $Z_{\nu/\mu/b}$ in order to specify the emission limits. All options take into account solely the resonances at the relevant location. If other locations in the respective network have to be considered with regard to possible resonances, this can only be done by detailed network studies.

Note:
The resonance factor $k_{\nu/\mu/b}$ is not identical with the quality factor g.

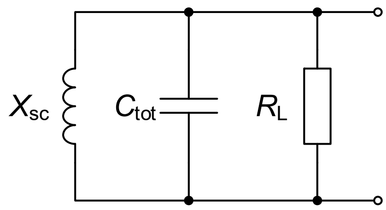
6.2.3.1 Option 1: Explicit consideration of all existing resonances

If all necessary input data and models with appropriate quality are available, a detailed network simulation provides the most reliable information on the frequency-dependent network impedance. Such a simulation is particularly recommended for networks, which, due to their configuration, are expected to show resonances at characteristic frequencies with significant excitation (e.g. 5th or 7th harmonic order). For different scenarios (e.g. peak-load/off-peak periods, different switching states), the worst case impedance values $Z_{\nu/\mu/b}$ shall be used for calculating the emission limits. For frequencies above the first parallel resonance, the results of a network simulation become less and less reliable.

Although the impedance above the first parallel resonance is often lower than the associated impedance line, due to the risk of resonance amplifications at other locations in the network, a value of $k_{v/\mu/b}$ = 0.8 .. 1 should be used. The Technical Report [IEC 61000-3-6] recommends $k_{v/\mu/b}$ = 1.

6.2.3.2 Option 2: Estimation of the first parallel resonance

The frequency-dependent network impedance has a maximum at the first parallel resonance, which is usually in the frequency range below 2 kHz. The first parallel resonance of the network with the resonance frequency f_{res} can be approximately determined using a simplified equivalent circuit according to Fig. 6-7.



X_{sc}	*Reactance of the short-circuit impedance at the relevant location*
C_{tot}	*Resulting capacitance at the relevant location (including cable capacitance, capacitance of non-choked power-factor correction systems, etc.)*
R_L	*Resulting resistance of the load at the relevant location (network load)*

Fig. 6-7: Simplified equivalent circuit for modelling the first parallel resonance

The following estimation applies:

$$f_{res} \approx f_N \sqrt{\frac{S_{sc\,act}}{Q_{tot}}} \tag{6-7}$$

where

f_N	*is the power frequency,*
$S_{sc\,act}$	*is the actual short-circuit power at the relevant location at power frequency,*
Q_{PCC}	*is the (capacitive) reactive power according to $Q_{tot} = 2\pi \cdot f_N \cdot C_{tot} \cdot U_N^2$.*

Assuming that the effective shares of the total capacitance C_{tot} are connected directly or very close to the considered location, the model provides results with good accuracy in most cases. Higher deviations can occur if the total capacitance C_{tot} is distributed over the network or is not directly connected to the considered point (e.g. connection via a cable). While this assumption applies in most cases in LV and MV networks, in HV networks it shall almost always be assumed that the capacitance in the network (cable capacitances) is distributed. in this case the actual resonance frequency can be higher than the resonance frequency estimated according to equation (6-7).

The network loading is significantly influencing the attenuation and thus the impedance rise at the first of parallel resonance compared to the impedance line. If no exact estimate is available, the values in Tab. 6-1 (LV) or Tab. 6-2 (MV, HV) can be used as a reference. The resonance factors refer to the centre frequencies of harmonics or interharmonics in the respective subgroups (see note below equation (6-2)).

Although the impedance above the first parallel resonance is often lower than the associated impedance line, due to possible resonance amplifications at other locations in the network, a value of $k_{v/\mu}$ = 0.8 .. 1 should be used. The technical report [IEC 61000-3-6] recommends $k_{v/\mu}$ = 1.

Tab. 6-1: Indicative values for the resonance factor $k_{v/\mu}$ in LV networks (frequency range $f \leq 2$ kHz)

$f/f_N < (f_{res}/f_N - 2.5)$	$(f_{res}/f_N - 2.5) \leq f/f_N \leq (f_{res}/f_N + 2.5)$	$f/f_N > (f_{res}/f_N + 2.5)$
$k_{v/\mu} = 1$	$k_{v/\mu}$ = 1.1 to 1.4	$k_{v/\mu}$ = 0.8 to 1

Tab. 6-2: Indicative values for the resonance factor $k_{v/\mu/b}$ in MV and HV networks (frequency range $f \leq 2$ kHz)

<table>
<tr><th></th><th>$f/f_N < (f_{res}/f_N - 2.5)$</th><th>$(f_{res}/f_N - 2.5) \leq f/f_N \leq (f_{res}/f_N + 2.5)$</th><th>$f/f_N > (f_{res}/f_N + 2.5)$</th></tr>
<tr><td>Networks with a high share of cables</td><td rowspan="2">$k_{v/\mu} = 1$</td><td>$k_{v/\mu}$ = 1.5 to 2.5</td><td rowspan="2">$k_{v/\mu/b}$ = 0.8 to 1</td></tr>
<tr><td>Networks with a high share of overhead lines</td><td>$k_{v/\mu}$ = 2 to 3</td></tr>
</table>

Note:
The resonance factors can vary within the resonance range. If a very low share of resistive loads is to be expected during off-peak periods, the resonance factor should be selected from the upper value range.

6.2.3.3 Option 3: General consideration of the first parallel resonance

For assessments in HV networks, it is generally recommended to individually consider the first parallel resonance in the calculation of current emission limits.

For LV and MV networks, the first parallel resonance can be taken into account as an estimate if it is not exactly known. For this purpose a respective resonance factor (Tab. 6-3) is defined depending on the network level for the frequency range in which an exceedance of the impedance line by the first parallel resonance can be expected. The first parallel resonance is usually in the frequency range below 2 kHz, so that only resonance factors for harmonics and interharmonics are given. For LV networks, it is also necessary to consider the value used for the impedance angle factor k_{XR} (Section 6.3) when calculating the emission limits.

Tab. 6-3: Indicative values for frequency range and resonance factor $k_{v/\mu}$ in LV and MV networks

Network level	Frequency range	Resonance factor within frequency range
LV	$7 \leq f/f_N \leq 25$	$k_{v/\mu} = 1.15$ ($k_{XR} > 0.95$) $k_{v/\mu} = 1.3$ ($k_{XR} \leq 0.95$)
MV	$2 \leq f/f_N \leq 19$	$k_{v/\mu} = 1.5$

Outside the frequency range indicated in Tab. 6-3, $k_{v/\mu/b} = 1$ shall be used. The approximation generally provides reasonable emission limit values, but can result in unacceptably high levels in individual cases. Therefore, accompanying measurements are recommended.

6.3 Consideration of the network impedance angle

The simplified extrapolation of the frequency-dependent network impedance based on the absolute value of the short-circuit impedance (impedance line) assumes that the reactive component of the impedance dominates, since the following approximation equation

$$\nu \cdot Z_{sc} = \nu \cdot \sqrt{R_{sc}^2 + X_{sc}^2} \approx \sqrt{R_{sc}^2 + \nu^2 \cdot X_{sc}^2} \qquad (6\text{-}8)$$

shows an appropriate accuracy only under the condition $X_{sc}/R_{sc} > 2.5$. While this condition is usually satisfied for locations in HV and MV networks as well as near the supply transformer in LV networks, the ratio X_{sc}/R_{sc} can be significantly lower in LV networks, especially at spur ends in LV cable networks. In this case, the extrapolation using equations (6-1) and (6-3) for frequencies outside the resonance range results in conservative assumptions regarding the frequency-dependent network impedance.

Therefore, an impedance angle factor k_{XR} is introduced for the calculation of emission limits for harmonics and interharmonics in LV networks, for which the values in Tab. 6-4 are recommended depending on the *X/R* ratio at the relevant location.

Tab. 6-4: Indicative values for the impedance angle factor k_{XR} in LV networks

X/R	k_{XR}		X/R	k_{XR}
X/R < 0.2	0.4		0.9 ≤ X/R < 1.1	0.8
0.2 ≤ X/R < 0.3	0.5		1.1 ≤ X/R < 1.4	0.85
0.3 ≤ X/R < 0.4	0.6		1.4 ≤ X/R < 1.8	0.9
0.4 ≤ X/R < 0.6	0.65		1.8 ≤ X/R < 2.5	0.95
0.6 ≤ X/R < 0.7	0.7		X/R ≥ 2.5	1
0.7 ≤ X/R < 0.9	0.75			

If the *X/R* ratio at the relevant location is unknown or if the network impedance angle is to be neglected when calculating the emission limits, $k_{XR} = 1$ applies.

Note:
For supraharmonics in LV networks, no application of the impedance angle factor is intended due to the deviating determination of the extrapolated impedance line compared to harmonics and interharmonics.

6.4 General methodology for determining emission limits

6.4.1 Harmonic components

Based on the compatibility level for LV networks according to [EN 61000-2-2] and applying the concept of its share between the different network levels according to Section 2.3, the global contribution of an LV, MV or HV network can be determined using the following equation:

$$u_{\nu\ \mathrm{glob\ xV}} = u_{\nu\ \mathrm{CL\ LV}} \cdot k_{\nu \mathrm{N\ xV}} \qquad (6\text{-}9)$$

where

$u_{\nu\ CL\ LV}$ *is the compatibility level in the LV network for the harmonic order ν,*

$u_{\nu\ glob\ xV}$ *is the global contribution of the LV, MV and HV network level to the harmonic order ν,*

$k_{\nu\ N\ xV}$ *is the sharing factor of the LV, MV and HV network level for the harmonic order ν.*

When determining the sharing factors (Fig. 6-8), the following was taken into account:

- With increasing harmonic order and for non-characteristic harmonic orders, the phase angle diversity of harmonic current emission of different customer installations usually increases.
- The probability of the simultaneous occurrence of harmonic current emission with the same order in different customer installations usually decreases with an increasing harmonic order and is usually lower for non-characteristic harmonic orders.
- With an increasing harmonic order, the attenuation increases and the propagation distance in the considered network level usually decreases.
- For harmonic orders with the zero-sequence system as the prevailing system, there is usually no significant transmission from LV to MV network level due to the switching group of the transformers typically used.
- An appropriate share of the compatibility level is reserved for the EHV network level.
- The share between the network levels is significantly determined by the short-circuit impedance of the transformers connected the network levels.

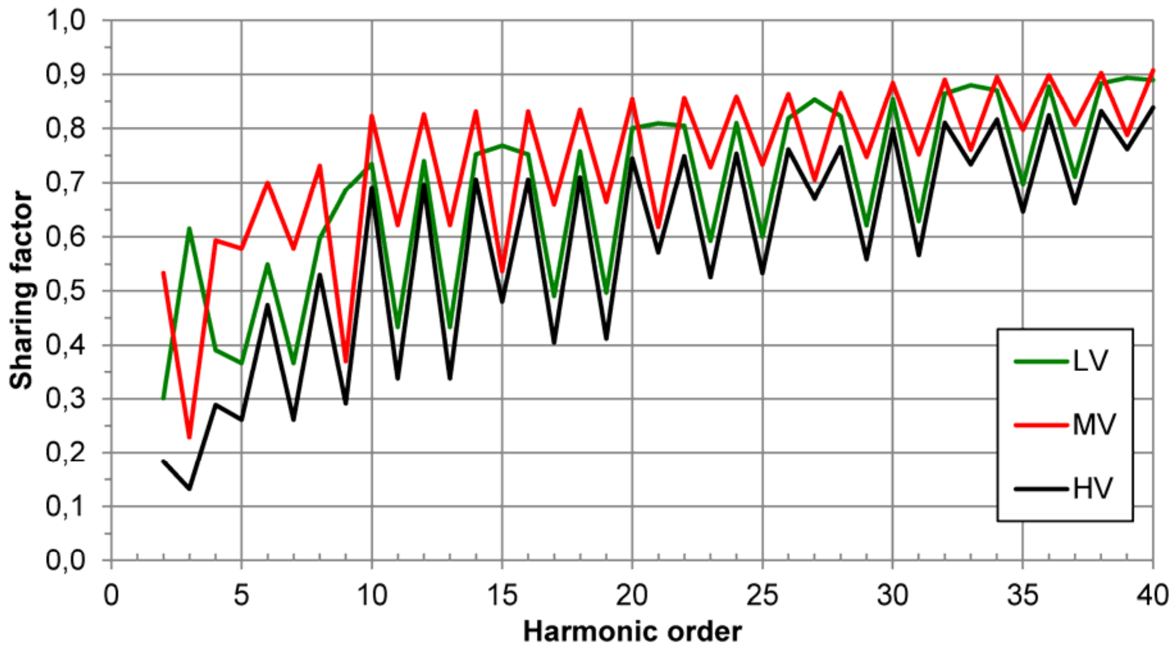


Fig. 6-8: Sharing factors for determining the global contributions per network level

The global contribution within the respective network level is divided proportionally according to their power between the individual customer installations.

6.4.2 Interharmonic components

Usually, it is assumed to be unlikely that several customer installations within a network simultaneously emit interharmonics in the same subgroup. If such a case occurs, the emissions are presumably independent of each other. Accordingly, the compatibility or planning level reduced by the factor √2 is used as the basis for calculating the emission limits of an individual customer installation.

Note:
If several customer installations show a similar emission of interharmonics or one or more customer installations with similar emission of interharmonics are connected to the upstream network level, unacceptably high levels in the considered network can result. In the latter case, series resonances can cause an unacceptable amplification of interharmonic voltages in the

downstream network level. In these situations, the explicit determination of lower emission limits by the DSO can be necessary.

6.4.3 Supraharmonic components

The specification of supraharmonic limits applies to the frequency range from 2 kHz to 9 kHz. For the frequency range between 9 kHz and 150 kHz, the limits are still under consideration. For a customer installation showing significant emissions in the frequency range from 9 kHz to 150 kHz, compliance of disturbance levels with the compatibility levels for public LV networks according to [EN 61000-2-2] can be used as indication until emission limits are available.

Usually, it is assumed to be unlikely that several customer installations within a network simultaneously emit supraharmonics in one frequency band. If such a case occurs, the emissions are likely to be independent of each other. Furthermore, experience has shown that at frequencies above 2 kHz, the propagation to the upstream network is low. Accordingly, the compatibility or planning level reduced by the factor $\sqrt{2}$ is used as the basis for calculating the emission limits of an individual customer installation.

Note:
If several customer installations show a similar emission of supraharmonics or one or more customer installations with similar emission of supraharmonics are connected to the upstream network level, unacceptably high levels in the considered network can result. In addition, series resonances can cause an unacceptable amplification of supraharmonic voltages in the downstream network level [13]. In these situations, the explicit determination of lower emission limits by the DSO can be necessary.

6.5 Conversion between POC and PCC

For the absolute harmonic, interharmonic or supraharmonic current the following approximation applies:

$$I_{\nu/\mu/b\ \mathrm{PCC}} \approx I_{\nu/\mu/b\ \mathrm{POC}} \tag{6-10}$$

where

$I_{\nu/\mu/b\ PCC}$ *is the harmonic, interharmonic or supraharmonic current of the customer installation at the PCC,*

$I_{\nu/\mu/b\ POC}$ *is the harmonic, interharmonic or supraharmonic current of the customer installation at the POC.*

Note:
The propagation in the network significantly depends on other connected appliances, especially in the frequency range above 2 kHz. Equation (6-10) is based on the assumption that there is only a line between the POC and the PCC without any other installations/appliances connected.

According to equation (6-10), the conversion of the emission limit of a customer installation as harmonic voltage from the POC to the PCC for harmonics, interharmonics and supraharmonics is approximated as follows:

$$u_{\nu/\mu/\mathrm{b\ PCC}} = \frac{k_{\nu/\mu/\mathrm{b\ PCC}}}{k_{\nu/\mu/\mathrm{b\ POC}}} \cdot \frac{k_{\mathrm{XR\ PCC}}}{k_{\mathrm{XR\ POC}}} \cdot \frac{S_{\mathrm{sc\ POC}}}{S_{\mathrm{sc\ PCC}}} \cdot u_{\nu/\mu/\mathrm{b\ POC}} \tag{6-11}$$

where

$u_{\nu/\mu/b\ PCC}$ *is the emission limit of the customer installation as harmonic, interharmonic or supraharmonic voltage at the PCC,*

$u_{\nu/\mu/b\ POC}$ *is the emission limit of the customer installation as harmonic, interharmonic or supraharmonic voltage at the POC,*

$k_{\nu/\mu/b\ POC}$ *is the resonance factor of the harmonic order* ν*, the interharmonic order* μ *or the supraharmonic band b at the POC,*

$k_{\nu/\mu/b\ PCC}$ *is the resonance factor of the harmonic order* ν*, the interharmonic order* μ *or the supraharmonic band b at the PCC,*

$k_{XR\ POC}$ *is the impedance angle factor of the harmonic order* ν *or the interharmonic order* μ *at the POC,*

$k_{XR\ PCC}$ *is the impedance angle factor of the harmonic order* ν *or the interharmonic order* μ *at the PCC,*

$S_{sc\ POC}$ *is the short-circuit power at the POC,*

$S_{sc\ PCC}$ *is the short-circuit power at the PCC.*

The impedance angle factor $k_{\mathrm{XR\ x}}$ is used only for harmonics and interharmonics in LV networks. In all other cases, the impedance angle factor $k_{\mathrm{XR\ x}} = 1$ shall be used (see Section 6.3). If the applicable impedance angle factor for harmonics or interharmonics in the LV network is unknown in equation (6-12), it can be simplified by $k_{\mathrm{XR\ x}} = 1$. The latter usually results in a more conservative estimate for the emission limit at the PCC.

If the resonance factors $k_{\nu/\mu/\mathrm{b\ x}}$ in equation (6-12) are unknown, they can be simplified by $k_{\nu/\mu/\mathrm{b\ x}} = 1$. This can result in a more conservative estimate for the emission limit at the PCC.

6.6 Assessment parameters

The absolute values of the individual harmonic currents I_ν for orders up to 40, of the individual interharmonic currents I_μ for orders up to 40 and of the supraharmonic currents I_b in the frequency range from 2 kHz to 9 kHz are used as the assessment parameters.

For measuring the emission of a customer installation, the assessment of the emitted voltages can be useful in addition to the assessment of the emitted currents.

Based on the harmonic current emission limit the harmonic voltage emission limit can be calculated using the following equation:

$$u_{\nu\ \text{perm POC}} = \frac{\nu \cdot k_{\text{corr}\ \nu} \cdot p_\nu}{1000} \cdot \frac{1}{\sqrt{k_\text{C} + k_\text{G} + k_\text{S}}} \cdot \sqrt{\frac{S_\text{A}}{S_\text{sc POC}}} \quad (6\text{-}12)$$

where

$u_{\nu\ perm\ POC}$	*is the emission limit of the customer installation as harmonic voltage at the POC,*
ν	*is the harmonic order,*
S_A	*is the agreed power of the customer installation,*
$S_{sc\ POC}$	*is the short-circuit power at the POC,*
p_ν	*is the proportionality factor for the harmonic order* ν,
$k_{corr\ \nu}$	*is the correction factor for the harmonic order* ν,
k_C	*is the consumption capacity factor,*
k_G	*is the generation capacity factor,*
k_S	*is the storage capacity factor.*

The correction factor $k_{\text{corr}\ \nu}$ (Tab. 6-5) shall only be used for LV networks (three-phase four-wire networks) and is intended to compensate for the additional reduction of the proportionality factors p_ν for harmonic orders that are multiples of 3. In all other cases $k_{\text{corr}\ \nu}$ is 1.

Tab. 6-5: Correction factor $k_{corr\ \nu}$ for proportionality factors for LV networks

ν	$k_{corr\ \nu}$	ν	$k_{corr\ \nu}$	ν	$k_{corr\ \nu}$	ν	$k_{corr\ \nu}$
3	4.0	15	3.0	27	3.0	39	2.0
6	1.3	18	1.5	30	1.5		
9	3.0	21	3.0	33	2.0		
12	1.5	24	1.5	36	1.5		

For interharmonic voltages the emission limits indicated in Tab. 6-6 apply.

Tab. 6-6: Emission limits $u_{\mu\ perm\ POC}$ of the interharmonic voltage of order μ

μ	$u_{\mu\ \text{perm POC}}$
1, 2	0.07 %
3 … 30	0.14 %
31 … 39	0.21 %

For supraharmonic voltages in the frequency range from 2 kHz to 9 kHz the following equation applies:

$$\text{NS:} \quad u_{b\ \text{perm POC}} = 1.435\% \cdot \left(\frac{b}{\text{kHz}}\right)^{-0.52} \quad (6\text{-}13)$$

$$\text{MS, HS:} \quad u_{b\ \text{perm POC}} = 1.015\% \cdot \left(\frac{b}{\text{kHz}}\right)^{-0.52} \quad (6\text{-}14)$$

where

$u_{b\ perm\ POC}$	*is the emission limit of the customer installation as supraharmonic voltage at the POC,*
b	*is the supraharmonic band with the centre frequency* f_b.

Note:
The supraharmonic voltage emission limits are based on the specifications of the compatibility levels in [IEC 61000-2-2]. Two ranges are specified in [IEC 61000-2-2]: from 2 kHz to 3 kHz with a constant value and from 3 kHz to 9 kHz with a linearly log-log decreasing gradient. For the sake of simplicity, a linearly log-log decreasing function is used in these Technical Rules for the entire range from 2 kHz to 9 kHz. This results in a maximum deviation of –18 % at the 3 kHz corner point.

Note:
The emission limit is not equal to the difference of the absolute value of the voltage distortion determined with and without a connected customer installation ("before and after measurement"), except for harmonics with orders lower than 5.
Due to the assumed diversity while calculating the emission limits, the acceptable absolute difference is lower than the emission limit. The permitted value depends on the number, size and distribution of the customer installations in the considered network and in some cases it can be only 20 % of the respective emission limit.

For the measurement-based assessment at the PCC, the conversion according to Section 6.5 shall be observed.

A very low impedance at a harmonic, interharmonic or supraharmonic component (e.g., due to a series resonance) can result in very high distorted currents even though the contributions to the voltage distortion are complied with. These can cause unacceptable voltage distortions at other locations in the network. In such cases, it is recommended to reduce the corresponding voltage emission limit according to the following equation:

$$u_{\nu/\mu/b\ \text{red POC}} = k_{\nu/\mu/b\ \text{POC}} \cdot u_{\nu/\mu/b\ \text{perm POC}} \qquad (6\text{-}15)$$

where

$u_{\nu/\mu/b\ red\ POC}$ *is the reduced emission limit of the customer installation as harmonic, interharmonic or supraharmonic voltage at the POC,*

$u_{\nu/\mu/b\ perm\ POC}$ *is the permitted emission limit of the customer installation as harmonic, interharmonic or supraharmonic voltage at the POC,*

$k_{\nu/\mu/b\ POC}$ *is the resonance factor of the harmonic order ν, the interharmonic order μ or the supraharmonic band b at the POC.*

If the resonance factor $k_{\nu/\mu/b\ \text{POC}}$ is unknown, it is recommended that the harmonic, interharmonic or supraharmonic currents do not exceed a multiple (in the range 1.5 .. 2.0) of the respective emission limit.

6.7 Classification of appliances generating harmonic components

For the assessment of the connection of a customer installation with regard to harmonics, it can be necessary to determine the non-linear (harmonics-generating) part of the agreed power of the customer installation.

For this purpose, the sum of the rated powers of all harmonics-generating appliances in the customer installation shall be calculated, classifying the appliances into three classes according to the total harmonic distortion of their current during rated operation.

- Class 1:
  This class includes equipment with low harmonic emission (THDi ≤ 25 %), such as converters with a pulse number $p \geq 12$, fluorescent lamps and other gas discharge lamps with inductive ballast, self-commutating converters (e.g. PV inverters or converters for storage devices) or equipment with active power-factor correction (e.g. charging units for electric vehicles, LED lighting).
- Class 2:
  This class includes equipment with medium harmonic emission (25 % < THDi ≤ 50 %), such as six-pulse converters with current DC-link or six-pulse converters with voltage DC-link and inductive smoothing.
- Class 3:
  This class includes equipment with high harmonic emission (THDi > 50 %), such as six-pulse converters with voltage DC-link without inductive smoothing, computers including peripheral devices, compact fluorescent lamps with electronic ballast, LED-lighting without active power-factor correction and consumer electronic devices.

When determining the harmonics-generating part of the agreed power of a customer installation, the possible future expansion with harmonics-generating appliances shall be considered.

6.8 Mitigation measures

Mitigation measures can be required both in the consumer installation (reducing the distorted currents emitted into the network) and in the distribution network (reducing the effects of the distorted currents on the distorted voltages). Depending on the economic situation as well as the local and technical conditions, one or more of these measures might be suitable. In addition, compensation effects can occur due to other customer installations nearby the POC of a considered customer installation, which may be taken into account when selecting suitable local mitigation measures.

6.8.1 Harmonics and interharmonics

Measures applicable on the network side:
Measures that are applicable on the network side to increase the short-circuit power are given in Section 2.8. In addition, the installation to be connected and other customer installations can be connected to different busbars.

Measures applicable on the installation side:

- use of appliances with lower total harmonic distortion THDi,
- improvement of smoothing in the DC link of converters,
- use of passive filters,
- use of active filters.

In the following sections, selected installation-side measures are described in more detail.

Note:
To avoid unwanted resonances, power-factor correction systems shall be suitably detuned. A detuning ratio of 14 % shall be selected if 3rd order voltage harmonics can occur in the network.

6.8.1.1 Passive filters

Passive filters are intended to reduce the effects of a customer installation on the distortion of the network voltage. A passive filter is a series resonant circuit with a resonance frequency near or equal to the harmonic or interharmonic emission to be eliminated. Passive filters usually consist of several such series resonant circuits tuned to different frequencies.

For the design of passive filters, special considerations apply:

- Passive filters can have an unacceptable influence on ripple control signals and shall therefore have an appropriate minimum impedance at the ripple-control frequency, which can be requested from the responsible DSO (see also Section 8).
- Permanent over-compensation at fundamental frequency shall always be avoided. Otherwise, the approval of the DSO shall be obtained.
- Passive filters do not only affect the current emissions generated in the customer installation, but can also be loaded by currents resulting from the existing distortion of the network voltage. This background distortion shall be taken into account when designing passive filters.

6.8.1.2 Active filters

Active filters are used to reduce distortions in the frequency range below 2 kHz (harmonics, interharmonics). Unlike passive filters consisting of passive elements (inductor, capacitor) only, active filters continuously analyse the current of the customer installation to be filtered (current-controlled active filters) and feed in an appropriate compensating current based on power electronics. The harmonic and, if necessary, interharmonic components of the compensation current are fed in by the active filter in phase opposition to those of the current in the customer installation. By using an active filter, it is possible to achieve the current of the customer installation to be almost sinusoidal.

Due to their input capacitances and internal control circuits, active filters can influence the local frequency-dependent network impedance. Additional points of resonance can modify the disturbances of the network voltage.

6.8.2 Supraharmonics

Measures applicable on the network side:
The frequency-dependent network impedance in the range above 2 kHz is determined primarily by the connected appliances and therefore network-side measures to increase the short-circuit power are only effective to a limited extent.

Measures applicable on the installation side:
On the installation side, care shall be taken to ensure that the installation is designed considering capacitive couplings and the earthing system. This includes the following:

- avoiding capacitive couplings (no parallel routing of interference-affected cables and interference-suppressed cables, power cables or control cables),
- using shielded motor cables for converter drives,
- direct feedback of supraharmonic leakage currents to the converter,
- low-resistance earthing in the frequency range of supraharmonic emissions; it should be taken into account that the impedance of cables with increasing frequency from a few kHz to several hundred kHz becomes significantly higher than at power frequency,
- ensuring a consistent reference potential,
- avoiding earth loops.

Furthermore, supraharmonics can be effectively reduced by using suitable passive filters or output filters in converters. Active filters are not suitable for reducing supraharmonic emissions due to their limited bandwidth.

6.9 Measurement

The measurement-based verification of compliance can be performed at different relevant points (see Section 2.5). The 95 % quantile of the measured 10 min average values of the harmonic, interharmonic or supraharmonic currents over a one-week period or one operating cycle of the customer installation shall be lower than the calculated emission limit. In addition, the 99 % quantile of the 3 s average values of each day shall not exceed the emission limit multiplied by a factor in the range 1.25 .. 2 (see [IEC 61000-3-14] and [IEC 61000-3-6]). If no exact value is known, a default factor of 1.25 is recommended.

If voltage emissions are to be considered in addition to current emissions (see Section 6.6), the same specifications apply as for current emissions.

Harmonics and interharmonics are to be regarded as subgroups according to [EN 61000-4-7] (see Fig. 6-9).

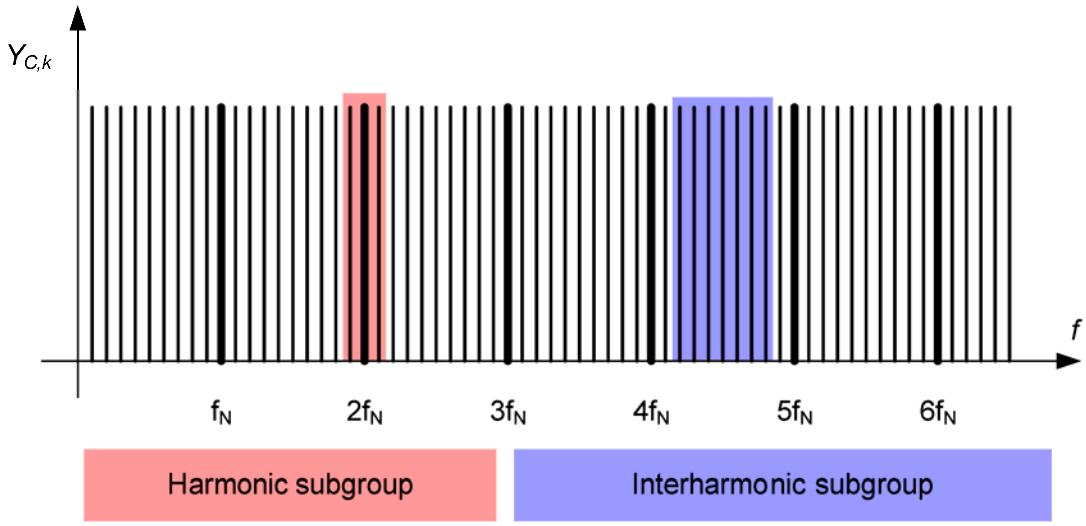


Fig. 6-9: Spectral components of the Fourier transform according to [EN 61000-4-7] with marked harmonic subgroup ν = 2 and interharmonic subgroup μ = 4 as an example

The r.m.s. value of a harmonic subgroup is calculated as the root-sum-square of the r.m.s. values of the spectral components of the harmonic and the two spectral components immediately adjacent to it.

The r.m.s. value of an interharmonic subgroup is calculated as the root-sum-square of the r.m.s. values of all spectral components in the interval between two successive harmonic spectral components, excluding the respective adjacent spectral components to the harmonic spectral components. The order of an interharmonic subgroup is equal to the order of the lower adjacent harmonic. For example, the (subgrouped) interharmonic between the harmonic orders ν = 5 and ν = 6 is μ = 5.

According to [EN 61000-4-7], supraharmonics in the relevant frequency range from 2 kHz to 9 kHz are to be assessed in terms of 200 Hz bands. The r.m.s. value of the 200 Hz band is calculated as the root-sum-square of the r.m.s. values of all spectral components in the range from *b* – 95 Hz to *b* + 100 Hz, where *b* is the centre frequency of the 200 Hz band. For example, the 200 Hz band with centre frequency 2.1 kHz includes all spectral components from 2.005 kHz to 2.2 kHz.

If (in LV networks) the disturbance levels in the frequency range from 9 kHz to 150 kHz are compared with the compatibility levels, a method based on 200 Hz bands shall be used. It should be noted that normative measurement procedures for the frequency range from 2 kHz to 150 kHz for inclusion in [EN 61000-4-30] are under preparation.

The accuracy of measured voltage values at frequencies other than the power frequency, especially at higher frequencies, can be affected by the frequency-dependent transfer ratio of the voltage transformers, which are usually not part of the measurement system and are consequently not calibrated with it [14]. In terms of measuring the current distortion, this effect is usually negligible.

7. Commutation notches

7.1 General

Converters with rated powers of up to several hundred megawatts are frequently used in power engineering, such as:

- static excitation units for synchronous generators or motors,
- starting converters,
- converters used in pumped-storage power stations,
- power supply in electrolysis technology and arc furnaces,
- rolling-mill drives,
- direct converters (used in interconnectors for HVDC transmission or railway applications).

Repetitively occurring dips in the supply voltage are typical for the operation of controlled line-commutated converters. They arise from two rapid voltage changes with negative and positive signs, which occur step-wise and last less than one cycle of the supply voltage. The cause is a short circuit between two phase conductors during commutation until the current is completely transferred between two semiconductor switches (usually thyristors). The depth of these commutation notches depends, among other things, on the trigger delay angle α and has a maximum at α = 90°.

An assessment of customer installations with regard to commutation notches only has to be carried out for controlled line-commutated converters.

Fig. 7-1 shows as an example the theoretical curve of phase to neutral voltage at the POC of a controlled six-pulse converter at the trigger delay angle α = 45°. Commutation notches are often associated with transient oscillations excited by the commutation process, also referred to as commutation oscillations, which depend on the value and the relations between R, L and C of the network and fall in the higher-frequency range (Fig. 7-1 b)). They can cause significant electrical interferences in the networks.

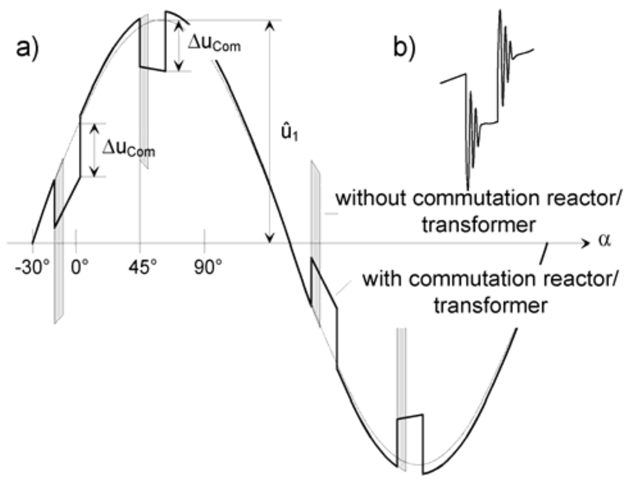


Fig. 7-1: Commutation notches in the phase to neutral voltage
a) Theoretical voltage characteristic of a six-pulse converter
b) Notch with commutation oscillations (detail of a))

The notches in Fig. 7-1 a) shown in grey would arise if the converter is directly connected to the POC. By connecting an commutation reactor and/or transformer between POC and converter, the depth of the notches is reduced, while their duration increases.

Commutation notches appear in the frequency domain in a broader frequency range extending up to several 10 kHz. As a result, they are only covered to a limited degree by the compatibility levels for harmonics, interharmonics and supraharmonics (see Section 6). Therefore, for the assessment of commutation notches, it is necessary to consider them in the time domain.

The relative depth of a commutation notch d_{Com} is defined as the maximum deviation Δu of the voltage waveform from the instantaneous value of the fundamental component, referred to the peak value of the fundamental component $\hat{u}_1$, and is to be calculated as follows:

$$d_{Com} = \frac{\Delta u_{Com}}{\hat{u}_1} \tag{7-1}$$

where

d_{Com} *is the relative depth of a commutation notch (repetitive voltage dip),*

Δu_{Com} *is the maximum deviation of the voltage from the instantaneous value of the fundamental component,*

$\hat{u}_1$ *is the peak value of the fundamental component.*

This definition is based on the deviation of the instantaneous voltage value $\Delta u(t)$, which is given by the absolute value of the difference between the instantaneous value of the (non-sinusoidal) supply voltage and the instantaneous value of its fundamental component at the same time.

Commutation notches including possibly superimposed oscillations primarily cause the following interferences:

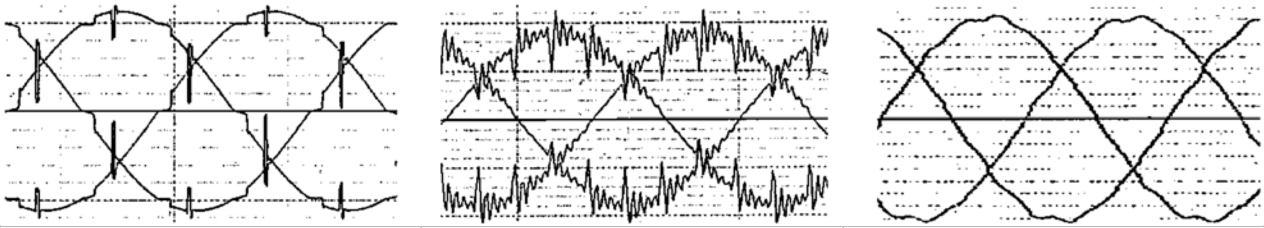
- acoustic interferences in electromagnetic components (motors, transformers and reactors in electrical appliances),
- transfer of higher-frequency components into the electronics via their power supply (in electro-acoustic devices, these can be audible through the loudspeakers),
- image interferences in monitors,
- radio frequency interferences,
- incorrect time display in clocks, if the reading is derived from the zero crossings of the supply voltage (e.g. certain clock radios),
- malfunction of protective devices and voltage controllers.

In converter installations, the following circuit types are preferred to reduce the depth of commutation notches:

- LV connection: Commutation reactor
- MV connection: Transformer
- HV connection: Transformer

In addition, combinations of a transformer and a commutation reactor are also suitable.

The selected examples of measurements in Fig. 7-2 show the variety of transient characteristics during commutation in the individual voltage levels.



Power station in the LV network (commutation notches clearly identifiable)	Winding machine in the MV network (commutation notches still identifiable)	Aluminium plant in the HV network (commutation notches no longer identifiable)

Fig. 7-2: Examples of measurements of commutation notches/commutation oscillations in different voltage levels [15]

7.2 Calculation

In order to comply with the emission limits, a commutation reactor and/or a transformer is connected between the converter installation and the POC. Only in special cases the network reactance $X_{\text{sc POC}}$ can be directly reduced to limit the depth of the commutation notch. Fig. 7-3 shows the equivalent circuit of a network with a connected converter installation comprising of the converter and the commutation reactance.

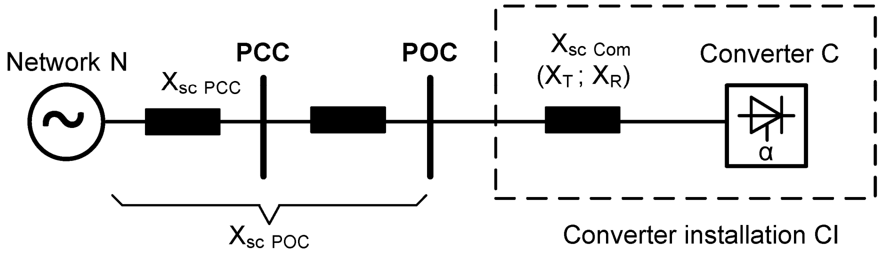


Fig. 7-3: Equivalent circuit of a network with connected converter C

In an inductive network, the depth of commutation notches at the POC of a six-pulse converter decreases according to the ratio of the network reactance to the sum of the network reactance and commutation reactance (voltage divider).

$$d_{\text{Com 6p POC}} \sim \frac{X_{\text{sc POC}}}{X_{\text{sc POC}} + X_{\text{sc Com}}} \qquad (7\text{-}2)$$

where

$d_{\text{Com 6p POC}}$	*is the relative depth of the commutation notch at the POC of a six-pulse converter,*
$X_{\text{sc POC}}$	*is the network reactance at the POC,*
$X_{\text{sc Com}}$	*is the sum of the reactances between the POC and the converter (commutation reactance).*

If the converter is operated with a trigger delay angle other than 90°, the lower depth of commutation notches can be taken into account with the factor of sin α. It should be noted that the commutation angle μ is neglected. The worst-case trigger delay angle during operation shall always be assumed for the assessment. Start-up processes shall also be taken into account.

The type of the converter connection can be taken into account using the *K* factor. For direct connection without transformer or when using a three-phase transformer with the uncommon vector groups Dd5 or Yy0, the following factor applies:

$$K = \frac{\sqrt{3}}{2}$$

In case of connection by means of a three-phase transformer with the common vector groups Dy5 or Yd5, the following factor is to be applied [16]:

$$K = 1$$

For converters with pulse numbers $p > 6$, a conversion according to the following equation is required:

$$d_{\text{Com}} = d_{\text{Com 6p}} \cdot \frac{6}{p} \tag{7-3}$$

where

d_{Com}	*is the relative depth of the commutation notch of converters with pulse number p,*
$d_{Com\ 6p}$	*is the relative depth of the commutation notch of a six-pulse converter,*
p	*is the pulse number of the converter.*

Taking into account the above contributing factors, the following general equation for calculating the relative depth of commutation notches is obtained for converters with a commutation reactance (commutation reactor and/or transformer):

$$d_{\text{Com POC}} = K \cdot \frac{6}{p} \cdot \frac{X_{\text{sc POC}}}{X_{\text{sc POC}} + X_{\text{sc Com}}} \cdot \sin\alpha \tag{7-4}$$

where

$d_{Com\ POC}$	*is the relative depth of the commutation notch at the POC,*
K	*is the connection factor (type of connection/transformer vector group),*
p	*is the pulse number of the converter,*
α	*is the trigger delay angle of the converter,*
$X_{sc\ POC}$	*is the network reactance at the POC,*
$X_{sc\ Com}$	*is the sum of the reactances between the POC and the converter (commutation reactance).*

Assuming identical references values (reference voltage, rated power) for the commutation reactor and/or the transformer being equal to those of the converter, the resulting commutation reactance $X_{\text{sc Com}}$ is calculated using the following equation (see Fig. 7-3):

$$X_{\text{sc Com}} = u_{\text{sc Com}} \frac{U^2}{S_{\text{CI}}} \tag{7-5}$$

where

$X_{sc\ Com}$	*is the sum of the reactances between the POC and the converter (commutation reactance),*
$u_{sc\ Com}$	*is the relative short-circuit voltage of the commutation reactance (reactance of the transformer and/or the commutation reactor),*
S_{CI}	*is the rated power of the converter installation,*
U	*is the reference phase-to-phase voltage (in LV networks, U is usually the nominal voltage U_n = 400 V).*

With the relation

$$X_{\text{sc POC}} = \frac{U^2}{S_{\text{sc POC}}} \tag{7-6}$$

where

$X_{sc\ POC}$	*is the network reactance at the POC,*
$S_{sc\ POC}$	*is the short-circuit power of the network at the POC,*
U	*is the phase-to-phase reference voltage (in LV networks, U is usually the nominal voltage U_n = 400 V),*

the relative depth of commutation notches at the POC is calculated using the following equation:

$$d_{\text{Com POC}} = \text{K} \cdot \sin\alpha \cdot \frac{6}{p} \cdot \left(u_{\text{sc Com}} \cdot \frac{S_{\text{sc POC}}}{S_{\text{CI}}} + 1 \right)^{-1} \tag{7-7}$$

where

$d_{Com\ POC}$	*is the relative depth of the commutation notch at the POC,*
K	*is the connection factor (type of connection/transformer vector group),*
$u_{sc\ Com}$	*is the relative short-circuit voltage of the commutation reactance (reactance of the transformer and/or the commutation reactor),*
$S_{sc\ POC}$	*is the short-circuit power of the network at the POC,*
S_{CI}	*is the rated power of the converter installation,*
p	*is the pulse number of the converter,*
α	*is the trigger delay angle of the converter.*

In case the rated power of the transformer, the commutation reactor and the converter differs, an individual determination of the $u_{\text{sc Com}}$ value is required. In order to support the customer in the design of its converter installation, respective equations are given in Annex B. These can be used for an approximate calculation of the inductance and the relative short-circuit voltage or the relative voltage drop of the commutation reactor respectively. As the calculated value is rather conservative, it is not expected that the commutation notches will exceed the emission limit, if the commutation reactor is designed according to the equations in Annex B.

Note:
For low ratios of short-circuit power at the POC and rated power of the converter installation, the calculation can result in commutation reactance values, which may not permit the operation of the converter.

7.3 Conversion between POC and PCC

Since the relative depth of commutation notches is assessed at the PCC, the values calculated for the POC shall be converted to the PCC.

The relative depth of commutation notches d_{Com} is converted from the POC to the PCC as an approximation using the following equation:

$$d_{\text{Com PCC}} = d_{\text{Com POC}} \cdot \frac{S_{\text{sc POC}}}{S_{\text{sc PCC}}} \tag{7-8}$$

where

$d_{Com\ POC}$	*is the relative depth of the commutation notch at the POC,*
$d_{Com\ PCC}$	*is the relative depth of the commutation notch at the PCC,*
$S_{sc\ POC}$	*is the short-circuit power at the POC,*
$S_{sc\ PCC}$	*is the short-circuit power at the PCC.*

7.4 Assessment parameters

The relative depth of the commutation notch at the PCC is used as the assessment parameter. It shall be compared with the relevant emission limit for the customer installation.

7.5 Mitigation measures

Measures applicable on the network side:
Measures that are applicable on the network side to increase the short-circuit power are given in Section 2.8.

Measures applicable on the installation side:
Increase of the commutation reactance:

- Improving the ratio of the network reactance $X_{sc\ PCC}$ to the commutation reactance $X_{sc\ Com}$. Annex B provides guidance for determining the relative short-circuit voltage of the commutation reactance $u_{sc\ Com}$ as a function of the $S_{sc\ PCC}/S_{CI}$ ratio.

Use of power-factor correction measures:

- Capacitor banks and passive filters, if properly designed, can contribute to a significant reduction in the duration and depth of commutation notches, especially at PCCs with relatively low short-circuit power. The actual influence can only be calculated by a computer simulation.
- However, non-detuned capacitor banks can create additional critical points of resonance, which can result in the amplification of commutation oscillations. Commutation oscillations, whose frequency is determined by capacitor banks can be reduced by appropriate filter circuits.

Selection of a different type of converter:

- For example, a frequency converter with network-side diode rectifier (uncontrolled line commutated converter) or a self-commutated converter with higher switching frequency can be used instead of a controlled line-commutated converter.

Increasing the pulse number:

- For controlled line-commutated converters, increasing the pulse number up to p = 48 can reduce the severity of commutation notches.

Active filters with RC damping circuit:

- This combination is often used to reduce commutation notches when the levels of harmonic components in the network are low. By using an RC circuit, a low-frequency harmonic component can be excited depending on the network impedance, which is reduced by an active filter connected in parallel.

7.6 Measurement

Commutation notches are measured at the POC using a transient recorder. The bandwidth of used transducers or sensors shall be suitable for measuring transients.

Due to the number of influencing parameters on the commutation notch and the triggered oscillations, a measurement-based assessment is highly recommended after commissioning.

8. Mains signalling voltages

8.1 General

In addition to the transmission of electrical energy, the distribution network can be used by the DSO for data transmission. For this purpose, the communication signals are superimposed to the network voltage resulting in an additional, but intentional distortion of the network voltage. Basically, a distinction is made between communication systems comprising one transmitter and several receivers on the customer side and communication systems comprising several communicating devices combining transmitter and receiver (transceivers). Independent on the applied system, the objective is to comply with the maximum signal levels and to achieve an adequate receiving level to ensure the proper function of the receivers. Customer installations can impair these two objectives and may lead to an unacceptable disturbance of the communication system.

8.2 Audio-frequency ripple control

In most audio-frequency ripple-control (AFRC) systems, audio-frequency signals in the range of 110 Hz to 2 000 Hz are superimposed to the network voltage by means of series or parallel coupling. The connected ripple-control receivers filter and validate the signals and perform certain functions in case of correct messages.

The distribution networks consist of a complex interconnection of cables, transformers, generators, capacitor banks, power electronic devices, etc. This often results in interactions at the ripple-control frequency, which are difficult to comprehend. Since the network impedances and the impedances of the customer installations are frequency-dependent, they result in a completely different loading at the ripple-control frequency than at the fundamental frequency. Measures, which mitigate the voltage distortion in distribution networks or the current distortion in customer installations (e.g. filter systems) can interfere with the operation of an AFRC system.

8.2.1 Interference mechanisms

8.2.1.1 Interferences of audio-frequency ripple controls

The functional reliability of an AFRC system requires a sufficiently high signal-to-noise ratio. The following conditions shall be met:

- The wanted signal shall be clearly above the disturbed voltages (the noise). Appliances in customer installations shall not cause unacceptably high emissions in the range of the AFRC frequency in order to avoid an unwanted response of the receivers. The response threshold level of the receivers shall therefore be higher than the noise with a sufficient safety margin.
- The AFRC level shall be above the response threshold of the receivers with a sufficient safety margin. Therefore, customer installations shall not reduce the AFRC level excessively due to their impedance at AFRC frequency. An assessment from a ripple-control point of view considers the effect of the entire customer installation at the PCC. Distributed generating installations can represent an additional loading for the AFRC system.

The interferences of an AFRC system can be classified into three different categories.

A. Interference of the AFRC signal due to customer installations

Harmonic and interharmonic emissions of electronic devices can adversely affect the AFRC signal. The most severe interferences are to be expected at the characteristic harmonics of 5th, 7th, 9th, 11th and 13th order. State-of-the-art power electronic equipment can also cause interferences at interharmonics or non-characteristic harmonics. Therefore, interferences of AFRC systems at such frequencies are expected to become more likely in the future.

The distribution network and the connected appliances or customer installations act like a diverse interconnection of capacitances and inductances. In the case of resonances at the AFRC frequency, the AFCR level can vary significantly. As the AFRC frequency increases, the interference effects usually increase. Interferences of the AFRC signal can also occur via possible interactions with the controls of state-of-the-art power electronic devices (e.g., inverters).

Examples of the interference mechanisms described include:

- Attenuation of the AFRC signal by a significant reduction of the network impedance at the AFRC frequency, e.g. by generating units or charging units for electric vehicles,
- Interference of the AFRC signal with active filters (control, input impedance),
- Summation of the effects (emission and/or impedance characteristics) of a larger amount of identical appliances,
- Effect of converters or inverters (control, input impedance),
  The effect depends on the rated power, the AFRC frequency used and the individual appliance (manufacturer and type).
- Amplification of the AFRC signal by series resonance between inductance of the MV/LV transformers and the distributed capacitances in the appliances of the customer installation connected to the LV network.

B. Interference of the AFRC signal due to the distribution network

MV lines with alternating overhead line and cable sections act like resonant circuits due to their inductive and capacitive characteristics. Especially at higher frequencies, the actual AFRC level at certain points in the distribution network can be increased considerably compared to the transmission level at the transmitter due to resonance phenomena.

C. Mutual interference of different AFRC systems

In the countries involved in the preparation of these Technical Rules (D, A, CH, CZ), the coordination of the AFRC frequencies used shall be performed by the DSO himself or by the suppliers of the AFRC system in order to avoid mutual interferences between the AFRC systems of different DSOs. It should be noted that such interferences can occur as a result of network resonances even across several network levels if the frequencies of the relevant AFRC systems are equal or are ±100 Hz (side bands) apart.

8.2.1.2 Interferences due to audio-frequency ripple-control systems

The AFRC signal also represents additional stress for appliances connected to the distribution network in the customer installations. In order to avoid interferences of these appliances by the AFRC system, the permitted AFRC level shall be complied with by the DSO. In addition, each customer in a distribution network with AFRC systems shall ensure that the appliances connected to his installation are sufficiently immune to interferences with respect to the maximum permitted AFRC level.

8.2.2 Mitigation measures

In case of interferences of the AFRC system, the following measures can be applied:

- encoding of the messages and coordination of the broadcasting times,
- re-transmission in the case of transmission interferences,
- decoupling using blocking circuits and passive filters at the POC of the customer installation,
- reduction of transmission levels in the disturbing distribution network,
- avoidance of critical switching states of the network.

Note:
Decoupling using blocking circuits and passive filters is more and more regarded as critical, since this can significantly influence the impedance of the network.

For further information, see references [17] and [18].

8.2.3 Measurement

A measurement-based verification is recommended, if the possible interference of the AFRC system by a customer installation cannot be determined with sufficient accuracy during the planning stage.

Compliance with the conditions defined in Section 8.2.1 is checked by means of a frequency-selective voltage/current measurement. The level of the ripple-control signal shall be determined according to [EN 61000-4-30] Class A based on r.m.s. values of 10 cycles. The 99 % quantile of the 3 s maximum values over a one-week period shall be assessed.

Note:
Measurement instruments that do not comply with this specification shall use a measurement method that correctly reproduces the level of the (rapidly time-varying) ripple-control signal. Measuring methods with longer averaging intervals without a suitable determination of maximum values are not suitable for this purpose.

The accuracy of the measured levels can be affected at higher AFRC frequencies by the frequency-dependent transfer ratio of the voltage transformers used.

8.3 Power Line Communication (PLC)

Narrowband PLC (power line communication) is used more and more for communication with electronic meters (smart meters). It operates primarily in the frequency range between 30 kHz and 95 kHz in the PLC band A (3 kHz to 95 kHz). In addition, applications in the range up to 500 kHz are increasingly expected in the future (FCC band).

In general, these applications are subject to comparable interference mechanisms as described in Section 8.2.1. However, the propagation of unintentional disturbances and PLC signals is usually limited to a few hundred meters at these frequencies. For this reason, the communicating devices are designed as transceivers, communicating directly with each other or transmitting data for other communicating devices. The manufacturers use different system architectures, modulation methods and protocols.

Permitted transmission levels for the PLC band A are specified in [EN 50065-1] and are currently regulated in the FCC band by national regulations. For the frequency range below 150 kHz, immunity requirements are specified in [EN 61000-4-19] and compatibility levels for the coordination between intentional and unintentional emissions (noise) in public LV networks are given in [EN 61000-2-2].

The assessment of network disturbances with respect to PLC is not within the scope of these Technical Rules.

Further information on the subject of interferences between electrical appliances and installations and narrowband PLC in the frequency range below 150 kHz is given in three documents published by CENELEC SC205A [19], [CLC 50627] and [CLC 50669].

9. Direct current (DC currents)

At present, there is limited knowledge about the sources, propagation in the network and interferences for DC currents. There is also no internationally recognized method for measuring DC currents.

Due to the current state of knowledge, the assessment of network disturbances caused by DC currents is not considered in this edition of the Technical Rules. However, some further explanations and literature references are given below.

DC currents can be divided into two categories with regard to their duration:

- short-term DC currents during faults and inrush currents,
- long-term DC currents caused by electrical appliances, such as inverters or converters [20].

Emissions of DC currents by electrical appliances are mainly caused by converter technologies, in which e.g. component tolerances or malfunctions of individual components result in asymmetrical half-cycles of voltage or current. Measurements on individual appliances have shown that especially appliances incorporating state-of-the-art power electronic equipment without a low-frequency transformer and with rated currents of 16 A and above emit significant DC currents [20], [21], [22]. Typical examples of this type of equipment are PV inverters, charging units for electric vehicles, converters for electric storage installations or drive system converters with active front end on the network side or equipment with half-cycle rectification [23].

The impact of DC currents in three-phase networks include malfunctions or damages due to saturation of the iron core in equipment such as distribution network transformers or protective devices. Furthermore, DC currents can cause increased corrosion of earthing systems [20]. If DC currents in LV networks occur as common-mode currents between L-PE or N-PE, the tripping of residual-current devices can be impaired.

In [EN 61000-2-2], no compatibility level is specified for DC voltages, since the DC current is the critical variable for interferences. Therefore, an acceptable DC voltage can only be determined on a case-by-case basis.

At present, no consistent international standards exist for emission limits. Section 6.1 of the standard [EN 61000-3-2] only defines the conditions under which devices with half-cycle rectification are permitted. Tab. 9-1 provides selected national guidelines that apply to the emission of DC components. With the exception of VDE AR-N 4100, these guidelines are limited to generating installations. VDE AR-N 4100 applies to any type of customer installation connected to LV networks.

Tab. 9-1: Selected limit values for the emission of DC currents from generating installations [24]

Country	***Guideline***	***Maximum DC component for inverter technologies with and without transformer***
Australia	AS 4777.2	5 mA
China	GB/T 50865 - 2013	0.5 % I_n
Germany	VDE-AR-N 4100	max {20 mA, 0.5 % I_n}
United Kingdom	ER G83/2	0.25 % I_n
Japan	Technical Guideline for the Grid Interconnection	1.0 % I_n
USA	IEEE 929-2000	0.5 % I_n

Concerning the measurement of DC currents, there are no approved definitions of the measurement interval over which they are to be determined and how several measured values are aggregated over time. However, this is an important aspect in order to take into account the different characteristics of DC currents (e.g. pulsating, constant), which also causes different effects. According to [AR-N 4100], for example, the DC component from the measurement procedure defined in [EN 61000-4-7] (measurement interval extends over 10 cycles) is to be used.

In order to derive appropriate limit values, further research in the field of DC voltages and DC currents in three-phase systems is indispensable. In addition to a more detailed analysis of the effects, this also includes the definition of a measurement methodology as well as studies on propagation and superposition.

List of standards

EN 50065-1:2012
Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz – Part 1: General requirements, frequency bands and electromagnetic disturbances

EN 50160:2020
Voltage characteristics of electricity supplied by public distribution networks. Version EN 50160:2010 + Cor.:2010 + A1:2015 + A2:2019 + A3:2019

CLC/TR 50627:2015
Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range below 150 kHz

CLC/TR 50669:2017
Investigation Results on Electromagnetic Interference in the Frequency Range below 150 kHz

IEC 60050:
International electrotechnical vocabulary

IEC/TR 60725 Ed. 3.0:2012
Consideration of reference impedances and public supply network impedances for use in determining the disturbance characteristics of electrical equipment having a rated current ≤75 A per phase

EN 61000-2-2:2020
Electromagnetic compatibility (EMC) – Part 2-2: Environment – Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems (IEC 61000-2-2:2002 + A1:2017 + A2:2018); German version EN 61000-2-2:2002 + A1:2017 + A2:2019

EN 61000-2-12:2003
Electromagnetic compatibility (EMC) – Part 2-12: Environment – Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems

EN 61000-3-2:2014
Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase)

EN 61000-3-3:2013
Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase

IEC 61000-3-6 Ed. 2.0:2008
Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

IEC 61000-3-7 Ed. 2.0:2008
Electromagnetic compatibility (EMC) – Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems

EN 61000-3-11:2000
Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤75 A per phase

EN 61000-3-12:2011
Electromagnetic compatibility (EMC) – Part 3-12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤75 A per phase

IEC/TR 61000-3-13 Ed. 1.0:2008
Electromagnetic compatibility (EMC) – Part 3-13: Limits – Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems

IEC/TR 61000-3-14 Ed. 1.0:2011
Electromagnetic compatibility (EMC) – Part 3-14: Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems

IEC/TR 61000-3-15 Ed. 1.0:2011
Electromagnetic compatibility (EMC) – Part 3-15: Limits – Assessment of low frequency electromagnetic immunity and emission requirements for dispersed generation systems in LV network

EN 61000-4-7:2002+A1:2009
Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

EN 61000-4-15:2011
Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications

EN 61000-4-19:2015
Electromagnetic compatibility (EMC) – Part 4-19: Testing and measurement techniques – Test for immunity to conducted, differential mode disturbances and signalling in the frequency range 2 kHz to 150 kHz at a.c. power ports (IEC 61000-4-19:2014)

EN 61000-4-30:2015 + Corr. 2017
Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods

VDE AR-N 4100:2019
Technische Regeln für den Anschluss von Kundenanlagen an das Niederspannungsnetz und deren Betrieb (TAR Niederspannung) (Technical Connection Rules for Low-Voltage)

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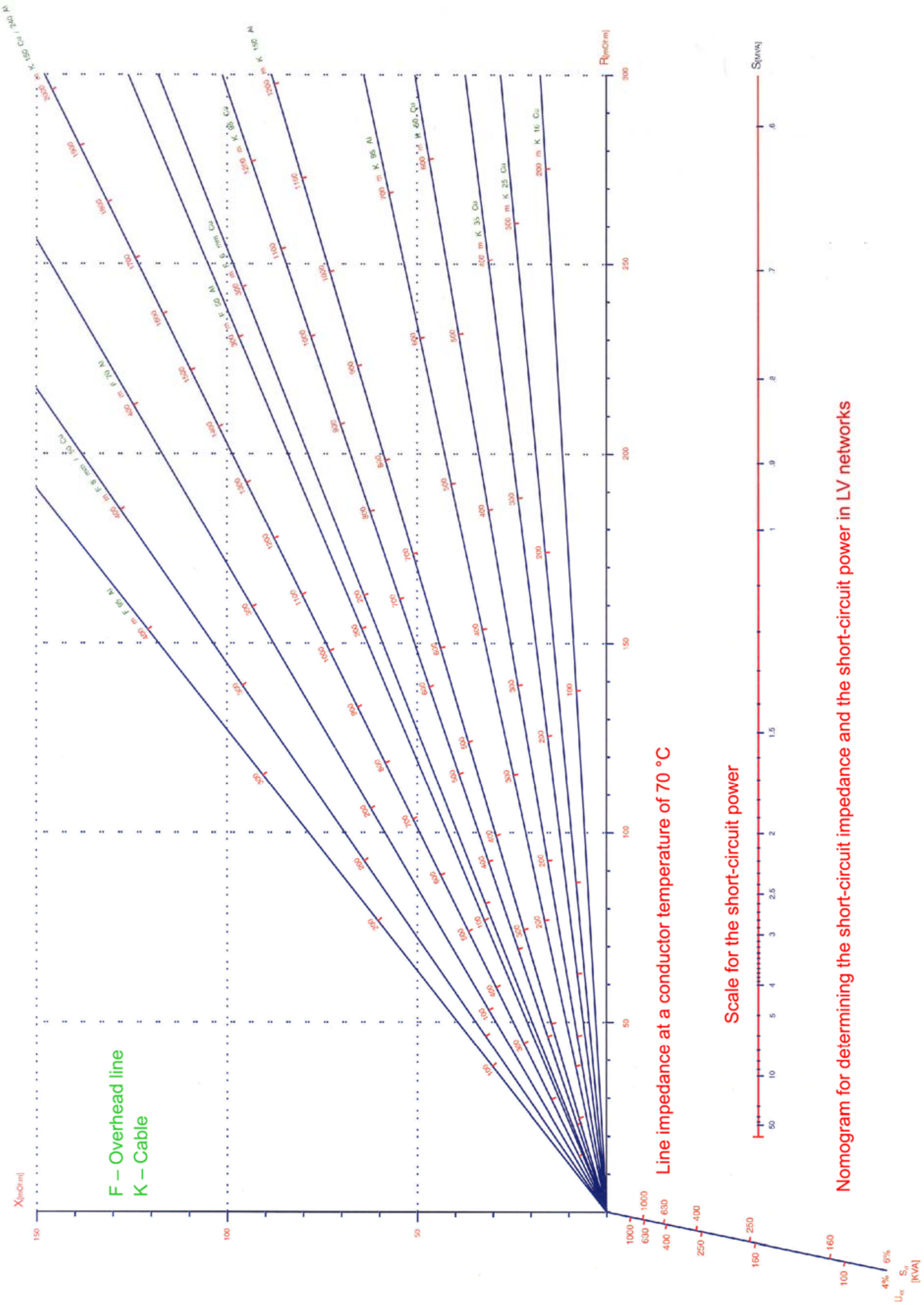
Annex A
Nomogram for short-circuit power calculation



Example for using the nomogram

A customer installation is supplied via a cable (4 x 95 Al, 70 m) and an overhead line (4 x 50 Al, 120 m) simultaneously with other customer installations (Fig. A-1). The level of short-circuit power $S_{sc\,PCC}$ at the PCC is to be determined.

Step ❶ (transformer impedance):
Enter point T in the lower left area of the nomogram according to the power $S_{r\,T}$ (500 kVA) and the short-circuit voltage u_{sc} of the transformer!

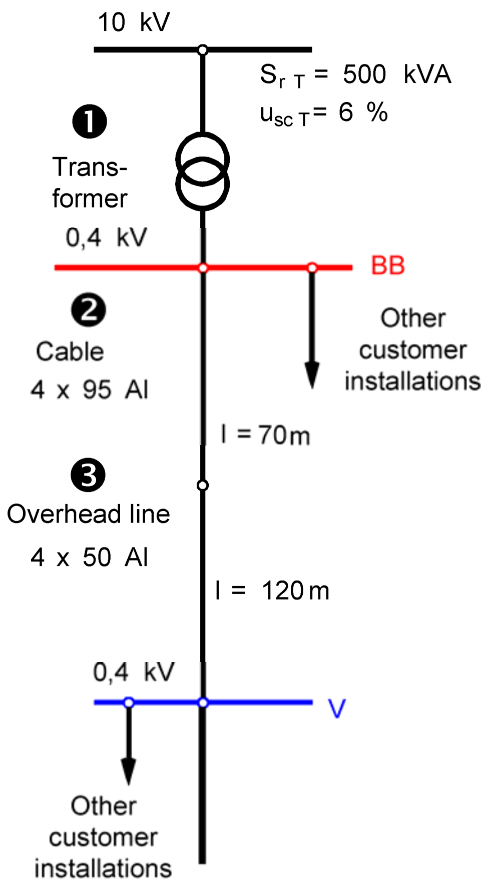


Fig. A-1: Network configuration

Steps ❷ and ❸ (line impedances):
Enter the points K (70 m, K 95 Al) and F (120 m, F 50 Al) in the upper right area of the nomogram on the curve corresponding to the line type at the given length!

Step ❹ (total impedance of all lines):
Add up all line impedances vectorially (cable $\overrightarrow{UK}$, overhead line $\overrightarrow{UF}$)! The result is point L. The length of the phasor $\overrightarrow{UL}$ corresponds to the total impedance of all lines.

Step ❺ (short-circuit impedance at the PCC):
Plot the straight-line segment $\overline{TL}$! The length of the straight-line segment $\overline{TL}$ corresponds to the short-circuit impedance $Z_{sc\,PCC}$ at the PCC.

Step ❻ (short-circuit power at the PCC):
Plot the straight-line segment $\overline{TL}$ on the "Scale for the short-circuit power S_{sc} in MVA"! Read the associated value for the short-circuit power $S_{sc\,PCC}$!

By plotting the straight-line segment $\overline{UT}$ on the "Scale for the short-circuit power S_{sc} in MVA", the short-circuit power $S_{sc\,BB}$ at the busbar BB is obtained accordingly.

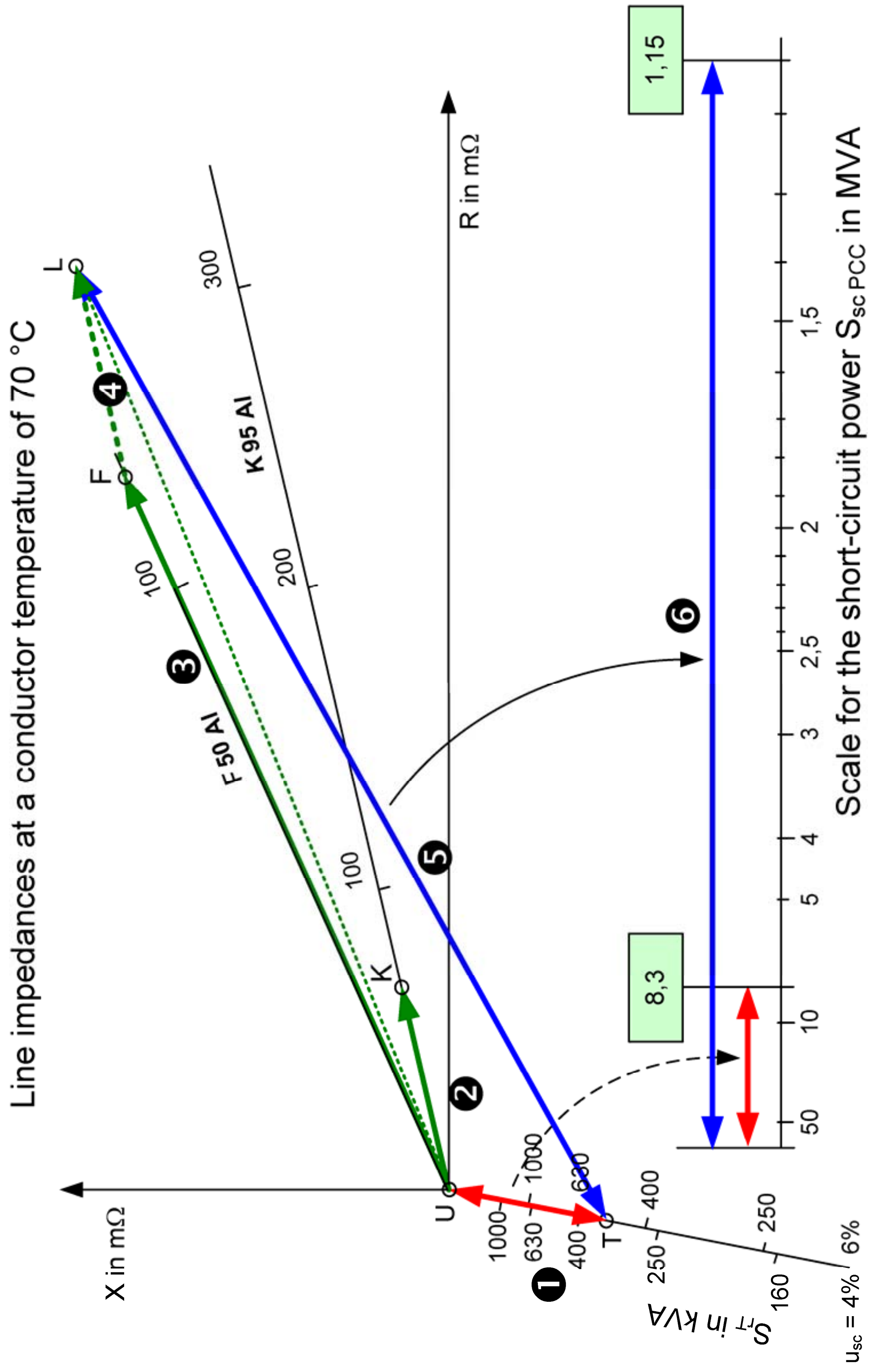


Fig. A-2: Procedure for determining the short-circuit power

Annex B
Guidelines for the design of the commutation reactance

Determining the required inductance of the commutation reactor

In the data sheets for commutation reactors, the manufacturers usually specify the inductance and the rated current. Commutation inductance $L_{sc\,\mathrm{Com}}$, voltage U, network frequency f and rated power of the converter $S_{\mathrm{r\,Con}}$ are related to each other as follows:

$$L_{\mathrm{sc\,Com}} = \frac{1}{2\cdot\pi\cdot f}\cdot u_{\mathrm{sc\,Com}}\cdot\frac{U^2}{S_{\mathrm{r\,Con}}} \tag{B-1}$$

where

$L_{sc\,Com}$	*is the inductance of the commutation reactance $X_{sc\,Com}$,*
f	*is the power frequency (usually the nominal frequency of the network f_N = 50 Hz),*
$u_{sc\,Com}$	*is the relative short-circuit voltage of the commutation reactance $X_{sc\,Com}$* (referred to the voltage U and the rated power of the converter $S_{r\,Con}$*),*
U	*is the phase-to-phase reference voltage (in LV networks, usually the nominal voltage U_n = 400 V is used),*
$S_{r\,Con}$	*is the power of the converter (usually the rated power of the converter installation S_{CI}).*

In the case that the commutation reactance $X_{\mathrm{sc\,Com}}$ consists of only one commutation reactor, equation (B-1) is directly applicable. If a transformer with a rated power $S_{\mathrm{r\,T}}$ and a short-circuit voltage $u_{\mathrm{sc\,T}}$ is already installed, the residual inductance L_{R} of the commutation reactor is determined using the following equation:

$$L_{\mathrm{R}} = \frac{1}{2\cdot\pi\cdot f}\cdot\left(u_{\mathrm{sc\,Com}}\cdot\frac{U^2}{S_{\mathrm{r\,Con}}} - u_{\mathrm{sc\,T}}\cdot\frac{U^2}{S_{\mathrm{r\,T}}}\right) \tag{B-2}$$

where

L_R	*is the residual inductance of the commutation reactor,*
f	*is the power frequency (usually the nominal frequency of the network f_N = 50 Hz),*
$u_{sc\,Com}$	*is the relative short-circuit voltage of the commutation reactance $X_{sc\,Com}$* (referred to the voltage U and the rated power of the converter $S_{r\,Con}$*),*
U	*is the phase-to-phase reference voltage (in LV networks, usually the nominal voltage U_n = 400 V is used),*
$S_{r\,Con}$	*is the power of the converter (usually the rated power of the converter installation S_{CI}),*
$u_{sc\,T}$	*is the relative short-circuit voltage of the transformer,*
$S_{r\,T}$	*is the rated power of the transformer.*

Determining the short-circuit voltage of the commutation reactance

The required relative short-circuit voltage $u_{sc\ Com}$ of the commutation reactance $X_{sc\ Com}$ as a function of the ratio $S_{Cl}/S_{sc\ PCC}$ for a six-pulse converter and a trigger delay angle of 90° is determined using the following equation:

$$u_{sc\ Com} = \frac{S_{Cl}}{S_{sc\ PCC}} \cdot \left(K \cdot \frac{1}{d_{Com}} - 1 \right) \quad \text{(B-3)}$$

where

$u_{sc\ Com}$ *is the relative short-circuit voltage of the commutation reactance* $X_{sc\ Com}$ (referred to the voltage *U* and the rated power of the converter installation S_{Cl}*),*

K *is the connection factor (type of connection/transformer vector group),*

d_{Com} *is the relative depth of the commutation notch,*

S_{Cl} *is the rated power of the converter installation,*

$S_{sc\ PCC}$ *is the short-circuit power at the PCC.*

If the inverter is operated with a trigger delay angle other than 90°, the lower depth of commutation notches can be taken into account with the factor of sin α. The worst-case trigger delay angle during operation shall always be assumed for the assessment. Start-up processes shall also be taken into account. The pulse number of the converter is taken into account by the parameter *p*.

Thus, the general equation for calculating the required relative short-circuit voltage of the commutation reactance is:

$$u_{sc\ Com} = \frac{S_{Cl}}{S_{sc\ PCC}} \cdot \left(K \cdot \sin\alpha \cdot \frac{6}{p} \cdot \frac{1}{d_{Com}} - 1 \right) \quad \text{(B-4)}$$

where

$u_{sc\ Com}$ *is the relative short-circuit voltage of the commutation reactance* $X_{sc\ Com}$*,*

K *is the connection type factor (type of connection/transformer vector group),*

d_{Com} *is the relative depth of a commutation notch,*

S_{Cl} *is the rated power of the converter installation,*

$S_{sc\ PCC}$ *is the short-circuit power at the PCC,*

p *is the pulse number of the converter,*

α *is the trigger delay angle of the converter.*

In general, it is sufficient to consider each converter installation separately, since the probability of overlapping commutation notches is low. If, on the other hand, several converter installations are operated synchronously, then care shall be taken to ensure that the cumulative effect remains below the respective emission limit.

The commutation reactance shall be specified with a short-circuit voltage of at least $u_{sc\ Com}$ = 4 %. A value of $u_{sc\ Com}$ > 12.5 % will result in long commutation times and high notch depths, which can severely impair the converter operation. The actual influence can only be calculated by a computer simulation.

The relative short-circuit voltage of the commutation reactance $u_{sc\ Com}$ can also be determined according to Fig. B-1 to Fig. B-3 as a function of the ratio $S_{sc\ PCC}/S_{Cl}$ for typical values of the relative depth of the commutation notch d_{Com}. The characteristic curves are shown for a connection factor *K* = 1. The $u_{sc\ Com}$ value can be read directly for six-pulse converters. For converters with higher pulse numbers or other types of connection, the resulting value of $u_{sc\ Com}$ shall be calculated using equation (B-4).

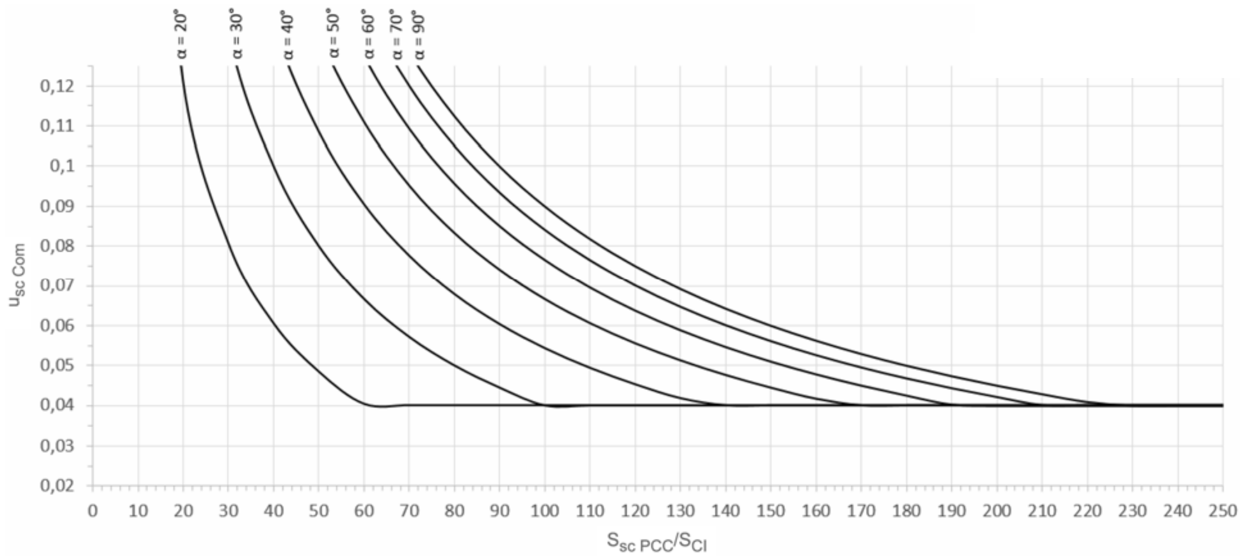


Fig. B-1: Required relative short-circuit voltage $u_{sc\ Com}$ of the commutation reactance $X_{sc\ Com}$ as a function of the ratio $S_{sc\ PCC}/S_{CI}$ for different trigger delay angles of six-pulse converters and d_{Com} = 10 % (LV)

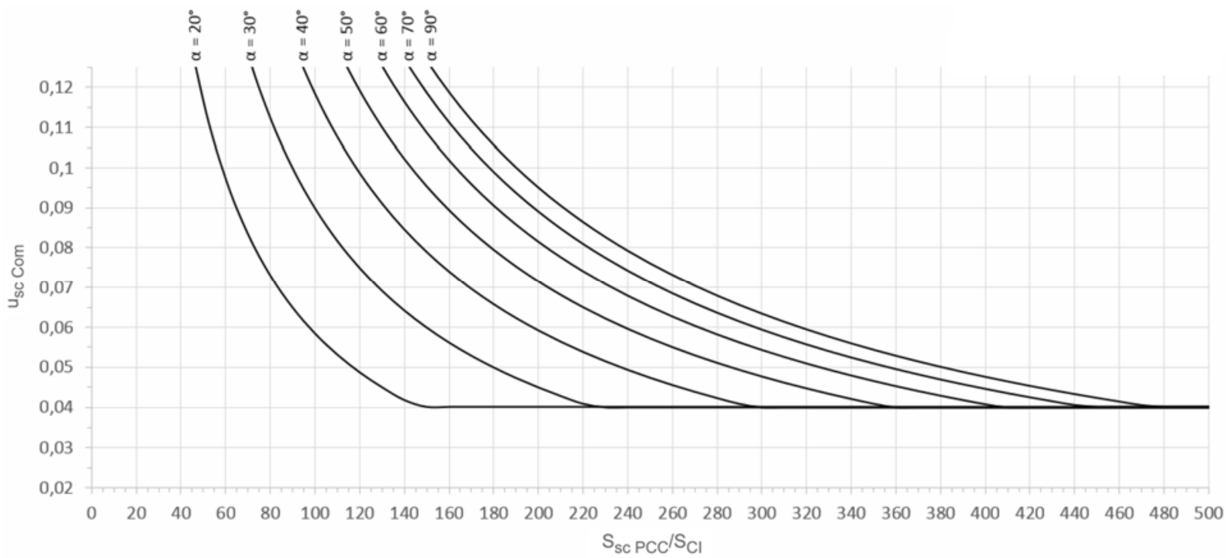


Fig. B-2: Required relative short-circuit voltage $u_{sc\ Com}$ of the commutation reactance $X_{sc\ Com}$ as a function of the ratio $S_{sc\ PCCV}/S_{CI}$ for different trigger delay angles of six-pulse converters and d_{Com} = 5 % (MV)

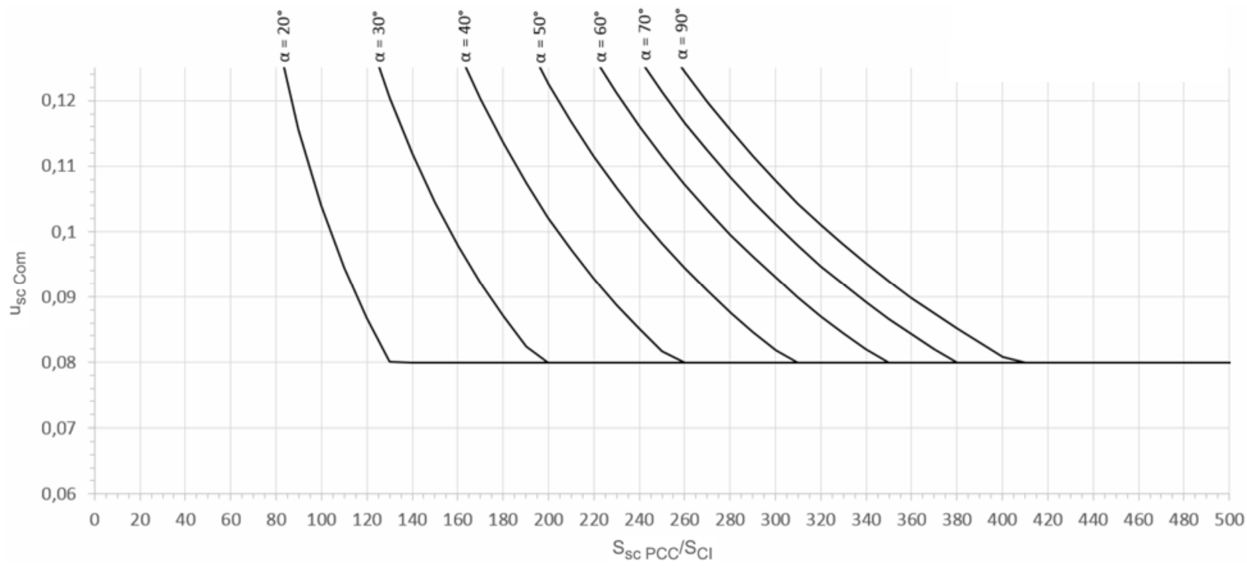


Fig. B-3: Required relative short-circuit voltage $u_{sc\ Com}$ of the commutation reactance $X_{sc\ Com}$ as a function of the ratio $S_{sc\ PCC}/S_{CI}$ for different trigger delay angles of six-pulse converters and d_{Com} = 3 % (HV)