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TECHNICAL REPORT

BASIC EMC PUBLICATION

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/TR 61000-3-6:2008(E)

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FOREWORD

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IEC/TR 61000-3-6, which is a technical report, has been prepared by subcommittee 77A: Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

This Technical Report forms Part 3-6 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107 [29][1].

This second edition cancels and replaces the first edition published in 1996 and constitutes a technical revision.

1 Figures in square brackets refer to the Bibliography.

This edition is significantly more streamlined than first edition, and it reflects the experiences gained in the application of the first edition. As part of this streamlining process, this second edition of IEC/TR 61000-3-6 does not address communications circuit interference. Clause 9 on this (section 10) was removed, as this did not suitably address emission limits for telephone interference. The scope has been adjusted to point out that IEC/TR 61000-3-6 does not address communications circuit interference. This edition has also been harmonised with IEC/TR 61000-3-7 [30] and IEC/TR 61000-3-13 [31].

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
77A/575/DTR	77A/637/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

A list of all parts of the IEC 61000 series, under the general title *Electromagnetic compatibility (EMC)*, can be found on the IEC website.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits
(in so far as they do not fall under the responsibility of product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts published either as International Standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

ACKNOWLEDGMENT

In 2002, the IEC subcommittee 77A made a request to CIGRE Study Committee C4 and CIRED Study Committee S2, to organize an appropriate technical forum (joint working group) whose main scope was to prepare, among other tasks, the revision of the technical report IEC 61000-3-6 concerning emission limits for harmonics for the connection of distorting installations to public supply systems at MV, HV and EHV.

To this effect, joint working group CIGRE C4.103/ CIRED entitled ''*Emission Limits for Disturbing Installations*'' was appointed in 2003. Some previous work produced by CIGRE JWG C4.07-Cired has been used as an input to the revision, in particular the planning levels and associated indices. In addition, using experience since the technical report IEC 61000-3-6 was initially published in 1996, WG C4.103 reviewed the procedure used to determine emission limits and the assessment methods used to evaluate emission levels for installations.

Subsequent endorsement of the document by IEC was the responsibility of SC 77A.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

1 Scope

This Technical Report, which is informative in its nature, provides guidance on principles which can be used as the basis for determining the requirements for the connection of distorting installations to MV, HV and EHV public power systems (LV installations are covered in other IEC documents). For the purposes of this report, a distorting installation means an installation (which may be a load or a generator) that produces harmonics and/or interharmonics. The primary objective is to provide guidance to system operators or owners on engineering practices, which will facilitate the provision of adequate service quality for all connected customers. In addressing installations, this document is not intended to replace equipment standards for emission limits.

The report addresses the allocation of the capacity of the system to absorb disturbances. It does not address how to mitigate disturbances, nor does it address how the capacity of the system can be increased.

Since the guidelines outlined in this report are necessarily based on certain simplifying assumptions, there is no guarantee that this approach will always provide the optimum solution for all harmonic situations. The recommended approach should be used with flexibility and judgment as far as engineering is concerned, when applying the given assessment procedures in full or in part.

The system operator or owner is responsible for specifying requirements for the connection of distorting installations to the system. The distorting installation is to be understood as the customer's complete installation (i.e. including distorting and non-distorting parts).

Problems related to harmonics fall into two basic categories.

- Harmonic currents that are injected into the supply system by converters and harmonic sources, giving rise to harmonic voltages in the system. Both harmonic currents and resulting voltages can be considered as conducted phenomena.
- Harmonic currents that induce interference into communication systems. This phenomenon is more pronounced at higher order harmonic frequencies because of increased coupling between the circuits and because of the higher sensitivity of the communication circuits in the audible range.

This report gives guidance for the co-ordination of the harmonic voltages between different voltage levels in order to meet the compatibility levels at the point of utilisation. The recommendations in this report do not address harmonic interference phenomena in communication circuits (i.e. only the first of the above categories is addressed). These disturbances need to be addressed in terms of international directives concerning the Protection of Telecommunication Lines against Harmful Effects from Electric Power and Electrified Railway Lines, International Telecommunication Union, ITU-T Directives [1][2] or in terms of locally applicable standards such as [2], [3] or [4].

[2] Figures in square brackets refer to the bibliography.

NOTE The boundaries between the various voltage levels may be different for different countries (see IEV 601-01-28 [32]). This report uses the following terms for system voltages:

– low voltage (LV) refers to Un ≤ 1 kV;

– medium voltage (MV) refers to 1 kV < Un ≤ 35 kV;

– high voltage (HV) refers to 35 kV < Un ≤ 230 kV;

– extra high voltage (EHV) refers to 230 kV < Un.

In the context of this report, the function of the system is more important than its nominal voltage. For example, a HV system used for distribution may be given a "planning level" which is situated between those of MV and HV systems.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050(161), *International Electrotechnical Vocabulary – Chapter 161: Electromagnetic compatibility*

3 Terms and definitions

For the purposes of this document, the following definitions apply as well as the definitions in IEC 60050(161).

3.1
agreed power
value of the apparent power of the disturbing installation on which the customer and the system operator or owner agree. In the case of several points of connection, a different value may be defined for each connection point

3.2
customer
person, company or organisation that operates an installation connected to, or entitled to be connected to, a supply system by a system operator or owner

3.3
(electromagnetic) disturbance
any electromagnetic phenomenon which, by being present in the electromagnetic environment, can cause electrical equipment to depart from its intended performance

3.4
disturbance level
the amount or magnitude of an electromagnetic disturbance measured and evaluated in a specified way

3.5
distorting installation
an electrical installation as a whole (i.e. including distorting and non-distorting parts) which can cause distortion of the voltage or current into the supply system to which it is connected

NOTE For the purpose of this report, all references to distorting installations not only include linear and non-linear loads, but generating plants, and any source of non-sinusoidal current emissions such as regenerative braking systems,

3.6
electromagnetic compatibility (EMC)
ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

NOTE 1 Electromagnetic compatibility is a condition of the electromagnetic environment such that, for every phenomenon, the disturbance emission level is sufficiently low and immunity levels are sufficiently high so that all devices, equipment and systems operate as intended.

NOTE 2 Electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that the immunity levels of the devices, equipment and systems at any location are not exceeded by the disturbance level at that location resulting from the cumulative emissions of all sources and other factors such as circuit impedances. Conventionally, compatibility is said to exist if the probability of the departure from intended performance is sufficiently low. See Clause 4 of IEC 61000-2-1 [33].

NOTE 3 Where the context requires it, compatibility may be understood to refer to a single disturbance or class of disturbances.

NOTE 4 Electromagnetic compatibility is a term used also to describe the field of study of the adverse electromagnetic effects which devices, equipment and systems undergo from each other or from electromagnetic phenomena.

3.7
(electromagnetic) compatibility level
specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity limits

NOTE By convention, the compatibility level is chosen so that there is only a small probability (for example 5 %) that it will be exceeded by the actual disturbance level.

3.8
emission
phenomenon by which electromagnetic energy emanates from a source of electromagnetic disturbance

[IEV 161-01-08 modified]

NOTE For the purpose of this report, emission refers to phenomena or conducted electromagnetic disturbances that can distort the supply voltage waveform.

3.9
emission level
level of a given electromagnetic disturbance emitted from a particular device, equipment, system or disturbing installation as a whole, assessed and measured in a specified manner

3.10
emission limit
maximum emission level specified for a particular device, equipment, system or disturbing installation as a whole

3.11
generating plant
any equipment that produces electricity together with any directly connected or associated equipment such as a unit transformer or converter

3.12
immunity (to a disturbance)
ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

3.13
immunity level
the maximum level of a given electromagnetic disturbance on a particular device, equipment or system for which it remains capable of operating with a declared degree of performance

3.14
non-linear load or equipment (see also distorting installation)
any load or equipment that draws a non-sinusoidal current when energised by a sinusoidal voltage

3.15
normal operating conditions
operating conditions of the system or of the disturbing installation typically including all generation variations, load variations and reactive compensation or filter states (e.g. shunt capacitor states), planned outages and arrangements during maintenance and construction work, non-ideal operating conditions and normal contingencies under which the considered system or the disturbing installation have been designed to operate

NOTE Normal system operating conditions typically exclude: conditions arising as a result of a fault or a combination of faults beyond that planned for under the system security standard, exceptional situations and unavoidable circumstances (for example: force majeure, exceptional weather conditions and other natural disasters, acts by public authorities, industrial actions), cases where system users significantly exceed their emission limits or do not comply with the connection requirements, and temporary generation or supply arrangements adopted to maintain supply to customers during maintenance or construction work, where otherwise supply would be interrupted.

3.16
planning level
level of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions from the installations in a particular system, in order to co-ordinate those limits with all the limits adopted for equipment and installations intended to be connected to the power supply system

NOTE Planning levels are considered internal quality objectives to be specified at a local level by those responsible for planning and operating the power supply system in the relevant area.

3.17
point of common coupling (PCC)
point in the public supply system, which is electrically closest to the installation concerned, at which other installations are, or could be, connected. The PCC is a point located upstream of the considered installation

NOTE A supply system is considered as being public in relation to its use, and not its ownership.

3.18
point of connection (POC)
point on a public power supply system where the installation under consideration is, or can be connected

NOTE A supply system is considered as being public in relation to its use, and not its ownership.

3.19
point of evaluation (POE)
point on a public power supply system where the emission levels of a given installation are to be assessed against the emission limits. This point can be the point of common coupling (PCC) or the point of connection (POC) or any other point specified by the system operator or owner or agreed upon

NOTE A supply system is considered as being public in relation to its use, and not its ownership.

3.20
short circuit power
a theoretical value expressed in MVA of the initial symmetrical three-phase short-circuit power at a point on the supply system. It is defined as the product of the initial symmetrical short-circuit current, the nominal system voltage and the factor $\sqrt{3}$ with the aperiodic component (DC) being neglected

3.21
spur
a feeder branch off a main feeder (typically applied on MV and LV feeders)

3.22
supply system
all the lines, switchgear and transformers operating at various voltages which make up the transmission systems and distribution systems to which customers' installations are connected

3.23
system operator or owner
the entity responsible for making technical connection agreements with customers who are seeking connection of load or generation to a distribution or transmission system

3.24
transfer coefficient (influence coefficient)
the relative level of disturbance that can be transferred between two busbars or two parts of a power system for various operating conditions

3.25
voltage unbalance (imbalance)
in a polyphase system, a condition in which the magnitudes of the phase voltages or the phase angles between consecutive phases are not all equal (fundamental component) [IEV 161-08-09 modified]

NOTE In three phase systems, the degree of the inequality is usually expressed as the ratio of the negative and zero sequence components to the positive sequence component. In this technical report, voltage unbalance is considered in relation to three-phase systems and negative sequence only.

3.26
phenomena related definitions
the definitions below that relate to harmonics are based on the analysis of system voltages or currents by the Discrete Fourier Transform method (DFT). This is the practical application of the Fourier transform as defined in IEV 101-13-09 [28]

NOTE 1 The Fourier Transform of a function of time, whether periodic or non-periodic, is a function in the frequency domain and is referred to as the frequency spectrum of the time function, or simply spectrum. If the time function is periodic the spectrum is constituted of discrete lines (or components). If the time function is not periodic, the spectrum is a continuous function, indicating components at all frequencies.

NOTE 2 For simplicity the definitions given in this report refer only to (inter)harmonic components, however, these should not be interpreted as a restriction on the use of other definitions given in other IEC documents, for example, IEC 61000-4-7 [11] where the reference to (inter)harmonic groups or subgroups are more appropriate for measuring rapidly varying signals.

3.26.1
fundamental frequency
frequency in the spectrum obtained from a Fourier transform of a time function, to which all the frequencies of the spectrum are referred. For the purpose of this technical report, the fundamental frequency is the same as the power supply frequency

NOTE In the case of a periodic function, the fundamental frequency is generally equal to the frequency corresponding to the period of the function itself.

3.26.2
fundamental component
component whose frequency is the fundamental frequency

3.26.3
harmonic frequency
frequency which is an integer multiple of the fundamental frequency. The ratio of the harmonic frequency to the fundamental frequency is the harmonic order (recommended notation: “h”)

3.26.4
harmonic component
any of the components having a harmonic frequency. For brevity, such a component may be referred to simply as a harmonic

3.26.5
interharmonic frequency
any frequency which is not an integer multiple of the fundamental frequency

NOTE 1 By extension from harmonic order, the interharmonic order is the ratio of an interharmonic frequency to the fundamental frequency. This ratio is not an integer. (Recommended notation “m”).

NOTE 2 In the case where m < 1 the term subharmonic frequency may be used.

3.26.6
interharmonic component
component having an interharmonic frequency. For brevity, such a component may be referred to simply as an “interharmonic”

3.26.7
total harmonic distortion – THD
ratio of the r.m.s. value of the sum of all the harmonic components up to a specified order (H) to the r.m.s. value of the fundamental component

$$THD = \sqrt{\sum_{h=2}^{H} \left(\frac{Q_h}{Q_1} \right)^2}$$

where

- Q represents either current or voltage,
- Q_1 is the r.m.s. value of the fundamental component,
- h is the harmonic order,
- Q_h is the r.m.s. value of the harmonic component of order h,
- H is generally 40 or 50 depending on the application.

4 Basic EMC concepts related to harmonic distortion

The development of emission limits (voltage or current) for individual equipment or a customer’s installation should be based on the effect that these emission limits will have on the quality of the voltage. Some basic concepts are used to evaluate voltage quality. In order for these concepts to be used for evaluation at specific locations, they are defined in terms of where they apply (locations), how they are measured (measurement duration, sample times, averaging durations, statistics), and how they are calculated. These concepts are described hereafter and illustrated in Figures 1 and 2. Definitions may be found in IEC 60050(161).

4.1 Compatibility levels

These are reference values (see Table 1) for co-ordinating the emission and immunity of equipment which is part of, or supplied by, a supply system in order to ensure the EMC in the whole system (including system and connected equipment). Compatibility levels are generally based on the 95 % probability levels of entire systems, using statistical distributions which represent both time and space variations of disturbances. There is allowance for the fact that the system operator or owner cannot control all points of a system at all times. Therefore, evaluation with respect to compatibility levels should be made on a system-wide basis and no assessment method is provided for evaluation at a specific location.

The compatibility levels for harmonic voltages in LV and MV systems are reproduced below from references IEC 61000-2-2 [5] and IEC 61000-2-12 [6]. These compatibility levels shall be understood to relate to quasi-stationary or steady-state harmonics, and are given as reference values for both long-term effects and very-short-term effects.

– The long-term effects relate mainly to thermal effects on cables, transformers, motors, capacitors, etc. They arise from harmonic levels that are sustained for 10 min or more.
– Very short-term effects relate mainly to disturbing effects on electronic devices that may be susceptible to harmonic levels sustained for 3 s or less. Transients are not included.

With reference to long-term effects, the compatibility levels for individual harmonic components of the voltage are given in Table 1. The compatibility level for the total harmonic distortion is *THD* = 8 %.

Table 1 – Compatibility levels for individual harmonic voltages in low and medium voltage networks (percent of fundamental component) reproduced from IEC 61000-2-2 [5] and IEC 61000-2-12 [6]

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,4	6	0,5
13	3	21	0,3	8	0,5
$17 \leq h \leq 49$	$2{,}27 \cdot \frac{17}{h} - 0{,}27$	$21 < h \leq 45$	0,2	$10 \leq h \leq 50$	$0{,}25 \cdot \frac{10}{h} + 0{,}25$
NOTE The compatibility level for the total harmonic distortion is THD = 8 %.					

With reference to the very-short term effects (3 s or less), the compatibility levels for individual harmonic components of the voltage are the values given in Table 1 multiplied by a factor k_{hvs}, where k_{hvs} is calculated as follows:

$$k_{hvs} = 1{,}3 + \frac{0{,}7}{45} \cdot (h - 5) \quad (1)$$

The compatibility level for the total harmonic distortion for very short-term effects is THD = 11 %.

Compatibility levels are not defined in IEC for HV and EHV systems.

4.2 Planning levels

4.2.1 Indicative values of planning levels

These are harmonic voltage levels that can be used for the purpose of determining emission limits, taking into consideration all distorting installations. Planning levels are specified by the system operator or owner for all system voltage levels and can be considered as internal quality objectives of the system operator or owner and may be made available to individual customers on request. Planning levels for harmonics are equal to or lower than compatibility levels and they should allow co-ordination of harmonic voltages between different voltage levels. Only indicative values may be given because planning levels will differ from case to case, depending on system structure and circumstances. Indicative values of planning levels for harmonic voltages are shown in Table 2.

Table 2 – Indicative planning levels for harmonic voltages (in percent of the fundamental voltage) in MV, HV and EHV power systems

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,8	1,4
7	4	2	9	1,2	1	4	1	0,8
11	3	1,5	15	0,3	0,3	6	0,5	0,4
13	2,5	1,5	21	0,2	0,2	8	0,5	0,4
$17 \leq h \leq 49$	$1{,}9 \cdot \frac{17}{h} - 0{,}2$	$1{,}2 \cdot \frac{17}{h}$	$21 < h \leq 45$	0,2	0,2	$10 \leq h \leq 50$	$0{,}25 \cdot \frac{10}{h} + 0{,}22$	$0{,}19 \cdot \frac{10}{h} + 0{,}16$

The indicative planning levels for the total harmonic distortion are THD_{MV} = 6,5% and $THD_{HV\text{-}EHV}$ = 3 %

NOTE 1 For some higher order harmonics, care should be exercised when specifying very low values such as 0,2 % because of practical limitations of measurement accuracy mainly at HV-EHV. Furthermore, depending on system characteristics a margin should exist between MV, HV and EHV planning levels in order to allow coordinating emission of disturbances between different voltage levels (measurement results can be used as a basis to determine appropriate margin).

NOTE 2 The planning levels in Table 2 are not intended to control harmonics arising from exceptional events such as geomagnetic storms, etc.

NOTE 3 In some countries, planning levels are defined in national standards or guidelines.

NOTE 4 Voltage characteristics that are quasi-guaranteed levels exist in some countries for MV and HV systems. They are generally selected to be higher than the planning levels [7].

With reference to very short term effects of harmonics (3 s or less), planning levels for individual harmonics should be multiplied by a factor k_{hvs} as given by Equation (1).

Where national circumstances make it appropriate depending on system characteristics, intermediate values of planning levels may be needed between the MV, HV and EHV values due to the possibly wide range of voltage levels included in HV-EHV (>35 kV). Additionally, an apportioning of planning levels between HV and EHV may also be necessary to take account of the impact on HV systems of disturbing installations connected at EHV. In this case, planning levels at EHV should be set at lower values than those given in the above table.

More guidance for adapting MV planning levels to specific system characteristics can be found in Annex B. An example of the method for sharing planning levels between different parts of an HV-EHV system is also given in Annex D.

The remainder of this report outlines procedures for using these planning levels to establish the emission limits for individual customer distorting installations.

4.2.2 Assessment procedure for evaluation against planning levels

The measurement method to be used for harmonic and inter-harmonic measurements is the class A method specified in IEC 61000-4-30 [12] and related IEC 61000-4-7 [11] The data flagged in accordance with IEC 61000-4-30 should be removed from the assessment. For clarity, where data is flagged the percentile used in calculating the indices defined below is calculated using only the valid (unflagged) data.

The minimum measurement period is one week of normal business activity. The monitoring period should include some part of the period of expected maximum harmonic levels.

One or more of the following indices may be used to compare the actual harmonic levels with the planning levels. More than one index may be needed for planning levels in order to assess the impact of higher emission levels allowed for shorter periods of time such as during bursts or start-up conditions.

– The 95 % weekly value of U_{hsh} (r.m.s. value of individual harmonics over "short" 10 min periods) should not exceed the planning level.
– The greatest 99 % probability daily value of U_{hvs} (r.m.s. value of individual harmonic components over "very short" 3 s periods) should not exceed the planning level times the multiplying factor k_{hvs} given in Equation (1) with reference to the compatibility levels given for very short time effects of harmonics.

NOTE 1 Harmonics are generally measured up to the 40th or 50th, depending on the application. In most cases, this is adequate for evaluating the distorting effects of power disturbances. However, higher order harmonics up to the 100th order can be an important concern in some cases. Examples include:

− large converters with voltage notching;
− large installations with converters of high pulse numbers (e.g. aluminium plants);
− power electronic equipment with PWM converters interfacing with the power system.

Such cases can result in induced noise interference in neighbouring sensitive appliances (e.g. sensors, communication systems, etc.). It is generally found that higher order harmonics vary more with location and with time than lower order harmonics. In many cases, high order harmonics are produced by a single disturbing installation, often in combination with power system resonance. There may be a need for more extensive evaluations when higher order harmonics are a concern.

NOTE 2 For harmonic measurement, the accuracy of the whole measurement chain needs to be considered. Apart from the monitor itself, transducers should be suitable for harmonic measurements (avoid clipping and distortion for the magnitude and frequency range to be measured). The existing current and voltage transformers for metering and protection purposes on MV and HV-EHV systems are not always suitable for harmonic measurements (especially when frequency is above 1 kHz).

4.3 Illustration of EMC concepts

The basic concepts of planning and compatibility levels are illustrated in Figure 1 and Figure 2. They are intended to emphasize the most important relationships between the basic variables.

Within an entire power system it is inevitable that some level of interference will occur on some occasions, hence there is a risk of overlapping between the distributions of disturbance levels and immunity levels (see Figure 1). Planning levels for harmonics are generally equal to or lower than the compatibility level. They are specified by the system operator or owner. Immunity test levels are specified by relevant standards or agreed upon between manufacturers and customers.

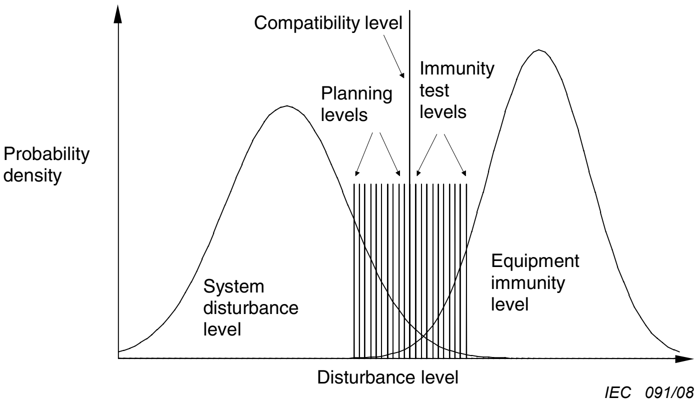


Figure 1 – Illustration of basic voltage quality concepts with time/ location statistics covering the whole system

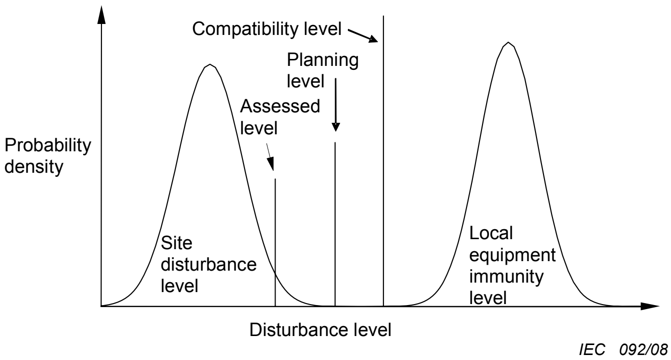


Figure 2 – Illustration of basic voltage quality concepts with time statistics relevant to one site within the whole system

As Figure 2 illustrates, the probability distributions of disturbance and immunity levels at any one site are normally narrower than those in the whole power system, so that at most locations there is little or no overlap of disturbance and immunity level distributions. Interference is therefore not generally a major concern, and equipment is anticipated to function satisfactorily. Electromagnetic compatibility is therefore more probable than Figure 1 appears to suggest.

4.4 Emission levels

The co-ordination approach recommended in this report relies on individual emission levels being derived from the planning levels. For this reason, the same indices are applied both when evaluating actual measurements against the emission limits and against the planning levels.

One or more of the following indices can be used to compare the actual emission level with the customer's emission limit. More than one index may be needed in order to assess the impact of higher emission levels allowed for short periods of time such as during bursts or start-up conditions.

- The 95 % weekly value of U_{hsh} (or I_{hsh}), the r.m.s. value of individual harmonics over "short" 10 min periods, should not exceed the emission limit.

- The greatest 99 % probability daily value of U_{hvs} (or I_{hvs}), the r.m.s. value of individual harmonic components over "very short" 3 s periods, should not exceed the emission limit multiplied by the factor k_{hvs} given in Equation 1. With reference to very short time effects of harmonics, use of the very-short time index for assessing emissions is only needed for installations having a significant impact on the system, so use of this index could be dependant on the ratio between the agreed power of the installation and the short-circuit power of the system (i.e. S_i/S_{sc}).

In order to compare the level of harmonic emissions from a customer's installation with the emission limits, the minimum measurement period should be one week. However, shorter measurement periods might be needed for assessing emissions under specific conditions. Such shorter periods should represent the expected operation over the longer assessment period (i.e. a week). In any case, the measurement period shall be of sufficient duration to capture the highest level of harmonic emissions which is expected to occur. If the harmonic level is dominated by one large item of equipment, the period should be sufficient to capture at least two complete operating cycles of this equipment. If the harmonic level is caused by the summation of several items of equipment, the period should be at least one operating shift.

Where significant, the following factors should also be taken into account (see also 6.2 , 6.3 and subclauses).

- Distorting equipment with normally expected non-ideal characteristics (normally power electronic) due to defects in manufacturing, operation and control.
- Harmonic filter detuning.
- Capacitor banks within the installation and their contribution to harmonic resonances.
- Interactions between different equipment within the installation.

The measurement method to be used is the class A measurement method defined in IEC 61000-4-30 [12] and associated IEC 61000-4-7 [11] for harmonics and inter-harmonics. The data flagged in accordance with IEC 61000-4-30 should be removed from the assessment. For clarity, where data is flagged the percentile used in calculating the indices defined above is calculated using only the valid (unflagged) data. When the signal to be analysed is rapidly varying (e.g. the current drawn by an arc furnace) the measurement of (inter) harmonic groups and subgroups should be used as described in IEC 61000-4-7, rather than the harmonic components.

At each (inter)harmonic frequency, the emission level from a distorting installation is the (inter)harmonic voltage (or current) assessed according to Clause 6.

5 General principles

The proposed approach for setting emission limits of distorting installations depends on the agreed power of the customer, the power of the harmonic-generating equipment, and the system characteristics. The objective is to limit the harmonic injection from the total of all distorting installations to levels that will not result in voltage distortion levels that exceed the planning levels. Three stages of evaluation are defined which may be used in sequence or independently.

5.1 Stage 1: simplified evaluation of disturbance emission

It is generally acceptable for a customer to install small appliances without specific evaluation of harmonic emission by the system operator or owner. Manufacturers of such appliances are generally responsible for limiting the emissions. For instance, IEC 61000-3-2 [8] and IEC 61000-3-12 [9] are product family standards that define harmonic emission limits for equipment connected to LV systems. There are currently no emission standards for MV equipment for the following reasons:

- medium voltage varies between 1 kV and 35 kV; and

- no reference impedance has been internationally defined for medium voltage systems.

Even without a reference impedance, it is possible to define conservative criteria for quasi-automatic acceptance of small size distorting installations on MV systems (and HV systems too). Indeed, if the total distorting installation, or the customer's agreed power, is small relative to the short circuit power at the point of evaluation, it should not be necessary to carry out detailed evaluation of the harmonic emission levels. A more refined approach is to calculate a "weighted distorting power" (see 8.1.2) as a criterion to determine the acceptability at stage 1 of the total distorting equipment connected within the customer's facility.

In 8.1 and 9.1, specific criteria are developed for applying stage 1 evaluation.

5.2 Stage 2: emission limits relative to actual system characteristics

If an installation does not meet stage 1 criteria, the specific characteristics of the harmonic generating equipment within the customer's installation should be evaluated together with the absorption capacity of the system. The absorption capacity of the system is derived from the planning levels, and is apportioned to individual customers according to their demand with respect to the total system capacity. The disturbance level transferred from upstream voltage levels of the supply system to lower voltage levels should also be considered when apportioning the planning levels to individual customers.

The principle of this approach is that, if the system is fully utilised to its designed capacity and all customers are injecting up to their individual limits, the total disturbance levels will be equal to the planning levels taking into account transfer factors between different voltage levels and the summation of various harmonic producing installations. A procedure for apportioning the planning levels to individual customers is outlined in Clause 8 and Clause 9.

NOTE If the capacity of the system increases in the future, the emission levels of individual customers should become lower. It is important therefore, where possible, to consider future expansions of the system.

5.3 Stage 3: acceptance of higher emission levels on a conditional basis

Under some circumstances, a customer may require acceptance to emit disturbances beyond the basic limits allowed in stage 2. In such a situation, the customer and the system operator or owner may agree on special conditions that facilitate connection of the distorting installation. A careful study of the actual and future system characteristics will need to be carried out in order to determine these special conditions.

5.4 Responsibilities

In the context of this report from the EMC point of view, the following responsibilities are defined.

- The customer is responsible for maintaining his emissions at the specified point of evaluation below the limits specified by the system operator or owner.
- The system operator or owner is responsible for the overall co-ordination of disturbance levels under normal operating conditions in accordance with national requirements. For evaluation purposes the system operator or owner should, where required, provide relevant system data such as harmonic impedance or the necessary data to calculate this (see 6.4), short-circuit levels, and existing levels of distortion. The evaluation procedure is designed in such a way that the harmonic emissions from all distorting installations do not cause the overall system harmonic voltage levels to exceed the planning and compatibility levels. However, given specific local conditions and the assumptions that are necessary in this evaluation procedure, there is no guarantee that the recommended approach will always avoid exceeding the levels.
- Finally, the system operator or owner and customers should co-operate when necessary in the identification of the optimum method to reduce emissions. The design and choice of method for this reduction are the responsibility of the customer.

NOTE This report is mainly concerned with emissions. However, harmonic absorption may also be a problem if filters or capacitor banks are connected without due consideration for their interaction with the harmonics normally present in the power system. The problem of harmonic absorption is also part of the customer's responsibility.

6 General guidelines for the assessment of emission levels

6.1 Point of evaluation

The point of evaluation (POE) is the point where the emission levels of a given customer's installation are assessed for compliance with the emission limits. This is also a point within the considered power system at which the planning levels are defined. This point could be the point of connection (POC) or the point of common coupling (PCC) of the disturbing installation or any other point specified by the system operator or owner or agreed upon. More than one point of evaluation may also be specified for a given customer's installation depending on the system structure and characteristics of the installation. In this case, the evaluation should be made considering the system characteristics and agreed powers applicable to the different evaluation points.

NOTE 1 It should be noted, however, that for the determination of the emission limits and for the evaluation of the emission levels it is often necessary to take account of system characteristics (such as the impact of resonance at remote points in the system) beyond the point of evaluation.

NOTE 2 Depending on the location of the point of common coupling compared to the point of connection of the distorting installation, harmonic voltage might be higher at the latter.

NOTE 3 It should be remembered that, as voltage characteristics or contracted limits apply at the point of connection, these should be taken into consideration in discussions between the parties.

6.2 Definition of harmonic emission level

The harmonic emission level from an installation into the power system is the magnitude of the harmonic voltage (or current) vector at each harmonic frequency, which is caused by the considered installation at the point of evaluation. This is illustrated in Figure 3 by the vector U_{hi} and its contribution (together with the harmonic vector caused by all other sources of harmonics when the installation under consideration is not connected to the system) to the measured harmonic vector at the point of evaluation, once the installation has been connected.

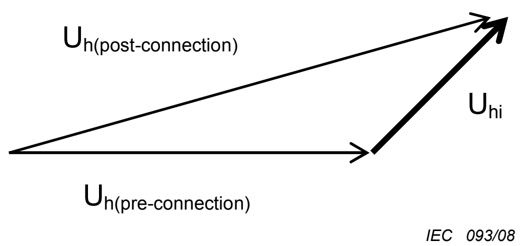


Figure 3 – Illustration of the emission vector $\underline{U}_{hi}$ and its contribution to the measured harmonic vector at the point of evaluation

Where the harmonic emission vector results in increased levels of harmonic distortion on the network, the emission level as defined above (i.e. $|U_{hi}|$) is required to be less than the emission limits assessed according to the relevant clauses in this document.

NOTE 1 The interaction between the supply system and customer's installation may in some cases result in amplification or in reduction of the voltage distortion levels at a given harmonic order (i.e. due to the creation of a parallel or a series resonance condition). This is possible even where the plant itself does not generate harmonics of this order. As this document addresses the EMC co-ordination requirements, such resonance situations need to be taken into consideration in the assessment of actual emission levels.

NOTE 2 Harmonic voltages or currents produced by different installations might not be in phase. This is addressed in Clause 7 and 8.3.

NOTE 3 If the installation exceeds the harmonic voltage emission limits it may be because

1) the system impedance is high due to the presence of harmonic resonance conditions,
2) the installation is resonating with the supply system, or
3) the harmonic currents generated by the installation are too high.

NOTE 4 For the pre-connection assessment of emission levels, the customer plant is considered only as a source of harmonic current. Harmonic current and/or voltage limits are also defined based on this assumption. During a post-connection assessment, the plant characteristics include those of its internal sources of harmonic current, as well as its impedance (giving rise to the possibility of resonance with the system).

6.3 Assessment of harmonic emission levels

This subclause is intended to provide general guidance on the assessment of harmonic emissions from distorting installations, taking account of various operating and non-ideal conditions that may exist on power systems and customer installations. More details on the assessment of the emission levels are given in references [13] and [14].

The pre-connection assessment of the harmonic emission level for an installation can be determined using basic assumptions about the characteristics of the system and the customer‘s installations. However, this calculated value is likely to be different from the actual emission level that will be observed when the installation is connected to the system, i.e., the actual emission level could be higher or lower than the calculated value. Therefore, it may be necessary to assess the level of emissions that will be present when the installation is connected to the system.

6.3.1 Operating conditions

The assessment of harmonic emission levels from distorting installations should consider the worst normal operating conditions including asymmetries and contingencies for which the system or the customer’s installation is designed to operate and that may last for a specified percentage of the time, for example more than 5 % of time based on a statistical average (an example is the prolonged outage of one 6-pulse rectifier unit in a large multiphase rectifier plant). Additionally, for large installations compared to the system size (e.g., S_{sc}/S_i <30. Note that the ratio of 30 can be adjusted to meet specific conditions), it may also be necessary to assess emission levels for occasional operating conditions lasting less than 5 % of time. However, higher emission limits may be allowed under such occasional conditions or during start-up or burst conditions (e.g., 1,5 to 2 times).

For simple cases, the harmonic injection from a given distorting customer’s installation can be assessed by using the maximum current at each harmonic and interharmonic frequency that can be produced over the possible range of operation of each piece of equipment. For large installations, this approach may lead to excessively conservative results. Alternatively, a set of harmonic and interharmonic currents consistent with the most onerous and simultaneous operating modes of all pieces of equipment that may realistically occur simultaneously can be considered for assessing the maximum harmonic injection.

6.3.2 Asymmetries and non-ideal conditions

In practical situations, it is inevitable that some degree of asymmetry will be present in the supply system and in the customer’s equipment, which will result in the generation of non-characteristic harmonics. These non-characteristic harmonics may be small relative to the characteristic harmonics, but for certain types of installations such as constantly varying loads, and large rectifier plants using high pulse number rectifiers, they can dominate and be amplified due to resonance with the filters. Hence, these non-characteristic harmonics need to be included in the assessment of emission levels.

The following non-ideal conditions should be considered as minimum conditions for assessing the performance of a distorting installation with respect to harmonic emissions (note that for the rating of an equipment and/or apparatus such as transformers, capacitors, reactors, filters etc., the criteria may be different from those given below which relate to performance instead of rating).

- Frequent or prolonged reduction of the pulse number in an installation due to the outage or the unbalanced operation of some of the converters forming a higher pulse number installation, thus increasing low order harmonics such as 5, 7, 11, 13, etc.
- Supply voltage unbalance: the presence of a negative sequence component of fundamental frequency on a three-phase supply voltage will usually produce odd-triple harmonics of positive and/or negative sequence. Generally a voltage unbalance factor (1 % to 2 % depending on the voltage level) should be considered for the non-ideal steady state operation of the power system. In some MV networks with single-phase spurs, an unbalance factor of up to 3 % may be considered, where indicated by the system operator or owner.
- Converter transformers and commutating impedance unbalance: manufacturing tolerances on the turns ratio (turns ratio not exactly equal to $\sqrt{3}$) and on the reactance between two transformers of a 12-pulse converter produces non-characteristic harmonics normally only associated with a 6-pulse converter. Asymmetry of the commutating impedance between phases produces non-characteristic harmonics that also depend on the transformer winding connections.
- Firing angles asymmetries: the variations of the valve firing instants can give rise to a wide spectrum of harmonics. The deviation in firing angles between valves depends on the particular design of the firing circuits.
- Filter detuning: when harmonic filters are required in order to comply with emission limits, the assessment of harmonic disturbances should also consider detuning effects, namely due to
  - the variation of the power frequency that may occur in steady state operation,
  - the initial mistuning due to manufacturing tolerances and changes in filter component values due to ambient temperature variations,
  - ageing of filter components,
  - planned switching operations of the filters and capacitor banks with the variation of load.

6.4 System harmonic impedance

Information on the system harmonic impedance is a prerequisite both for the system operator or owner for assessing emission limits and for the customer in order to assess the emission levels of the considered installation. With reference to how the harmonic impedance is to be used, it is possible to identify three different kinds.

6.4.1 Impedance for converting emission limits from voltage to current

For converting emission limits from voltage into current limits, there are two ways to assess the harmonic system impedance depending on the size of the distorting installation and the system characteristics:

- For general application, a declared or generic system harmonic impedance covering different types of systems, different voltage levels, etc. may be used by the system operator or owner in order to define generic sets of emission limits based on typical system characteristics. Correction factors may be introduced when needed to compensate for other than generic system characteristics (e.g. an amplification factor based on typical resonance conditions for such networks). This application is generally better at lower system voltages, where damping of resonant conditions tends to be better than at HV and particularly at EHV.
- For large installations compared to system size especially at HV-EHV, the best estimate of the maximum harmonic impedance of the system over the worst operating conditions at the point of evaluation can also be used. It may also include an assessment of the impact on remote points in the network.

In any case, exceptionally low values of harmonic impedance should be disregarded as they often relate to series resonance for which the harmonic voltage may exceed planning levels in other parts of the system. In this case, the impedance value should be disregarded and be replaced by a default value (for example Z_1 * h, where h is the harmonic order and Z_1 the system impedance at the fundamental frequency).

6.4.2 Impedance for pre-connection assessment of emission levels

For enabling a pre-connection assessment of the harmonic emission levels for large disturbing installations in particular, the system harmonic impedances at the point of evaluation can be obtained by simulation for various system operating conditions (including future conditions). In some cases this impedance may be based on the short-circuit impedance and in other cases (e.g. in the case of large installations) the locus of the harmonic impedance, or the data to calculate this, should be provided. Particularly for large installations (or small S_{sc}/S_i ratio), it is important to properly assess the possibility of resonance so that filters/capacitors can be designed as to avoid problems or damage (not only system resonance, but also resonance between the considered filters or capacitors and the supply system) . It is necessary to consider the range of variation of harmonic impedance not only the maximum impedance values in order to identify possible resonance. The range of variation of the phase angle of the harmonic impedance characterizes the resistive part of the impedance and defines the damping in case of resonance.

6.4.3 Impedance for assessing actual emission levels

For assessing the actual emission levels from a given distorting installation, the actual system harmonic impedance can be measured or calculated for use in combination with other measured parameters in order to assess the actual emission levels.

6.4.4 General guidelines for assessing the system harmonic impedance

Most distorting installations behave as sources of harmonic currents. Knowledge of the harmonic impedance of the system, as seen from the point of evaluation, is necessary to predict the harmonic voltages that will appear at that point when the installation is connected. The following indications relate to the cases described in 6.4.2 and 6.4.3 above, where the system harmonic impedance is needed to assess the emission levels from a large distorting installation.

The assessment of the harmonic impedance can be a very complex problem. Several measurement and calculation methods are available, see [15], [16], [17] and [18], but none is entirely satisfactory. Furthermore, the harmonic impedance of the system may vary significantly with time. So when important changes are expected between the present and the future system configuration, a different set of harmonic impedance data should be provided in order for the customer to assess his emission levels for both situations and to achieve an optimal design of his equipment.

For enabling a pre-connection assessment of emission levels, the harmonic impedance of the system needs to be determined, usually obtained by simulation. As for the assessment of emission levels, the determination of the system harmonic impedance should consider the different normal operating conditions including system abnormal operating conditions where these situations may last for a specified portion of the time, for example more than 5 % of time annually based on a statistical average. Known or foreseeable future system changes should be included.

In particular, the various reactive compensation or filter states (e.g. shunt capacitor states) have to be considered (in the latter case, these states should correspond with the system loading normally associated with these states, for example a lightly loaded system may give rise to significant harmonic amplification).

The variations of the system harmonic impedance due to the tolerance on the electrical parameters of the network components and inaccuracies in the modelling should be accounted for by assessing the impedance over an equivalent frequency range of deviation for each harmonic (the tolerance on the inductive and capacitive components of the apparatus can be converted in terms of equivalent frequency deviations). For high harmonic orders, this should also allow considering possible resonance between some harmonic frequencies.

Where required (e.g. for large installations) the system harmonic impedance data should be given in the form of a locus or a table giving the minimum and maximum expected magnitude and phase angle variations of impedance over the harmonic range of interest, or the network data needed to calculate this impedance data provided. The disturbing installation under consideration is generally not well known at the early stage of a pre-connection assessment. Hence it is customary to provide the system harmonic impedance without including the effect of the disturbing installation to be assessed. Once the customer has achieved his preliminary design, he can combine the harmonic impedance of his own installation with that of the system in order to evaluate his emission levels, taking into account the possible resonance that his installation might create with the supply system.

In addition to the above considerations, the following factors may also affect the impedance:

- The short circuit equivalent at the substation tends to be the dominating inductance when calculating resonance frequencies on MV systems.
- Without shunt capacitor banks, resonances are determined by the capacitance of cables and overhead lines. Without significant cable lengths, these resonances will typically be above the 13th harmonic.
- Shunt capacitor banks on the system create resonances at lower order harmonic frequencies. It is not uncommon for the most important resonance to be at the fifth harmonic or below.
- MV systems that supply a mix of residential, commercial, and industrial loads typically exhibit damping characteristics that prevent high magnification (in excess of 2-3) at the low order resonance frequencies.
- Some MV systems that supply primarily industrial load may have less damping and resonances can cause higher magnification levels.

Other customers' facilities also affect the system harmonic impedance. Special attention should be paid to their capacitor banks, which can modify resonances or create additional ones. This is particularly important when the capacitor banks are connected within the customer installation. The system operator or owner generally will not have complete information about existing customers' facilities, so they can only provide approximate information.

7 General summation law

The co-ordination of conducted disturbances requires the adoption of hypotheses relevant to the summation of the disturbances produced by various installations. In the case of harmonic disturbances, the actual harmonic voltage (or current) at any point on a system is the result of the vector sum of the individual components of each source.

On the basis of experience, a general summation law can be adopted for both harmonic voltage and current. The law for resulting harmonic voltage of order h is:

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \qquad (2)$$

NOTE The same equation can be used for the summation of harmonic current.

where

U_h is the magnitude of the resulting harmonic voltage (order h), for the considered aggregation of sources (probabilistic value);

U_{hi} is the magnitude of the various individual emission levels (order h) to be combined;

α is an exponent depending mainly upon 2 factors:

- the chosen value of the probability for the actual value not to exceed the calculated value;
- the degree to which individual harmonic voltages vary randomly in terms of magnitude and phase.

Taking into account:

- Harmonic emission co-ordination mainly refers to 95 % non-exceeding probability values.
- Sources which combine in emission correspond to
  - those of major installations connected to MV/LV distribution systems,
  - disturbances transferred from one voltage level of the system to another,
  - the aggregated global emission of many LV installation.
- Low order odd harmonics have
  - magnitudes that are significant almost everywhere in the systems and remain generally stable for long periods,
  - phase angles with a relatively narrow variation range (limited variations at the sources; limited variations due to the propagation in the system if no low-frequency resonance occurs).
- High order harmonics vary widely in magnitude and phase angle.

On the basis of the information available to date, the following set of exponents can be adopted in the absence of further specific information:

Table 3 – Summation exponents for harmonics (indicative values)

Harmonic order	α
$h < 5$	1
$5 \leq h \leq 10$	1,4
$h > 10$	2

NOTE 1 When it is known that the harmonics are likely to be in phase (i.e. phase angle differences less than 90°), then an exponent $\alpha = 1$ should be used for order 5 and above.

NOTE 2 Conversely, some low order non-characteristic harmonics (e.g. 3rd) may have different causes that are unlikely to produce in-phase harmonics, therefore an exponent higher than 1 could be used for these cases (e.g. $\alpha = 1,2$).

NOTE 3 Higher summation exponents can be used for even harmonics that are less likely to be in phase (for $h \leq 10$).

8 Emission limits for distorting installations connected to MV systems

8.1 Stage 1: simplified evaluation of disturbance emission

In stage 1, the connection of small installation or installations with only a limited amount of distorting equipment can be accepted without detailed evaluation of the emission characteristics or the supply system response.

Two possible criteria are given in this subclause for Stage 1 evaluation. If the assumptions related to 8.1.1 or 8.1.2 are in doubt then it will be necessary to conduct an assessment according to Stage 2 criteria given in 8.2.

8.1.1 Agreed power as a criterion

If the following condition is fulfilled:

$$\frac{S_i}{S_{sc}} \leq 0{,}2\% \qquad (3)$$

(S_i = agreed power of customer i and S_{sc} = short circuit power at the point of evaluation), then any distorting installation may be connected to the supply system without further examination.

NOTE S_{SC} may be calculated (or measured) for the specific point of evaluation, or may be estimated for typical MV system with similar characteristics to that under consideration.

The figure of 0,2 % is based on a number of assumptions.

- The system is currently operating with a level of distortion sufficiently below the planning level that the connection of the new installation will not cause the planning level to be exceeded.
- The amplification as a result of resonance is not expected to exceed a factor of two.
- There is no risk of interference with other customers / system equipment caused by connection of the new installation.

8.1.2 Weighted distorting power as a criterion

This approach involves calculating a "weighted distorting power", S_{Dwi}, to characterize the amount of distorting equipment within the customer's facility. This can be done using the weighting factors W_j in Table 4 for common types of harmonic producing equipment.

The weighted distorting power is calculated as follows:

$$S_{Dwi} = \sum_j S_{Dj} \cdot W_j \qquad (4)$$

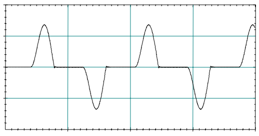
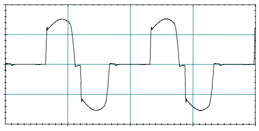
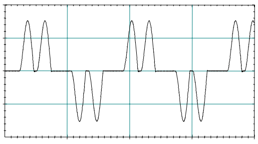
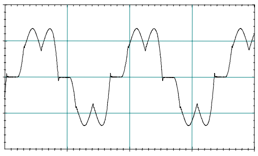
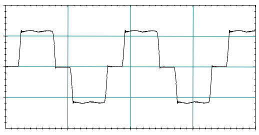
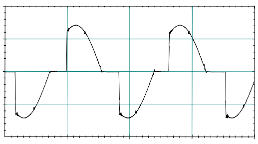
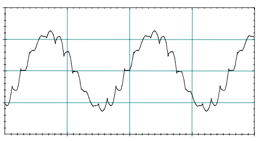
where S_{Dj} is the power of each distorting equipment (j) in the facility (i).

If the characteristics of the harmonic producing equipment are unknown, a weighting of 2,5 can be assumed.

Acceptance of a customer's installation under stage 1 may be determined by comparing the weighted distorting power with the short-circuit power at the point of evaluation. The following conservative criterion can be used for acceptance under stage 1:

$$\frac{S_{Dwi}}{S_{sc}} \leq 0{,}2\% \qquad (5)$$

Table 4 – Weighting factors W_j for different types of harmonic producing equipments

Typical equipment connected to LV, MV or HV	Typical current waveform	Typical current THD	Weighting Factor (W_j)
Single phase power supply (rectifier and smoothing capacitor)		80 % (high 3rd)	2,5
Semi-converter		High 2nd,3rd, 4th at partial loads	2,5
6-pulse converter, capacitive smoothing, no series inductance		80 %	2,0
6-pulse converter, capacitive smoothing with series inductance > 3%, or d.c. drive		40 %	1,0
6-pulse converter with large inductor for current smoothing		28 %	0,8
AC voltage regulator		Varies with firing angle	0,7
12-pulse converter		15 %	0,5

8.2 Stage 2: emission limits relative to actual system characteristics

Considering the actual absorption capacity of the system, due to the phase differences of the harmonic currents as well as the system impedance and future load, higher emissions than those according to stage 1 criteria may be granted.

In this stage, the allowable global contribution to the overall level of disturbance is apportioned to each individual installation in accordance with its share of the total capacity of the supply system (S_t) to which this installation is connected. This ensures that the disturbance level due to the emissions of all customers connected to the system will not exceed the planning level.

Two approaches are presented hereafter. The first (simplified) approach is based on the allowed harmonic current as a function of the fundamental current. The second is based on the general summation law, allowing a more general method for setting emission limits for larger distorting installations.

8.2.1 Relative harmonic currents as emission limits

The permissible share of the total voltage distortion will generally not be exceeded when appropriate limits are set on the “relative harmonic currents”. Table 5 gives an example of these limits. It applies to customers with an agreed power $S_i \leq 1$ MVA and with S_i / S_{sc} < 1 %, provided that the pre-existing harmonic level allows it and if the customer does not use power factor correction capacitors and/or filters.

Table 5 – Indicative values for some odd order harmonic current emission limits relative to the size of a customer installation

Harmonic order h	5	7	11	13	> 13
Harmonic current emission limit $E_{Ihi} = I_{hi}/I_i$ (%)	5	5	3	3	$\frac{500}{h^2}$

where

E_{Ihi} is the harmonic current emission limit of order h for the customer I,

I_{hi} is the harmonic current of order h caused by the distorting installation of customer I,

I_i is the r.m.s. current corresponding to his agreed power (fundamental frequency).

8.2.2 General approach based on the summation law

8.2.2.1 Global emission to be shared between customers

Consider a typical MV system as illustrated in Figure 4. The aim is to set emission limits at MV.

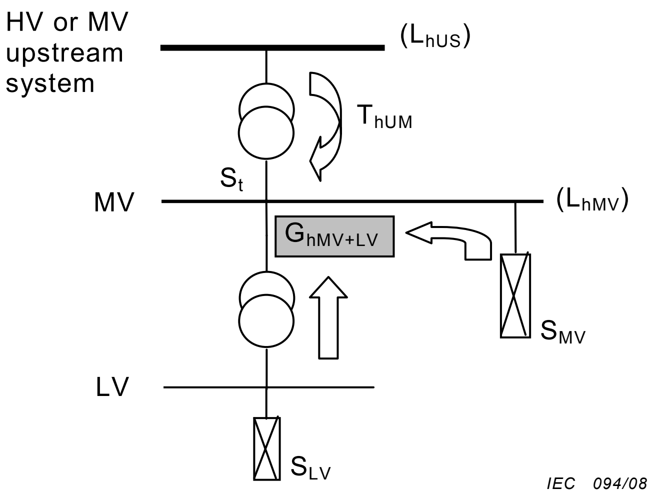


Figure 4 – Example of a system for sharing global contributions at MV

Firstly an application of the general summation law (Equation 2) is necessary to determine the global contribution of all harmonic sources present in a particular MV system. Indeed, for each harmonic order, the actual harmonic voltage in a MV system results from the vector summation of the harmonic voltage coming from the upstream system (note that upstream system may be a HV or another MV system for which intermediate planning levels have been set before) and of the harmonic voltage resulting from all distorting installations connected to the considered MV and LV system. This total harmonic voltage should not exceed the planning level of the MV system, given by:

$$L_{hMV} = \sqrt[\alpha]{G_{hMV+LV}^{\alpha} + \left(T_{hUM} \cdot L_{hUS}\right)^{\alpha}} \qquad (6)$$

and thus the global harmonic voltage contribution that can be allocated to the total of MV and LV installations supplied from the considered MV system is given by:

$$G_{hMV+LV} = \sqrt[\alpha]{L_{hMV}^{\alpha} - \left(T_{hUM} \cdot L_{hUS}\right)^{\alpha}} \qquad (7)$$

where

G_{hMV+LV}, is the maximum global contribution of the total of MV and LV installations that can be supplied from the MV busbar to the h^{th} harmonic voltage in the MV system (expressed in percent of the fundamental voltage),

L_{hMV} is the planning level of the h^{th} harmonic in the MV system,

L_{hUS} is the planning level of the h^{th} harmonic in the upstream system (for reasons explained before, different planning levels may be needed for intermediate voltage levels between MV and HV-EHV; this is why the general term of upstream system planning level is used),

T_{hUM} is the transfer coefficient of harmonic voltage distortion from the upstream system to the MV system under consideration at harmonic order h. T_{hUM} can be determined by simulation or measurements. For an initial simplified evaluation, the transfer coefficients T_{hUM} from the upstream system on a MV system can be taken as equal to 1. In practice however, it may be less than 1 (e.g. 2/3), due to the presence of downstream system elements, or higher than 1 (typically between 1 and 3), due to resonance. It is the responsibility of the system operator or owner to determine the relevant values depending on the system characteristics,

α is the summation law exponent (see Table 3 and the discussion in Clause 7).

An example illustrating the use of the above equation is shown in Annex C.

When the planning levels for MV systems are equal to those for the upstream systems as it is in Table 2 for h = 15 and 21 and higher order triplen harmonics, the application of Equation 7 would result in a zero contribution for the MV and LV customers (see Annex C). In these cases, an equitable share of emissions between the different system voltage levels should be allocated instead.

8.2.2.2 Individual emission limits

For each customer only a fraction of the global emission limits G_{hMV+LV} will be allowed. A reasonable approach is to take the ratio between the agreed power S_i and the total supply capability S_t of the MV system. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system.

$$E_{Uhi} = G_{hMV+LV} \sqrt[\alpha]{\frac{S_i}{S_t}} \qquad (8)$$

where

E_{Uhi} is the harmonic voltage emission limit of order h for the installation (i) directly supplied at MV (%),

G_{hMV+LV} is the maximum global contribution of the total of MV and LV installations that can be supplied from the considered MV system to the h^{th} harmonic voltage in the MV system, as given by Equation (7),

$S_i = P_i / \cos\varphi_i$ is the agreed power of customer installation i, or the MVA rating of the considered distorting installation (either load or generation),

S_t is the total supply capacity of the considered system including provision for future load growth (in principle, S_t is the sum of the capacity allocations of all installations including that of downstream installations that are or can be connected to the considered system, taking diversity into consideration). S_t might also include the contribution from dispersed generation, however more detailed consideration will be required to determine its firm contribution to S_t and its effective contribution to the short-circuit power as well,

α is the summation law exponent (see Table 3).

NOTE In some cases, dispersed generation may actually be a source of harmonics and should be accounted for accordingly.

It may happen at some locations that the pre-existing level of harmonics is higher than the normal share for the existing installations. In this case the emission limit for any new installations can be reduced, a reconsideration of the allocation of the planning levels between the different voltage levels could be considered, or the system harmonic current absorption capacity could be increased.

For customers having a low agreed power, Equation 8 may yield impractically low limitations. If the voltage emission limit at some harmonic orders becomes smaller than 0,1 %, it shall be set equal to 0,1 % (except if there is a risk of telephone interference, or if it corresponds to a remote control frequency for which a more severe restriction may be justified).

It may be preferred to specify harmonic current limits to the distorting installation, even if the aim is to limit the harmonic voltages in the system. It will be the responsibility of the system operator or owner to provide data concerning the frequency-dependent impedance of the system, in order to enable expressing these limits in terms of harmonic currents:

$$E_{Ihi} = \frac{E_{Uhi}}{Z_{hi}} \quad (9)$$

where

E_{Ihi} is the corresponding harmonic current emission limit of customer “i” at harmonic order h,

Z_{hi} is the harmonic impedance of the system at the point of evaluation for customer “i” assessed considering the actual purpose of converting voltage to current emission limits (see 6.4.1).

8.2.2.3 Case of long MV feeders

The rules proposed above for establishing the individual emission limits do not account explicitly for variation of the short-circuit power through MV networks. When installations are connected to a virtual common busbar, the short-circuit power does not vary significantly, and the methods for sharing emission limits presented so far are adequate. Such is the case for distribution systems with cables less than 10 km in length / overhead lines less than 5 km in length. These conditions are typical of networks supplying rather heavy loads (particular industrial loads, etc.).

NOTE When a series reactor is present between the busbar and the feeder for the purpose of reducing the short circuit power, the word “busbar” is to be understood as the feeder side point of the reactor.

For distribution systems with long cables and overhead lines, where customer installations are distributed along the length of the feeders, the above approach may result in specifying too strict harmonic current limits, thus penalizing customers connected at some distance down the line where the short-circuit power may be significantly lower than at the sending end of the feeder. An approach for sharing the acceptable global emission G_{hMV} among the individual MV installations in order to compensate for this effect is given in Annex B.

The method proposed and illustrated in annex B is suitable for specific cases as well as for developing general purpose emission rules. Therefore, that method can be used by a system operator or owner for establishing its own harmonic current emission limits tailored to the peculiarities of a reference distribution system. The method is based on a mathematical model in which it is assumed that each feeder has its MV installations distributed uniformly and continuously along it. Each feeder is assumed to have constant impedance per unit length, but individual feeders can vary from each other. In such a system, the highest value of harmonic voltage will appear at the end of the feeder having the worst voltage regulation. The method aims to estimate this voltage and limit it to the planning level.

In the case where the system response is dominated by resonance caused by cables or shunt capacitors, the method in annex B is not appropriate for the harmonic frequency at which the resonance occurs.

8.3 Stage 3: acceptance of higher emission levels on a conditional basis

Under some circumstances, the system operator or owner may accept a distorting installation to emit disturbances beyond the basic limits allowed in stage 2. This is especially the case when stage 2 limits are generic limits derived using typical but conservative system characteristics. The following factors may leave a margin on the system for allowing higher emission limits, for example:

- Some installations do not produce significant harmonics because they do not have distorting equipment of significant magnitude. Therefore some of the available supply capacity of the system may not be utilized for a period of time.
- The general summation law may be too conservative in some instances: some distorting installations can produce harmonics with opposite phase; or phase shifting within the system may lead to partial cancellation of harmonics.
- It may happen that some distorting installations never operate simultaneously, due to system or load constraints.
- If the stage 2 limits were set using a generic harmonic impedance or considering an amplification factor due to resonance, the actual impedance may be less than hypothesized.
- In some cases, higher planning levels may be defined after reallocation of the planning levels between MV and HV-EHV systems, to take account of local phenomena such as special attenuation effect or absence of disturbing installations at a certain voltage level or resonance effects.
- In some cases, a disturbing installation may comply to its emission limits in normal system configurations, while exceeding the stage 2 emission limits only occasionally under degraded configurations (e.g. when a nearby generation plant is out of service).

In all the cases, when appropriate the system operator or owner may decide to allocate higher emission limits under stage 3. A careful study of the connection should always be carried out, taking account of the pre-existing distortion and of the expected contribution from the considered installation for different possible operating conditions. Acceptance of higher than normal emission limits may be given to customers only on a conditional basis and limitations may be specified by the system operator or owner, for instance:

- Temporary stage 3 limits for
  - as long as spare supply capacity remains available in the system for allowing more emissions,
  - as long as most other customers do not make full use of their normal stage 2 emissions limits,
  - the time needed for a new installation, in order to implement additional corrective measures whenever needed.
- Reduced or non-operation of the distorting installations for some supply system or customer configurations.

8.4 Summary diagram of the evaluation procedure

Figure 5 gives an overview of the evaluation procedure presented so far in this report.

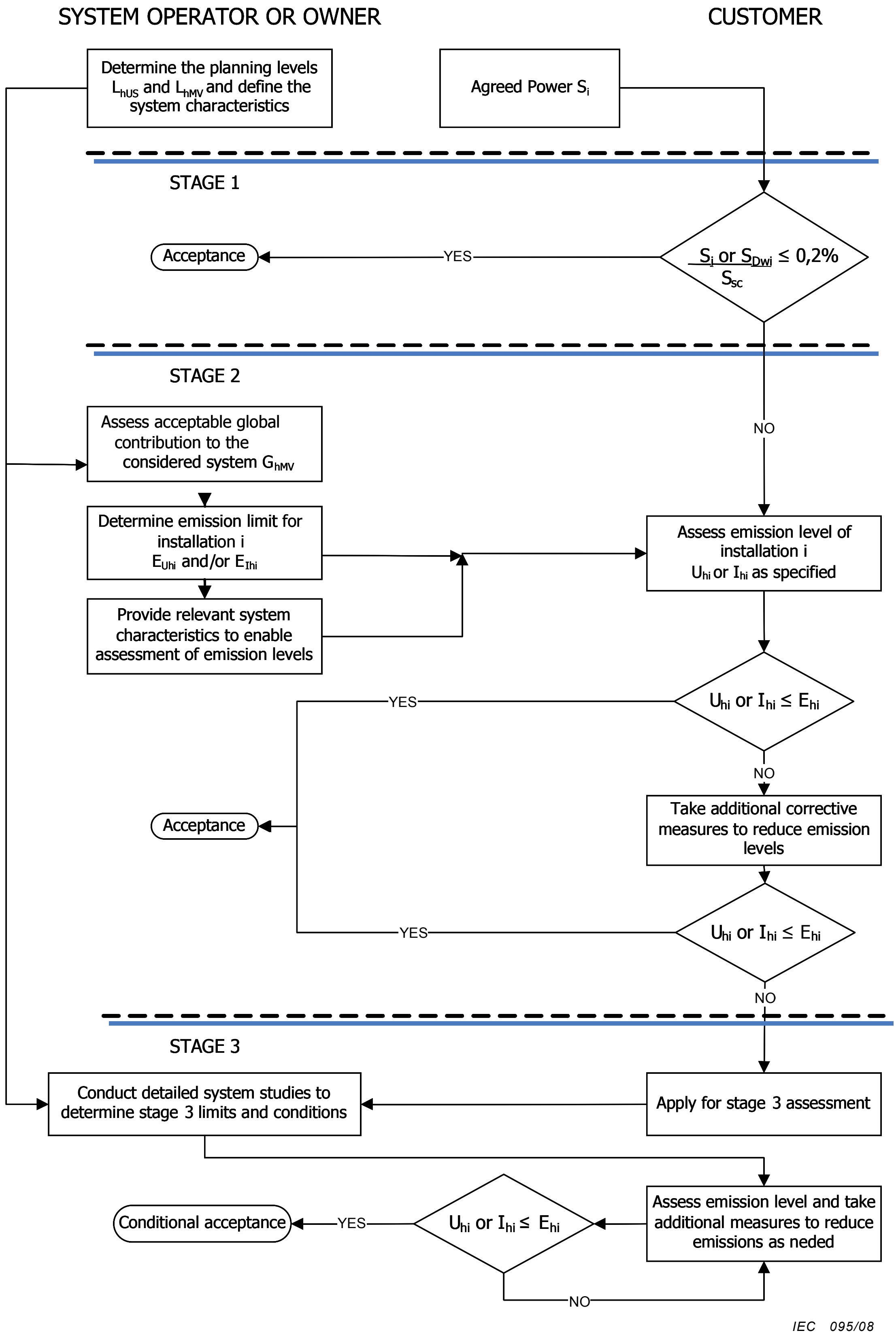


Figure 5 – Diagram of evaluation procedure at MV

9 Emission limits for distorting installations connected to HV-EHV systems

9.1 Stage 1: simplified evaluation of disturbance emission

The same criteria for connection at stage 1 as given in 8.1.1 and 8.1.2 can be used at HV-EHV.

9.2 Stage 2: emission limits relative to actual system characteristics

9.2.1 Assessment of total available power of a substation

Assessing S_t is much more difficult in HV and EHV networks than for the MV case. As a first approach when considering the case of an industrial customer connected at a given HV or EHV substation, the basic information is the forecasts of power flows taking account of the system evolution in the future.

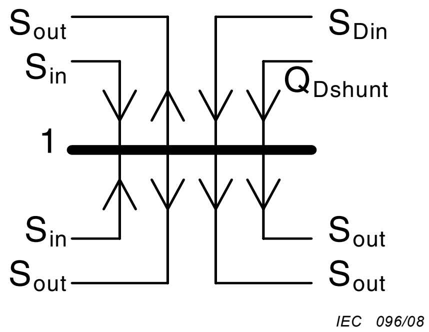


Figure 6 – Determination of S_t for a simple HV or EHV system

A simplified assessment is:

$$S_t = \Sigma\, S_{Din} + \Sigma\, S_{out} + \Sigma\, Q_{Dshunt} \qquad (10)$$

where

S_t (in MVA)	is an approximation of the total power of all installations for which emission limits are to be allocated to in the foreseeable future,
S_{out} (in MVA)	is power flowing out of the considered HV-EHV busbar (including provision for future load growth),
S_{Din} (in MVA)	is the power of any HVDC stations or non-linear generating plants,
Q_{Dshunt} (in MVAR)	is the dynamic rating of any thyristor-controlled reactor (TCR) of any Static Var Compensators connected at the busbar under consideration.

This approximation of St is intended to remain conservative.

NOTE This first approximation may not be conservative if shunt capacitors are located at nearby busbars.

9.2.2 Method for sharing planning levels between busbars at HV and EHV

Before allocating emission limits to distorting installations in a given HV-EHV system, it is first required to share the common HV-EHV planning levels ($L_{hHV\text{-}EHV}$ see Table 2) between the different substations or busbars in a given system.

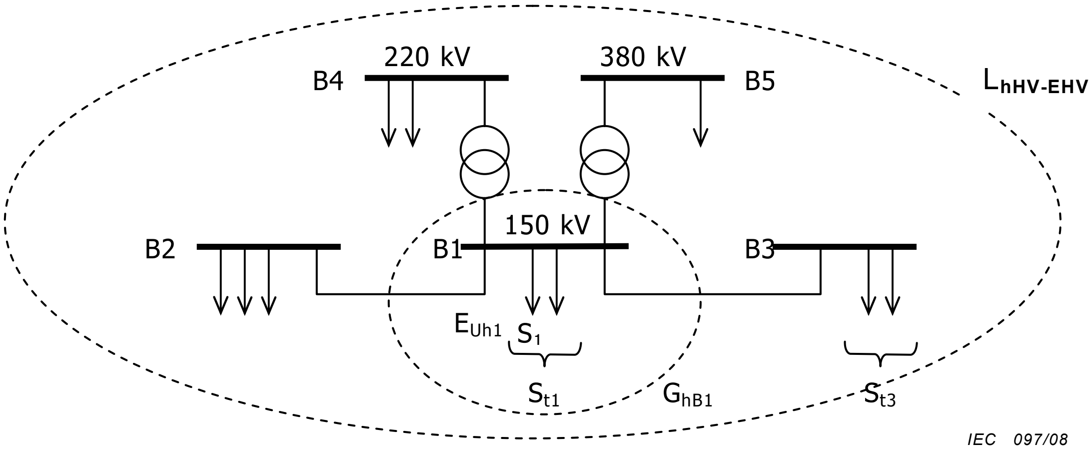


Figure 7 – Allocation of planning level to a substation in HV-EHV system

Figure 7 illustrates a synthesized HV-EHV system. The first requirement is to determine the global contributions (G_{hB1}, G_{hB2},…G_{hBn}) of all distorting installations connected to different substations or busbars B_1, B_2,…B_n.

As before, the basic philosophy is that when all distorting installations i are injecting levels of harmonic distortion equal to their emission limits, the total disturbance level anywhere in the system should not exceed the planning level. The general condition to be satisfied is:

$$\sqrt[\alpha]{\left(\sum_{i\,at\,B1} E_{Uhi}{}^{\alpha}\right)+\left(\sum_{i\,at\,B2} E_{Uhi}{}^{\alpha}\right)+\ldots+\left(\sum_{i\,at\,Bn} E_{Uhi}{}^{\alpha}\right)} \leq L_{hHV-EHV} \quad (11)$$

where $\sum_{i\ at\,Bj} E_{Uhi}{}^{\alpha} \leq G_{hBj}{}^{\alpha}$

and

$L_{hHV-EHV}$ is the planning level,

E_{Uhi} is the emission level for each installation i connected at substation or busbar j,

G_{hBj} is the maximum global contribution to the h^{th} harmonic voltage of all the distorting installations that can be supplied from a given substation or busbar B_j in the HV-EHV system under consideration.

Let us consider the m^{th} busbar or substation in the system under consideration. A simple approach to set the global contribution (G_{hBm}) is to apportion planning levels between busbars or substations proportionally to their share of the total supply capacity of the system (ΣS_{tj}).

$$G_{hBm} \leq \sqrt[\alpha]{\frac{S_{tm}}{(S_{t1})+(S_{t2})+\cdots+(S_{tn})}} \cdot L_{hHV-EHV} \quad (12)$$

Meshed EHV or HV systems often need a more general or advanced approach in order to take into account the magnitude of the influence coefficients $K_{hj\text{-}m}$ between the considered node m and each of the n-1 other substations or busbars. The influence coefficient $K_{hj\text{-}m}$ is the harmonic voltage of order h which is caused at node m when a 1 p.u. harmonic voltage of order h is applied at node j; the calculation of $K_{hj\text{-}m}$ usually requires the use of a computer program. The influence coefficients are related to the elements of the node impedance matrix of the system for the harmonic order of interest. Taking influence coefficients into account, Equations 11 and 12 then become:

$$\left(K_{h1-m}{}^{\alpha} \left(\sum_{i \text{ at } B1} E_{Uhi}{}^{\alpha} \right) + K_{h2-m}{}^{\alpha} \left(\sum_{i \text{ at } B2} E_{Uhi}{}^{\alpha} \right) + \cdots + K_{hn-m}{}^{\alpha} \left(\sum_{i \text{ at } Bn} E_{Uhi}{}^{\alpha} \right) \right)^{\frac{1}{\alpha}} \le L_{hHV-EHV} \qquad (13)$$

Based on the same apportioning method as before, the acceptable global contribution G_{hBm} from all the distorting installations that can be connected to the considered busbar B_m should meet the following condition:

$$G_{hBm} \le \sqrt[\alpha]{\frac{S_{tm}}{\left(K_{h1-m}^{\alpha} \cdot S_{t1}\right) + \left(K_{h2-m}^{\alpha} \cdot S_{t2}\right) + \ldots + \left(S_{tm}\right) + \cdots + \left(K_{hn-m}^{\alpha} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad (14)$$

adding $(K_{h\,j-m}{}^{\alpha} \cdot S_{tj})$ terms as long as they remain significant as compared to S_{tm}.

Calling m the considered node and j any one of the other n-1 nodes located in the vicinity, the values of S_{tm} and S_{tj} can be calculated according to 9.2.1 and Equation (10), while ignoring all power flow S_{out} between any two of these nodes.

It is also worthwhile mentioning that conditions defined by equations (13) and (14) must be satisfied not only at the node m of interest, but also at the n-1 other nodes or substations in the system considered.

More details on the method including an example of application considering resonance effects are given in Annex D of this report.

9.2.3 Individual emission limits

At each harmonic order h, each distorting installation i will be allowed a contribution (E_{Uhi}) to the global contribution of substation or busbar B_m (G_{hBm}) in the considered HV-EHV system according to the ratio between its power (S_i) and the total available power (S_{tm}) of substation m.

$$E_{Uhi} = G_{hBm} \sqrt[\alpha]{\frac{S_i}{S_{tm}}} \qquad (15)$$

where

E_{Uhi}	is the emission limit of non-linear installation i (HV or EHV) at harmonic order h,
G_{hBm}	is the maximum global contribution to the h^{th} harmonic voltage of all the distorting installations that can be connected to a given substation B_m in the HV-EHV system under consideration (obtained according to the indications given in 9.2.2 and Annex D),
$S_i = P_i / \cos\varphi_i$	is the agreed power of customer installation i, or the MVA rating of the considered distorting installation (either load or generation),
S_{tm}	is the total supply capacity of substation m in the system under consideration and assessed according to 9.2.1 and 9.2.2,
α	is the summation law exponent (see Table 3)

It may happen at some locations that the pre-existing level of harmonics is higher than the normal share for the existing installations. In this case the emission limit for any new installations can be reduced, a reconsideration of the allocation of the planning levels between the different voltage levels could be considered, or the system harmonic current absorption capacity could be increased.

For customers having a low agreed power, Equation (15) may yield impractically low limitations. If the voltage emission limit at some harmonic orders becomes smaller than 0,1 %, it shall be set equal to 0,1 % (except if there is a risk of telephone interference, or if it corresponds to a remote control frequency for which a more severe restriction may be justified).

It may be preferred to specify harmonic current limits to the distorting installation, even if the aim is to limit the harmonic voltages in the system. It will be the responsibility of the system operator or owner to provide data concerning the frequency-dependent impedance of the system, in order to enable expressing these limits in terms of harmonic currents:

$$E_{Ihi} = \frac{E_{Uhi}}{Z_{hi}} \tag{16}$$

where

E_{Ihi} is the corresponding harmonic current emission limit of customer i at harmonic order h,

Z_{hi} is the harmonic impedance of the system at the point of evaluation for installation i assessed considering the actual purpose of converting voltage to current emission limits (see 6.4.1).

9.3 Stage 3: acceptance of higher emission levels on a conditional basis

The considerations presented in 8.3 apply equally to stage 3 at HV-EHV.

10 Interharmonics

In standard IEC 61000-2-12 [6], compatibility levels are given only for the case of an interharmonic voltage occurring at a frequency close to the fundamental frequency (50 Hz or 60 Hz), resulting in amplitude modulation of the supply voltage which causes flicker. The compatibility level for a single interharmonic voltage in this case is based on a flicker level of P_{st} = 1 (see Figure 2 in [6]). However, for other cases of interharmonic voltages, IEC 61000-2-12 does also provide indicative values for the level of interharmonics that might cause other effects. This clause provides general guidance on the effect of interharmonics on some known susceptible items of equipment.

Some of the reasons for needing to restrict the level of interharmonic voltages U_m (where m is not an integer of the fundamental frequency) are listed below.

NOTE All % values quoted in this list relate to the fundamental voltage.

- Below twice the fundamental frequency, interharmonics should be limited to 0,2 % to avoid flicker problems with incandescent and fluorescent (thin tubes) lamps [19], [20].
- Ripple control receivers may be disturbed if the minimal functional voltage (0,3 %) is exceeded [21].
- In the frequency range up to 2,5 kHz, the interharmonic voltages should not exceed 0,5 % if problems of interference with the following items of equipment are to be avoided: television sets, induction rotating machines (audible noise and vibrations) and frequency relays [22].
- In the range from 2,5 kHz up to 5 kHz, 0,3 % should not be exceeded in order to avoid audible noise, for example in radio receivers and other audio equipment.

- In the presence of non-linear installations, an interharmonic at frequency f_m is accompanied by side-band components at frequencies [f_m ± 2·n (fundamental frequency)], with n = 1, 2, 3,...; the magnitude of the [f_m ± 2·n (fundamental frequency)] components may be quite near the magnitude of the considered interharmonic [23]. The frequencies that could interfere with ripple control systems are the ones which differ by twice the fundamental from the ripple control frequency.

With respect to these effects, a conservative planning level for interharmonics can be set to 0,2 %.

NOTE MV equipment may be less affected.

Interharmonic voltages can be added arithmetically only if frequencies and phases are equal. These conditions are met infrequently and for short periods of time. For that reason, in practice, not more than double the value of the highest interharmonic voltage can arise.

If the interharmonic voltage from an installation is below 0,1 %, no disturbance will be considered.

If higher values are permitted, the interharmonic frequencies should not exceed the flicker criteria and should not exist in an area where ripple control frequencies (and their side-band frequencies with a distance of twice the fundamental) are used. Under certain circumstances, ripple control frequencies of adjacent system operators or owners should also have to be taken into account.

In order to avoid problems of mechanical resonance, it is necessary to take particular care when interharmonics, mainly sub-harmonics, are present near rotating machines, especially steam turbine generators. Because these torsional interactions involve sub-harmonic currents, it may be necessary that the sub-harmonic currents flowing in any generator be limited to very small values. Consultations with the generator manufacturer are necessary to establish the specific limits at specific frequencies; sub-harmonic current levels of 0,1 % or less have been sufficient to create problems in the past. In some cases involving mechanical resonance, therefore, the recommended 0,2 % interharmonic voltage limit may be reduced or, alternatively, the generator manufacturer may be consulted to determine if control system changes are possible to avoid potential mechanical resonance problems.

Annex A
(informative)

Envelope of the maximum expected impedance

Based on several site measurements, "worst case impedance curves" have been defined in some countries [24]. If calculations using those empirical curves indicate that an installation can be connected (i.e. still meet the voltage emission limits at the point of evaluation), this may be done with minimum risk. However, if these calculations give results that indicate that the installation's emission levels will exceed the voltage emission limits, a more refined approach should be used.

At low voltage, the maximum impedance curve is derived from the short circuit power and is taken as varying directly with the harmonic number in a straight line relationship.

At 11 kV, the maximum impedance curve is shown in Figure A.1 for a typical urban substation without large capacitors or filters. It is derived from the short circuit power and is taken as rising from its value at 50 Hz on a line directly related to twice the fundamental impedance by the harmonic number up to 400 Hz. Thereafter it drops to the line related to the fundamental impedance by the harmonic number.

Figure A.1 – Example of maximum impedance curve for a 11 kV system

$$\text{Up to } h = 8\text{: } Z_h = 2\ h\ X_1$$
$$\text{Above } h = 8\text{: } Z_h = h\ X_1$$

At 33 kV, the maximum impedance values are taken as 1,25 times those that would be derived directly from the short circuit power up to 800 Hz. Specific measurements might be required according to circumstances when considering frequencies above that level.

Above 33 kV such generalization is not possible.

Annex B
(informative)

Guidance for allocating planning levels and emission levels at MV

Clause B.1 of this annex provides guidance on how to determine planning levels for an MV distribution system with several MV voltage levels (for example both 33 kV and 11 kV). The approach has been devised to give an adequate harmonic allocation at each voltage level. Subclause B.2.1 then gives a method for allocating emission levels in MV distribution systems where their feeders display a significant variation in short circuit power from sending to far end. The method is based on the allocation of harmonic volt-amps (VA) rather than harmonic voltage as this gives more usable allocation for customers connected far from the feeder supply end. This method is difficult to calculate in general, but some useful simplified approximations can be made in the case where the MV installations are roughly uniformly distributed along the feeders (see B.2.2). An example showing the application of the method is given in B.2.3.

In the case where the system response is dominated by resonance caused by cables or shunt capacitors, the method provided in this annex is not appropriate for the harmonic frequency at which the resonance occurs.

B.1 Guidance for adapting planning levels at MV

Some distribution systems have several MV voltage levels in series. In this case there needs to be a variation in planning level across the MV voltage levels to allow an allocation of harmonic emission limits to MV installations. The profiling of the planning levels will affect the relative allocation of harmonic emission levels to installations at different MV levels and it should be chosen to give the desired effect. A detailed discussion of how this has been done for MV distribution systems in one country is given in Section 2 of reference [27] his approach is summarised below.

Profiling of the planning levels between different MV voltage levels cascaded in series needs information on the following:

a) a typical system topology and impedance values,
b) a typical distribution of customer installations across the different voltage levels,
c) choice of harmonic voltage objectives for the downstream LV system and planning levels for the upstream system,
d) an allocation policy for how harmonic current should be distributed across the different voltage levels.

Data for (a) and (b) will depend on the planning and construction practices of particular utilities. Regarding (c), downstream or LV harmonic voltages need to be equal or slightly less than the LV compatibility levels in Table 1 depending on the margin needed. Upstream planning levels can be based on HV-EHV values in Table 2 or based on their interpolation for intermediate voltage levels.

One allocation principle for meeting (d) is to give all MV installations the same percentage current distortion. A possible approach is to take advantage of diversity as expressed by the summation law giving:

$$I_{hi} = A_h \cdot \sqrt[\alpha]{S_i} \qquad \text{(B.1)}$$

where

h is the harmonic order,

α is the general summation law exponent (Table 3),

S_i is the agreed power of customer's installation "i",

I_{hi} is the harmonic current emission level of customer's installation "i",

A_h is an allocation constant to be determined (see below).

The representation of LV installations is more difficult to generalize as high load density areas can be very different from low load density areas. For the latter, the representation is simpler if LV installations can be considered as having a second order effect on harmonic voltage profiles and the choice of MV planning levels.

The power system needs to be modelled so that harmonic voltage profiles can be determined as a function of A_h. A relatively simple computer analysis can be developed, for example using a spreadsheet, by assuming that all feeders/distributors at each voltage level are identical and that the installations at each level are uniformly distributed. This allows considerable consolidation of installations and circuits into a few components. Expressions need to be determined for the largest harmonic voltage in the system, at the end of a studied LV circuit, as a function of the following voltage contributions:

– the upstream system voltage taken as the chosen planning level;
– the contributions of all upstream MV loads determined from their current and the common impedance with the studied LV circuit:
– the contributions of all upstream LV installations determined from their current and the common impedance with the studied LV circuit;
– the contributions of the LV installations on the studied circuit, determined by lumping all such installations at the mid-point of the circuit.

These voltage contributions need to be combined accounting for diversity by the summation law (see Clause 7). The value of A_h then needs to be adjusted so that the largest LV harmonic voltage just reaches the chosen objective. This value represents the maximum harmonic loading which can be applied to the representative distribution system under the given allocation scheme.

The resulting harmonic voltage profile can be used as an objective to be applied to all of the distribution system operator or owner's sub-systems, in which case the harmonic voltages are suitable as planning levels. This procedure can be applied independently at each harmonic. Alternatively, especially when high frequency models are not reliable, it is possible to determine planning levels for higher order harmonics by decreasing levels versus frequency similarly to compatibility levels while still taking into consideration the exponent of the summation law accounts for more diversity for high order harmonics. Reference [25] gives an example on how planning levels at all harmonic orders can be obtained from detailed analysis of only a few harmonic values.

B.2 General case of MV installations spread along the feeders: sharing of emission

B.2.1 Theory

Some long MV feeders can have short circuit powers and impedances which vary by 10:1 or more from the supply to the far end. An allocation policy needs to be developed which gives a useful emission allocation to each installation and makes effective use of the harmonic absorption capacity of the distribution system. If installations of similar agreed power are allocated equal harmonic voltage, installations at the far ends of feeders will receive a much lower allocation of harmonic current than those at the supply end. Alternatively, if they are allocated equal harmonic current, installations connected to strong points will be given allocations no greater than that given for weak connection points and the power systems harmonic absorption capacity is underutilised. The use of harmonic VA gives a good compromise between these two allocation policies and is the approach adopted here. This is equivalent to allocating a harmonic current which reduces in inverse proportion to the square root of the impedance at point of evaluation of the installation under consideration.

When allocating emission based on harmonic VA, the harmonic current not only varies with the agreed power, but also reduces in inverse proportion to the square root of the impedance at the point of evaluation of the installation under consideration. Hence, where the supply harmonic reactance is x_h, the allocated emission current is taken as:

$$E_{Ihi} = \frac{A_{hMV} S_i^{(1/\alpha)}}{\sqrt{x_{hi}}} \tag{B.2}$$

where

S_i is the agreed power of the installation,

x_{hi} is the MV network harmonic reactance at the point of evaluation of customer's installation "i",

A_{hMV} is an allocation constant (defined below).

The allocation constant A_{hMV} needs to be calculated for a specific MV subsystem using the condition that the highest harmonic voltage in the subsystem is not to exceed the planning level. One method for determining A_{hMV} for a specific subsystem is to assume an initial value of unity, determine the allocated current for each MV installation, and then combine each voltage contribution and compare it with the global allocation for MV installations. The ratio of G_{hMV} to this combined voltage gives the required value for A_{hMV}. If, for example, the combined voltage is a value of half G_{hMV}, then A_{hMV} can be taken as two. The approach is general, and can be applied to mesh systems and systems with spur lines, but it requires values of the agreed power and impedance at the POE of every significant MV installation. A simplified approach which can be used in most practical situations is given in B.2.2.

In making calculations of harmonics in MV systems, it is necessary to estimate the contribution of LV installations to MV harmonic voltages. It is assumed that an LV installation with an agreed power S_{LVi} gives a harmonic current:

$$I_{hLVi} = A_{hLV} \cdot \sqrt[\alpha]{S_{LVi}} \tag{B.3}$$

A_{hLV} varies with harmonic order and may differ from country to country (or even from region to region) depending on the penetration of electronic equipment and their usage pattern. It can be estimated from the measurement of the harmonic current for a representative feeder supplying a known installation. Where there is a large difference in the short circuit power between LV and MV systems (for example where the LV feeders are overhead lines of a hundred or more meters in length), and the voltage in the LV system is known to be acceptable, the MV voltage caused by LV installations is a fraction of that in LV systems. This condition also applies to situations where the total power of distorting installations connected at LV is relatively low compared to MV distorting installations.

B.2.2 Particular case of LV and MV installations spread out uniformly along feeders in a radial system

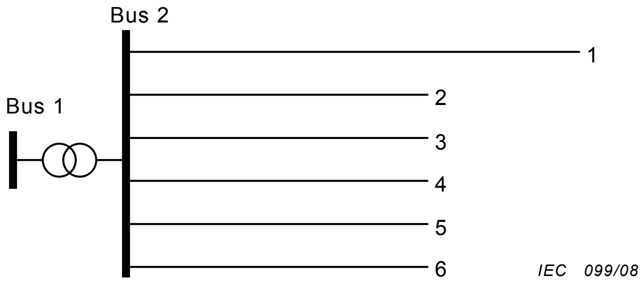


Figure B.1 – Example of an MV distribution system showing the MV transformer and feeders 1-6

Consider an MV subsystem such as that shown in Figure B.1 consisting of a number of feeders with uniform reactance/km and with LV and MV installations approximately uniformly distributed along them. It is not necessary to assume that the installations are distributed with the same density on each feeder. The highest harmonic voltage is assumed to be at the remote end of the feeder which has the worst voltage regulation. In the absence of precise data, this feeder can be taken as the one for which the product of supply capability and length is the largest [26].

A mathematical treatment of the case of feeders with a uniform distribution of installations has been developed in [26] which simplifies the task of calculating the allocation coefficient A_{hMV} in Equation (B.2). Steps in the allocation procedure are:

i) for each feeder in the subsystem (e.g. those shown 1-6 in Figure B.1) determine the quantity F, defined as the ratio of sending end to remote end short circuit power;

ii) define F_w as the value of F for the weakest feeder. Determine F_a, the average F for the remaining feeders. If there is a wide range in the values of F for these feeders, a value should be obtained weighted according to the load capability of each feeder. Similarly we define S_{LVW} as the LV load connected to the weakest feeder and S_{LVn} as the LV load connected to the n remaining feeders;

iii) estimate the harmonic voltage caused by LV installations at the MV level from:

$$U_{hLV} = A_{hLV}\, x_h \sqrt[\alpha]{S_{LVw} F_w^{0,7\alpha} + S_{LVn}} \qquad \text{(B.4)}$$

where x_h is the harmonic reactance at the supply busbar (Bus 2 in Figure B.1).

iv) Determine the harmonic voltage allowance available to all MV installations in the subsystem

$$G_{hMV} = \sqrt[\alpha]{L_{hMV}^{\alpha} - T_{hUM}^{\alpha} L_{hUS}^{\alpha} - U_{hLV}^{\alpha}} \qquad \text{(B.5)}$$

v) Determine the allocation constant for all MV installations in the subsystem, noting carefully that the denominator of next equation contains a square root as well as a root.

$$A_{hMV} = \frac{G_{hMV}}{\sqrt{x_h}\,\sqrt[\alpha]{S_{MVw} F_w^{0,33\alpha} + S_{MVn} F_a^{-0,3\alpha}}} \qquad \text{(B.6)}$$

where S_{MVW} is the MV load connected to the weakest feeder and S_{MVn} is the LV load connected to the n remaining feeders.

Having found the constant A_{hMV} for a particular sub-system, one can determine the harmonic current allocation for a particular MV installation using Equation (B.2) above. Note that this equation applies to all MV installations in the subsystem, not just those connected to the weakest feeder.

B.2.3 Example of application of the approach presented in B.2.2

A 132 kV/11 kV substation with an 11 kV short circuit power of 150 MVA supplies five feeders with characteristics as given in Table B.1 below. The aim is to determine the 5^{th} harmonic current allocation for a 500 kVA installation connected half-way along feeder No 4 where the short circuit power is 47 MVA. The 132 kV and 11 kV 5^{th} harmonic planning levels are 2 % and 5 % respectively. In this example, it is assumed that harmonic emissions from LV installations can be ignored.

Table B.1 – Feeder characteristics for the system under consideration

Feeder ID	**Feeder length ℓ** km	**Feeder load (MVA)** (incl. future load)	**Short circuit power at far end (MVA)**
1	5	4	47
2	5	4	47
3	7	5	37
4	10	6	28
5	15	5	20

Determine the values of F and S for the weakest feeder and the rest of the feeders: the main part of this calculation is shown in Table B.2 below and can easily be accomplished by means of a spreadsheet.

Table B.2 – Determination of F and Sxℓ values for the feeders

Feeder ID	**Feeder length** ℓ km	**Feeder load S (MVA)** (incl. future load)	**Short circuit power at far end (MVA)**	**Sxℓ**	**F**
1	5	4	47	20	3,19
2	5	4	47	20	3,19
3	7	5	37	35	4,05
4	10	6	28	60	5,36
5	15	5	20	75	7,50

Column 5 is the product of length times load. Column 6 is the quotient of the supply short circuit power of 150 MVA and Column 4. Column 5 shows that feeder No 5 is the weakest and S_{MVW} = 5MVA, F_w = 7,50. For feeders 1-4, we find S_{MVn} = 19MVA and F_a = 3,95 (from the sum of Column 3 entries and the average of Column 6 entries respectively).

For the 5^{th} harmonic, α = 1,4 , L_{hMV} = 5 %, L_{hUS} = 2%.

Determine the global voltage available from Equation. (B.5) with the assumption that T_{hUM} is equal to 1 and that U_{hLV} can be neglected here.

$$G_{hMV} = \sqrt[\alpha]{L_{hMV}{}^{\alpha} - L_{hUS}{}^{\alpha}} = \sqrt[1,4]{0,05^{1,4} - 0,02^{1,4}} = 0,04 \text{ pu} \quad \text{(B.7)}$$

Determine the MV subsystem allocation constant. From supply short circuit power of 150 MVA and using a 1 MVA base,

$$x_{h=5} = \frac{5}{150} = 0{,}033 \ \text{pu} \tag{B.8}$$

From Equation (B.6)

$$A_{hMV} = \frac{G_{hMV}}{\sqrt{x_h} \cdot \sqrt[\alpha]{S_{MVw} \ F_w^{\ 0,33\,\alpha} + S_{MVn} \ F_a^{\ -0,3\,\alpha}}}$$

$$= \frac{0{,}04}{\sqrt{0{,}033} \cdot \sqrt[1,4]{5 \times 7{,}50^{\,0,33 \times 1,4} + 19 \times 3{,}95^{\,-0,3 \times 1,4}}} = 0{,}022\ 9 \tag{B.9}$$

Determine the installation allocation current: The installation has an agreed power S_i = 0,5 pu. Using the short circuit power of 47 MVA at the point of evaluation gives

$$x_{5i} = \frac{5}{47} = 0{,}106 \ \text{pu} \tag{B.10}$$

From Equation.(B.2)

$$E_{Ihi} = \frac{A_{hMV} \ S_i^{\,(1/\alpha)}}{\sqrt{x_{hi}}} = \frac{0{,}022\ 9 \cdot 0{,}5^{\,1/1,4}}{\sqrt{0{,}106}} = 0{,}043 \ \text{pu} \tag{B.11}$$

In terms of the installation's fundamental current, this corresponds to 8,5 % of 5th harmonic distortion.

Annex C
(informative)

Example of calculation of global MV+LV contribution

For illustration purposes, Equation (7) has been applied in the particular case of a MV system, assuming that the transfer coefficient from the upstream HV system is equal to 1 at all harmonic frequencies and assuming that the planning levels in the HV and MV systems are those of Table 2. The results are given in Table C.1.

Table C.1 – Acceptable global contribution G_{hMV+LV} of the MV and LV installations to the MV harmonic voltages if the transfer coefficient from the HV-EHV system is considered to be unity

Odd harmonics non multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order h	Harmonic voltage %	Order h	Harmonic voltage %	Order h	Harmonic voltage %
5	4	3	2	2	0,4
7	2,8	9	0,4	4	0,2
11	2,6	15	0	6	0,2
13	2	21	0	8	0,2
17	1,2			10	0,2
19	1,0				
23	0,8				
25	0,7				

In order to illustrate a case of resonance in the vicinity of the 5th harmonic, the following shows the application of Equation (7) with three different values of the transfer coefficient at the 5th harmonic:

– $T_{5UM} = 1$; $G_{5MV+LV} = [5^{1,4} – (1x2)^{1,4}]^{1/1,4} = 4$ %
– $T_{5UM} = 2$; $G_{5MV+LV} = [5^{1,4} – (2x2)^{1,4}]^{1/1,4} = 2$ %
– $T_{5UM} = 3$; $G_{5MV+LV} = [5^{1,4} – (3x2)^{1,4}]^{1/1,4} = 0$ %

From the above results it is clear that the approach should be used with care when the transfer coefficient from the upstream system to the MV system is greater than 1. It should also be remembered that the transfer coefficients not only depend on harmonic order and location but may also vary with time (for example due to various capacitor bank states).

Annex D
(informative)

Method for sharing planning levels and allocating emission limits in meshed HV – EHV systems

D.1 General method for sharing planning levels in HV-EHV systems

Let us recall and extend the method introduced in 9.2.2 for sharing planning levels between different busbars or substations in a given HV-EHV system.

Referring to Figure 7, the general conditions given by Equation (13) are to be satisfied at any substation m of the n substations forming the system under consideration:

$$\left(K_{h1-m}{}^{\alpha}\left(\sum_{i\text{ at }B1} E_{Uhi}{}^{\alpha}\right) + K_{h2-m}{}^{\alpha}\left(\sum_{i\text{ at }B2} E_{Uhi}{}^{\alpha}\right) + \cdots + K_{hn-m}{}^{\alpha}\left(\sum_{i\text{ at }Bn} E_{Uhi}{}^{\alpha}\right)\right)^{\frac{1}{\alpha}} \leq L_{hHV-EHV} \qquad \text{(D.1)}$$

where $\sum_{i\text{ at }Bj} E_{Uhi}{}^{\alpha} \leq G_{hBj}{}^{\alpha}$

NOTE Equation (D.1) represents the summation of the transferred disturbances across the system, hence similar conditions should also be satisfied at all substations or busbars forming the considered HV-EHV system, not only at the station of interest.

At each harmonic order h, the influence coefficients K_{hj-m} need to be determined: the influence coefficient K_{hj-m} is the harmonic voltage of order h which is caused at node m when a 1 p.u. harmonic voltage of order h is applied at node j; the calculation of K_{hj-m} usually requires the use of a computer program. The influence coefficients are related to the elements of the node impedance matrix of the system for the harmonic order of interest.

Based on the same apportioning method as before, according to Equation (14) the acceptable global contribution from all the distorting installations that can be supplied by the considered station B_m (G_{hBm}) should be a fraction of the common HV-EHV planning level ($L_{hHV-EHV}$) taken as the ratio of the power S_{tm} to the total supply capacity of the system.

$$G_{hBm} \leq \sqrt[\alpha]{\frac{S_{tm}}{\left(K_{h1-m}^{\alpha} \cdot S_{t1}\right) + \left(K_{h2-m}^{\alpha} \cdot S_{t2}\right) + \ldots + \left(S_{tm}\right) + \cdots + \left(K_{hn-m}^{\alpha} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.2)}$$

adding $(K_{h\,j-m}{}^{\alpha} \cdot S_{tj})$ terms as long as they remain significant as compared to S_{tm}.

Calling m the considered node and j any one of the other n-1 nodes located in the vicinity, the values of S_{tm} and S_{tj} can be calculated according to 9.2.1 and Equation (10), while ignoring all power flow S_{out} between any two of these nodes.

Additionally, in order to meet Equation (D.1) at node m, the contribution G_{hBj} at each of the n-1 other busbars also needs to satisfy the following condition:

$$G_{hBj} \leq \sqrt[\alpha]{\frac{S_{tj}}{\left(K_{h1-j}^{\alpha} \cdot S_{t1}\right) + \left(K_{h2-j}^{\alpha} \cdot S_{t2}\right) + \ldots + \left(S_{tj}\right) + \cdots + \left(K_{hn-j}^{\alpha} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.2')}$$

For instance, let us consider the acceptable global contribution of all the distorting installations that can be connected at station B1 (G_{hB1}). The following equations which result from the application of equations (D.2) and (D.3) at busbar B1 level have to be satisfied:

For B1, it gives:
$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{S_{t1} + \left(K^{\alpha}_{h2-1} \cdot S_{t2}\right) + \left(K^{\alpha}_{h3-1} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-1} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.4)}$$

For B2, it gives:
$$G_{hB2} \le \sqrt[\alpha]{\frac{S_{t2}}{S_{t1} + \left(K^{\alpha}_{h2-1} \cdot S_{t2}\right) + \left(K^{\alpha}_{h3-1} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-1} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.5)}$$

and so on, for B3, B4 and B5.

Similar conditions have also to be satisfied at the level of other busbars. For example at busbar B2 level, we have:

For B1, it gives:
$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{\left(K^{\alpha}_{h1-2} \cdot S_{t1}\right) + S_{t2} + \left(K^{\alpha}_{h3-2} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-2} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.6)}$$

For B2, it gives:
$$G_{hB2} \le \sqrt[\alpha]{\frac{S_{t2}}{\left(K^{\alpha}_{h1-2} \cdot S_{t1}\right) + S_{t2} + \left(K^{\alpha}_{h3-2} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-2} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.7)}$$

and so on, for B3, B4 and B5.

In the end, we obtain n conditions for each busbar. For example for busbar 1:

Condition 1:
$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{S_{t1} + \left(K^{\alpha}_{h2-1} \cdot S_{t2}\right) + \left(K^{\alpha}_{h3-1} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-1} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.8)}$$

Condition 2:
$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{\left(K^{\alpha}_{h1-2} \cdot S_{t1}\right) + S_{t2} + \left(K^{\alpha}_{h3-2} \cdot S_{t3}\right) + \cdots + \left(K^{\alpha}_{hn-2} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.9)}$$

Condition n:
$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{\left(K^{\alpha}_{h1-n} \cdot S_{t1}\right) + \left(K^{\alpha}_{h2-n} \cdot S_{t2}\right) + \cdots + \left(S_{tn}\right)}} \cdot L_{hHV-EHV} \qquad \text{(D.10)}$$

This method can then be applied for sharing the planning level in order to obtain the global contribution G_{hBj} for all the other sub-stations or busbars B2, B3, etc… forming the considered HV-EHV system. However, in the case of resonance, G_{hBj} may be very difficult to assess and the mere application of equations D.1, D.2 and D.3 could result in a near-zero contribution for some substations. In these cases, an equitable share of emissions between the different parts of the system should be allocated instead. An example of this case is discussed further in the following subclauses.

Finally, it should be kept in mind that despite the most accurate determination of the actual acceptable global contributions at each busbar, future system changes can also have a significant impact on the transfer coefficient and the share of the disturbance levels between different busbars in the system.

D.2 Example of application considering resonance effects

The following example illustrates a simplified application of the method described in 9.2.2 and in the previous Clause D.1 for sharing planning levels and allocating emission limits in a HV-EHV system. Methods for dealing with resonance within the system are also discussed.

In this example, the aim is to define emission limits for the 5th, 7th, 11th and 13th harmonic for a new customer's installation (S_i = 80 MW) to be connected to Jupiter 150 kV substation (node 1).

NOTE 1 When calculating emission limits it is recommended to take into account not only the existing installations, but also new installations that could be connected to the system in the future.

NOTE 2 In this example, the network is considered to be fully loaded. The addition of new installation to the network will call for changes in the system (new transformers & lines) which are not considered in this example.

Figure D.1 below shows part of a system where customers can be connected at different voltage levels. Node 1 is of interest for the connection of the considered customer's installation, but the figure also includes nearby installations which can have an impact on harmonic levels at node 1. Remote parts of the upstream and downstream system are represented by their equivalent source impedances (for an accurate assessment of the influence coefficients, the system should be modelled at least 2-3 nodes away from nodes of interest).

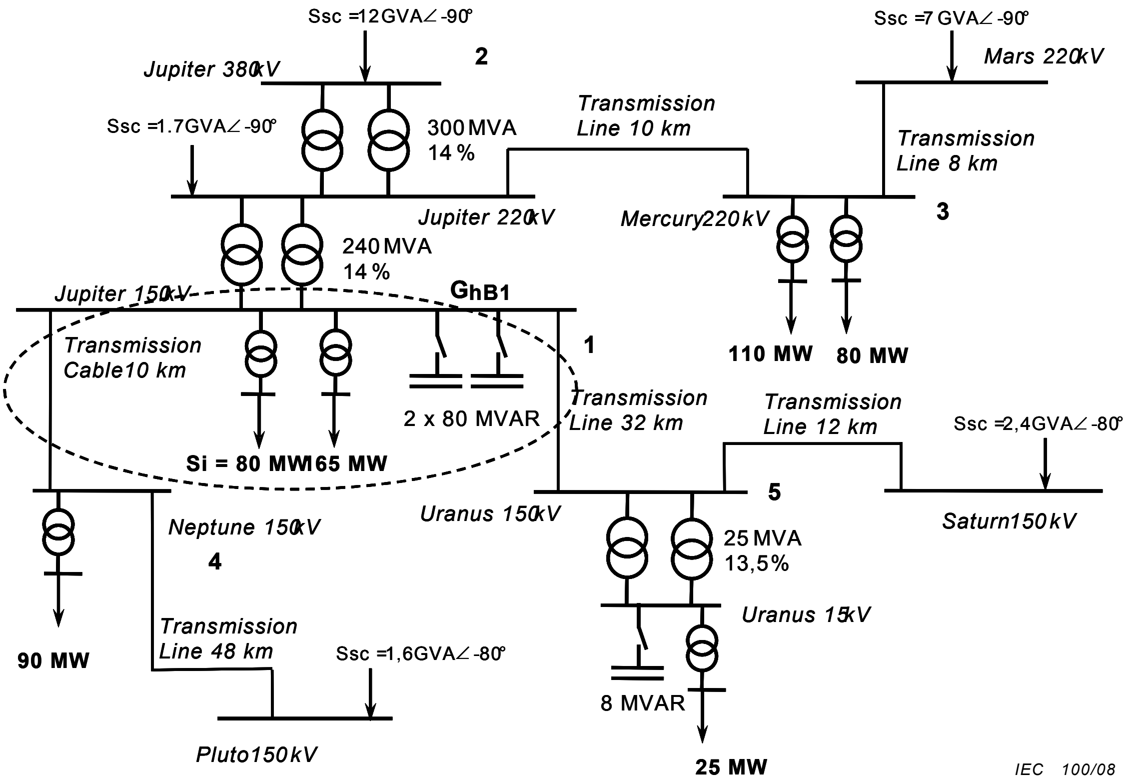


Figure D.1 – HV-EHV system considered for the connection of a new distorting installation at node 1 substation

The harmonic impedance of the system at substation Jupiter 150 kV (node 1) is shown on Figure D.2. When the capacitor banks at Jupiter 150 kV are switched off, a parallel resonance near the 11th harmonic exists due to the HV cable connecting with Neptune 150 kV (node 4). Depending on the load, the capacitor banks at Jupiter 150 kV (node 1) substation can be switched on, thus causing resonance either at the 5th (2 × 80 Mvar) or the 7th harmonic (1 × 80 Mvar). The straight line 1 on Figure D.2 represents the harmonic impedance for a purely inductive system; other lines identified as 2, 3 & 4 represent theoretical values of that impedance considering amplification factors of 2, 3 & 4 respectively.

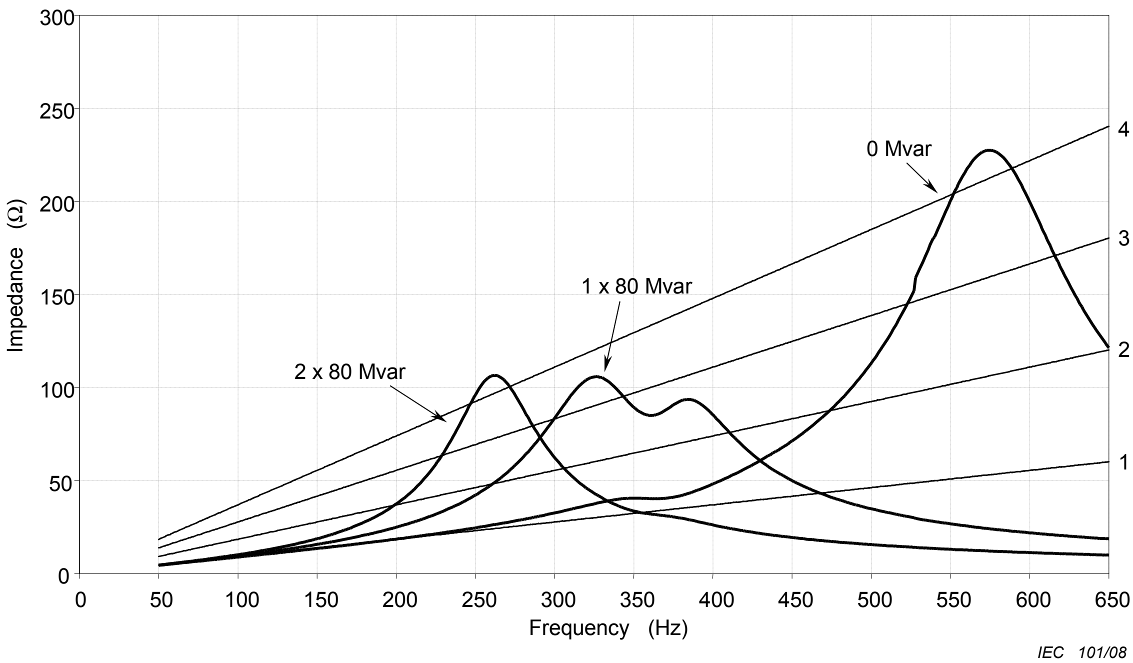


Figure D.2 – Harmonic Impedance at node 1

NOTE In this example, the power frequency is 50Hz.

D.2.1 Influence coefficients

The influence coefficients between the different substations are assessed according to Clause D.1 by using a harmonic simulation program. The influence coefficient between node j and 1, is the harmonic voltage of order h at node 1 when a harmonic voltage of 1 p.u. is applied at node j. Table D.1 shows some of the values calculated for this example.

Table D.1 – Influence coefficients K_{hj-1} between node j and node 1

System configuration		Substation	Node	K_{hj-1} for h=5	K_{hj-1} for h=7	K_{hj-1} for h=11	K_{hj-1} for h=13
1	Capacitor Bank in: 2 × 80 MVAR in Jupiter 150 kV	Jupiter 380 kV	2	0,86	0,22	0,05	0,04
		Mercury 220 kV	3	1,75	0,61	0,14	0,09
		Neptune 150 kV	4	1,00	1,24	3,77	8,3
		Uranus 150 kV	5	1,16	1,56	0,22	0,14
2	Capacitor Bank in: 1 × 80 MVAR in Jupiter 150 kV	Jupiter 380 kV	2	0,37	0,59	0,11	0,07
		Mercury 220 kV	3	0,81	1,49	0,29	0,17
		Neptune 150 kV	4	0,90	1,02	1,48	2,14
		Uranus 150 kV	5	0,71	1,53	0,52	0,28
3	Capacitor Bank Off in Jupiter 150 kV	Jupiter 380 kV	2	0,22	0,24	0,82	0,45
		Mercury 220 kV	3	0,50	0,59	1,66	1,31
		Neptune 150 kV	4	0,85	0,87	0,92	0,96
		Uranus 150 kV	5	0,51	0,58	1,24	3,20

The acceptable global contribution of all the distorting installations that can be supplied from station B1 (G_{hB1}) will be a fraction of the common HV-EHV planning level ($L_{hHV\text{-}EHV}$) as given below considering only Equation (D.2) for the sake of simplicity.

$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{S_{t1} + K_{h2-1}{}^{\alpha} \cdot S_{t2} + K_{h3-1}{}^{\alpha} \cdot S_{t3} + K_{h4-1}{}^{\alpha} \cdot S_{t4} + K_{h5-1}{}^{\alpha} \cdot S_{t5}}} \cdot L_{hHV-EHV} \qquad \text{(D.11)}$$

D.2.2 Effects of resonance

In case of under damped resonance, the influence coefficient can be high, unduly limiting emissions.

Let us consider the case of a series resonance. In the last row, last column of Table D.1, the influence coefficient is $K_{h5\text{-}1}$ = 3,2 at the 13th harmonic. Using this value in the above equation in combination with an exponent α = 2, results in that the total power of the installations connected at node 5 would have to be multiplied by a factor $K_{h5\text{-}1}{}^{\alpha}$ as high as 10,2.

As a result of the mere application of the above equation, the global contribution (G_{hB1}) allowed to substation 1 can become very low. In this case, because of the high value of the influence coefficient due to a series resonance between node 5 and node 1, the distortion caused by the installations connected to node 5 will have more impact on the voltage distortion at node 1, than at node 5.

Indeed, the harmonic impedance at h = 13 (650 Hz) seen from node 5 is quite low as shown on in Figure D.3.

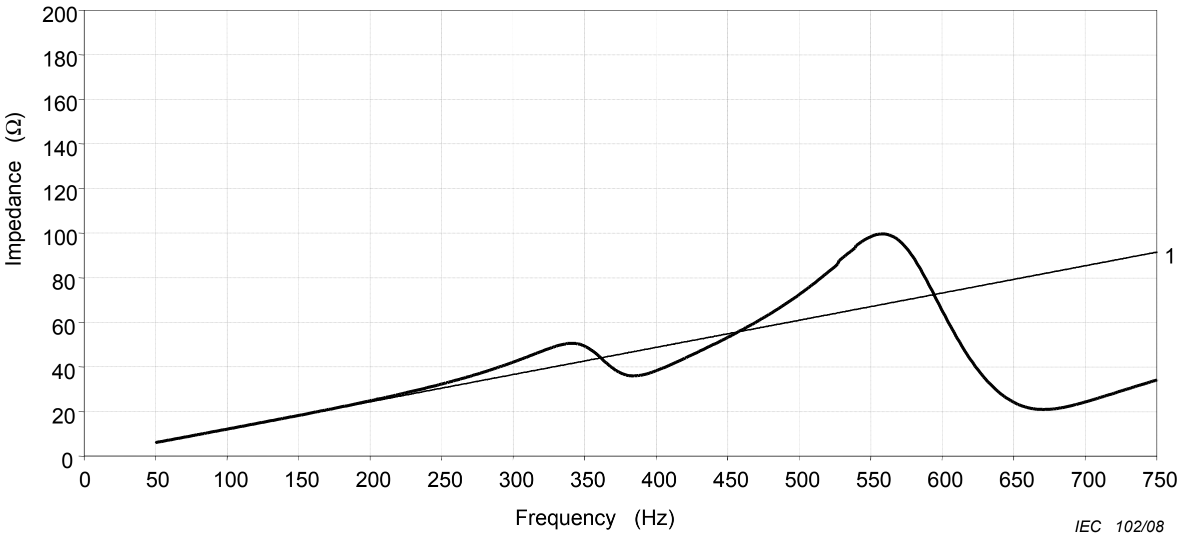


Figure D.3 – Harmonic Impedance at node 5 'Uranus 150 kV', when the capacitor banks at Jupiter 150 kV are switched off

The approach discussed hereafter is considering the fact that the effects of this type of resonance should also be dealt with in setting lower emission limits at node 5, rather than only or unduly limiting emissions at node 1. A possible approach to achieve this is to define emission limits at node 5 in terms of current obtained by substituting a minimum value of harmonic impedance as reference value, for example, using an ideal inductive system impedance equal to hZ_1. Another approach would be to assess voltage emission limits for installations connected at node 5 considering their impact on the harmonic voltage at node 1.

So for the assessment of the acceptable global contribution (G_{hB1}) at node 1, let us consider that whenever the harmonic impedance at node j becomes smaller than h times the fundamental frequency system impedance Z_1, the influence coefficient $K_{hj\text{-}1}$ between node j and 1 can be multiplied by a reduction factor F_Z taken as the ratio between the value of harmonic impedance and the linear extrapolation of the fundamental frequency impedance as follows.

$$F_{zj} = \frac{Z_{hj}}{h \cdot Z_{1j}} \qquad (D.12)$$

where

Z_{hj} = harmonic impedance at node j for order h,

Z_{1j} = impedance at node j at system frequency.

For example, when the capacitor banks at node 1 are switched off (system configuration 3 in Table D.1), the impedance at 13th harmonic at node 5 is 3,2 times smaller than the minimum reference impedance taken as equal to h.Z_1 at node 5 (see Figure D.3 at 650 Hz). The influence coefficient $K_{h5\text{-}1}$ between node 5 and 1 can thus be multiplied by a F_{Zj} factor of 0,31 as shown in Equation D.13 and in Table D.2.

This reduction factor F_{Zj} can be applied whenever the influence coefficient is higher than 1. The revised equation to calculate the global contribution at node 1 becomes:

$$G_{hB1} = \sqrt[\alpha]{\frac{S_{t1}}{S_{t1} + (F_{Z2} \cdot K_{h2-1})^{\alpha} \cdot S_{t2} + (F_{Z3} \cdot K_{h3-1})^{\alpha} \cdot S_{t3} + (F_{Z4} \cdot K_{h4-1})^{\alpha} \cdot S_{t4} + (F_{Z5} \cdot K_{h5-1})^{\alpha} \cdot S_{t5}}} \cdot L_{hHV-EHV} \qquad (D.13)$$

NOTE 1 If the reduction factor F_{Zj} exceeds 1, this would be due to a parallel resonance and a different approach might be needed (e.g.: allowing a reasonable amplification factor such as 2-3).

NOTE 2 Equation D.13 applies to find G_{hB1} at busbar 1 even if the factor F_{Z1} is less than 1. But in this case to calculate the harmonic current emission limits at busbar 1, the actual value of harmonic impedance $Z_{h\text{-}1}$ needs to be replaced by the reference value $h^*Z_{1\text{-}1}$.

The reduction factors F_{Zj} are given in Table D.2 for cases where the influence coefficient exceeds unity.

Table D.2 – Reduction factors

System configuration		Substation	Node j	Reduction factors F_{Zj}			
				h=5	**h=7**	**h=11**	**h=13**
1	Capacitor Bank in: 2 × 80 MVAR in Jupiter 150 kV	Jupiter 380 kV	2	-	-	-	-
		Mercury 220 kV	3	(1,10)	-	-	-
		Neptune 150 kV	4	(3,57)	**0,73**	**0,06**	**0,02**
		Uranus 150 kV	5	(1,79)	**0,41**	-	-
2	Capacitor Bank in: 1 × 80 MVAR in Jupiter 150 kV	Jupiter 380 kV	2	-	-	-	-
		Mercury 220 kV	3	-	**0,85**	-	-
		Neptune 150 kV	4	-	(1,73)	**0,34**	**0,14**
		Uranus 150 kV	5	-	**0,97**	-	-
3	Capacitor Bank Off in Jupiter 150 kV	Jupiter 380 kV	2	-	-	-	-
		Mercury 220 kV	3	-	-	(1,11)	**0,73**
		Neptune 150 kV	4	-	-	-	-
		Uranus 150 kV	5	-	-	(1,47)	**0,31**

The global contribution can then be calculated for different system configurations and harmonic orders. The results are given in Table D.3.

Example of calculations for the 7th harmonic for system configuration No. 2 follows using Equation (D.13).

$$G_{7B1} = \sqrt[\alpha]{\frac{S_{t1}}{S_{t1} + (F_{Z2} \cdot K_{h2-1})^{\alpha} \cdot S_{t2} + (F_{Z3} \cdot K_{h3-1})^{\alpha} \cdot S_{t3} + (F_{Z4} \cdot K_{h4-1})^{\alpha} \cdot S_{t4} + (F_{Z5} \cdot K_{h5-1})^{\alpha} \cdot S_{t5}}} \cdot L_{hHV-EHV}$$

$$G_{7B1} = \sqrt[1,4]{\frac{245}{245 + (0,59)^{1,4} \cdot 180 + (0,85 \cdot 1,49)^{1,4} \cdot 190 + (1,02)^{1,4} \cdot 90 + (0,97 \cdot 1,53)^{1,4} \cdot 25}} \cdot 2\,\%$$

$$G_{7B1} = 0{,}92\,\%$$

For each harmonic order, only the worst-case needs to be considered as shown in Table D.3.

Table D.3 – Global contributions G_{hB1} at node 1

Harmonic order		h=5	h=7	h=11	h=13
Planning Level $L_{hHV\text{-}EHV}$		2%	2%	1,5%	1,5%
Summation law exponent α		1,4	1,4	2	2
System Configuration		**G_{hB1} (U_h/U_1)%**			
1	Capacitor Bank in: 2 × 80 MVAR in Jupiter 150 kV	**0,77%**	1,29%	1,37%	1,39%
2	Capacitor Bank in: 1 × 80 MVAR in Jupiter 150 kV	1,16%	**0,92%**	1,28%	1,36%
3	Capacitor Bank Off in Jupiter 150 kV	1,36%	1,30%	**0,69%**	**0,92%**

The global contributions that can be allowed to all other distorting installations connected to busbars B2 (G_{hB2}), B3(G_{hB3}), etc., can be obtained in the same way, but as an additional step in the method, one should also make sure that the conditions stated in Equation (D.3) continue to be satisfied for all the so determined contributions. In this example, we assumed this was the case for the sake of simplicity.

D.2.3 Emission limits

The harmonic voltage emission limits can then be determined using Equation (15) given in 9.2.3 which is a function of the ratio between the agreed power of the installation (S_i-MVA) and the total supply capacity (S_{t1}) at substation 1 in this case:

– 5th harmonic: $E_{U5i} = G_{5B1}\sqrt[\alpha]{\frac{S_i}{S_{t1}}} = 0{,}77\,\% \cdot \sqrt[1,4]{\frac{80}{245}} = 0{,}35\,\%$

– 7th harmonic: $E_{U7i} = G_{7B1}\sqrt[\alpha]{\frac{S_i}{S_{t1}}} = 0{,}91\,\% \cdot \sqrt[1,4]{\frac{80}{245}} = 0{,}41\,\%$

– 11th harmonic: $E_{U11i} = G_{11B1}\sqrt[\alpha]{\frac{S_i}{S_{t1}}} = 0{,}69\,\% \cdot \sqrt[2]{\frac{80}{245}} = 0{,}39\,\%$

– 13th harmonic: $E_{U13i} = G_{13B1}\sqrt[\alpha]{\frac{S_i}{S_{t1}}} = 0{,}92\,\% \cdot \sqrt[2]{\frac{80}{245}} = 0{,}53\,\%$

The emission limits defined in terms of harmonic currents can be derived using the harmonic impedance of the system (see Figure D.2 and 6.4.1). However, here too, very low values of impedance (amplification factor < 1) due to series resonance should be disregarded as explained in 6.4.1.

As explained in section D.2.2, if at some harmonic orders the impedance Z_{hj} is less than a reference value h^*Z_{1j}, it should be replaced by that reference value to calculate harmonic current emission limits for these harmonic orders.

In case there is a parallel resonance due to the network that is causing an amplification factor in excess of 2 or 3, the system operator or owner should examine possible measures to reduce the amplification. For instance, capacitor banks can be detuned to avoid resonance at 5^{th} and 7^{th} harmonics. However, when resonance is due to the capacitance of the lines or cables, it could be difficult to change resonance conditions as happens in this example where a cable resonance at 11^{th} harmonic appears when the capacitor banks are out of service at node 1.

Annex E
(informative)

List of symbols and subscripts

E.1 Letter symbols

A	Allocation constant depending on the harmonic voltage response of a given system
α	exponent of the summation law
C	compatibility level
E	emission limit
F	a ratio of the sending end to remote end short circuit power on an MV feeder
F	a ratio of the actual harmonic impedance relative to that determined by multiplying the impedance at fundamental frequency by the harmonic order – in the case of HV and EHV systems
G	acceptable global contribution of emissions in some part of a system
h	harmonic order
i	single customer or customer's installation
I	current
K, k	coefficient or ratio between two values (general meaning)
ℓ	length of a line or a feeder
L	planning level
PCC	Point of Common Coupling
POC	Point of Connection
POE	Point of Evaluation
P	active power
S	apparent power
T	transfer coefficient
U	voltage
x	reactance
Z	impedance

E.2 List of subscripts

a	average
h	harmonic order
hUM	transfer of upstream harmonic voltage (e.g at HV) to MV at order h
i	customer or customer's installation (i)
j	device (j) (distorting equipment) or a node (other than node m) in a system
LV	Low Voltage
m	station or busbar number (the considered node)
MV	Medium Voltage
n	number of stations, busbars or feeders in a system
w	weakest feeder

E.3 List of main symbols

(Self-explaining symbols are not listed)

B_m	Busbar or station in a system ($1 \leq m \leq n$)
E_{Ihi}	harmonic current emission limit of order h for the customer (i)
E_{Uhi}	harmonic voltage emission limit of order h for the customer (i)
G_{hMV+LV}	acceptable global contribution to the h^{th} harmonic voltage for all MV and LV distorting installations that can be supplied by the MV system under consideration (%)
G_{hBm}	maximum global contribution to the h^{th} harmonic voltage of all the distorting installations that can be supplied from a given substation B_m in the HV-EHV system under consideration (%)
HVDC	High Voltage Direct Current
I_{hi}	harmonic current emission level of order h of customer (i)
k_{hvs}	multiplying factor for short time harmonic voltage compatibility levels of order h to obtain the corresponding very short time compatibility levels (as defined in [6] - see also 4.1 Equation 1)
K_{hj-m}	the harmonic voltage of order h which is caused at node m when a 1 p.u. harmonic voltage of order h is applied at node j
$L_{hHV-EHV}$	harmonic voltage planning level of order h for HV-EHV (%)
L_{hMV}	harmonic voltage planning level of order h for MV (%)
POE or POEi	point of evaluation of a customer's emissions (i)
P_i	active agreed power of the individual customer or customer's installation (i)
SVC	Static Var Compensator
Q_{Dshunt}	the dynamic rating (in MVAR) of any thyristor-controlled reactor (TCR) of any Static Var Compensators connected at the busbar under consideration
S_{Dwi}	weighted distorting power of customer i
S_i	$S_i = P_i / \cos\varphi_i$ agreed power of customer installation i, or the MVA rating of the considered distorting installation (either load or generation).
S_{LV}	total power of the installations supplied directly at LV (including provision for future load growth) through the station HV/MV transformer(s)
S_{MV}	total power of the installations directly supplied at MV (including provision for future load growth) through the HV/MV station transformer
S_{out}	the power (in MVA) on a circuit leaving the considered HV-EHV busbar (including provision for future load growth)
S_{Din}	the power (in MVA) of any HVDC stations or non-linear generating plants connected to the considered HV-EHV bubsar
S_{SC}	Short-circuit power
S_t	total supply capacity of the considered system including provision for future load growth (in principle, S_t is the sum of all installations including downstream installations that are or can be supplied from the considered system)
TCR	Thyristor Controlled Reactor
THD	Total harmonic distortion – ratio of the r.m.s. value of the sum of all the harmonic components up to a specified order (H) to the r.m.s. value of the fundamental component
T_{hUM}	upstream to MV harmonic voltage transfer coefficient of order h; value depending on system characteristics, load levels and harmonic order
U_h	harmonic voltage of order h (generic)

U_{hHV} harmonic voltage of order h on HV

U_{hMV} harmonic voltage of order h on MV

U_{hLV} harmonic voltage of order h on LV

U_{hi} harmonic voltage emission level of order h of customer (i)

x_{hi} supply system harmonic reactance of order h at the point of evaluation of installation i

Z_{hi} harmonic impedance of order h of the supply system at the Point of evaluation (POE) for installation i.

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