TECHNICAL REPORT

IEC TR 61000-1-4

First edition
2005-05

Electromagnetic compatibility (EMC) –

Part 1-4: General – Historical rationale for the limitation of power-frequency conducted harmonic current emissions from equipment, in the frequency range up to 2 kHz

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-4: General – Historical rationale for the limitation of power-frequency conducted harmonic current emissions from equipment, in the frequency range up to 2 kHz

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 61000-1-4, which is a technical report, has been prepared by subcommittee 77A: Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

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

DTR	Report on voting
77A/477/DTR	77A/481/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.

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.

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).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-4: General – Historical rationale for the limitation of power-frequency conducted harmonic current emissions from equipment, in the frequency range up to 2 kHz

1 Scope

This part of IEC 61000, which is an IEC technical report, reviews the sources and effects of power frequency conducted harmonic current emissions in the frequency range up to 2 kHz on the public electricity supply, and gives an account of the reasoning and calculations leading to the *existing* emission limits for equipment in the editions of IEC 61000-3-2, up to and including the second edition (2000) and its first amendment (2001), and in the first edition of IEC 61000-3-12 (2004).

The concepts in this technical report apply to all low voltage AC systems, but the numerical values apply specifically to the European 230 V/400 V 50 Hz system.

NOTE A rationale for the limits in future complete revisions of IEC 61000-3-2 or IEC 61000-3-12 or both will be included in a new technical report.

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 61000-2-2:2002[1)], *Electromagnetic compatibility (EMC) – Part 2-2: Environment – Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*

IEC 61000-3-2:2000[2)], *Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)*[3)]
Amendment 1 (2001)

IEC 61000-3-3:1994, *Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage fluctuations and flicker in public low-voltage supply systems for equipment with rated current ≤ 16 A*[4)]
Amendment 1 (2001)

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1) This technical report also refers to the first edition of IEC 61000-2-2 (1990), *Electromagnetic compatability (EMC) – Part 2: Environment – Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*, since superseded by the second edition of that publication.

2) This technical report also refers to the first edition of IEC 61000-3-2 (1995), *Electromagnetic compatability (EMC) – Part 3: Limits – Section 2: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase),* and its Amendment 1 (1995), since superseded by the second edition and its amendments of that publication.

3) A consolidated edition 2.2 exists, which includes IEC 61000-3-2:2000 and its Amendments 1 (2001) and 2 (2004).

4) A consolidated edition 1.1 exists, which includes IEC 61000-3-3:1994 and its Amendment 1 (2001), *Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection*

IEC 61000-3-4, *Electromagnetic compatibility (EMC – Part 3-4: Limits – Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A*

IEC 61000-3-6, *Electromagnetic compatibility (EMC) – Part 3: Limits – Section 6: Assessment of emission limits for distorting loads in MV and HV power systems*

IEC 61000-3-11, *Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤ 75 A and subjet to conditional connection*

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

IEC 61000-4-13, *Electromagnetic compatibility (EMC) – Part 4-13: Testing and measurement techniques – Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests*

3 Definitions

Definitions of terms used in this technical report can be found in other publications in the IEC 61000 series.

4 General appraisal

The electricity supply industry intends to supply electric power with a sinusoidal voltage waveform, and customers' equipment is designed to operate correctly on such a supply. However, because the internal impedance of the supply system is not zero, a non-linear load connected by one customer produces distortion of the voltage waveform that may adversely affect another customer's equipment, as well as equipment in the supply system itself. There is no type of load or supply system equipment that is totally immune to distortion of the voltage waveform, although 'natural' immunity levels (those achieved by customary designs without special attention to improving immunity) vary greatly. Based largely on experience of the amounts of voltage distortion that give rise to evidence of malfunction of, or damage to, equipment, compatibility levels of voltage distortion for the low-voltage (LV) public supply system have been determined and are given in IEC 61000-2-2. The correspondences between these levels and other values are shown schematically in Figure 1. See Annex A of IEC 61000-2-2 from which that figure is taken. Compatibility levels are set as an acceptable compromise between immunity to harmonics and reduction of emissions. Methods to check that the immunity of equipment to voltage distortion is adequate are given in IEC 61000-4-13.

NOTE For the purposes of this technical report, the compatibility levels in the first edition of IEC 61000-2-2 apply.

The intention of applying limits on the harmonic current emissions of equipment connected to the public low-voltage (LV) system is to keep the actual levels of voltage distortion on the system below the compatibility levels for a very large proportion of the time, and below lower levels, known as planning levels, for a lesser but still large proportion of the time. (See Figure 1.)

NOTE 1 Emissions into the medium-voltage (MV) and high voltage (HV) systems can be controlled by other methods and procedures. See IEC 61000-3-6.

NOTE 2 In some countries, the electricity supply industry places reliance on IEC 61000-3-2 to control emissions from portable equipment, whether the point of common coupling is at LV, MV or HV.

Emissions from equipment are expressed as currents, because these are largely, but not completely, independent of the source impedance of the supply system, whereas the voltage distortion produced by the equipment is almost proportional to the supply-system impedance and therefore has no definite value. A product that draws a non-linear current from the supply system may alternatively be regarded as drawing a sinusoidal current, while emitting into the supply system harmonic currents of the opposite polarity to those that it actually draws.

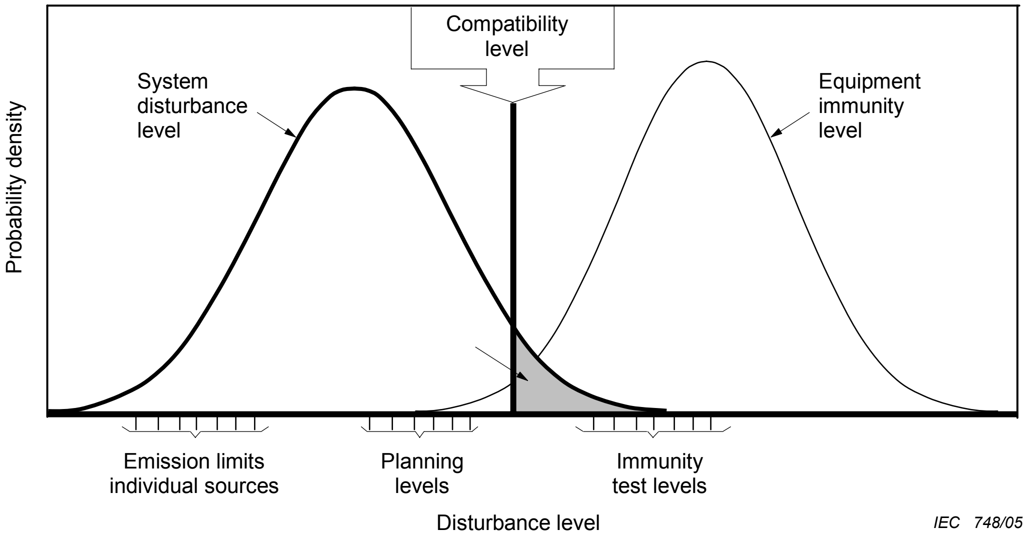


Figure 1 – Diagram showing compatibility level in relation to disturbance and immunity levels

5 Acceptable provisions in standards related to regulatory legislation

The equipment manufacturing industry can accept requirements in a voluntary standard, whose application may be determined by custom or moderated during individual contract negotiations, that would be unacceptable in a standard backed by regulatory enforcement. For example, a standard may contain provisions that, if fully applied, would result in very long test times. Parties to a contract might waive these provisions, wholly or partly (calculation or simulation might be employed, for example) whereas in an enforcement situation, no deviation from the provisions might be allowed.

Both 7.1 of EN 50006 and 5.3.1 of IEC (60)555-2[5)] required the test operator to search for worst-case conditions using the controls of the equipment under test, and in IEC (60)555-2, this was required for each harmonic in turn. Such a test might well take many days, with no assurance that another test operator might not find a different worst-case condition for just one harmonic. Such a provision was also contained in clause C.1 of IEC 61000-3-2:1995 and was not removed until the publication of Amendment 1 to IEC 61000-3-2:2000.

A standard must not include regulatory requirements: it is concerned only with the procedures necessary to determine whether a product within its scope meets its requirements.

5) IEC (60)555-2 was withdrawn in 1995 and replaced by IEC 61000-3-2.

6 History of IEC 61000-3-2 and its predecessors

6.1 Before 1960

The most numerous non-linear loads were television receivers with half-wave rectifiers. Because most of these had mains connectors of reversible polarity, the d.c. components approximately cancelled. The number of receivers installed was insufficient to create any significant system problems due to harmonic current emissions, but there is evidence that there was enough random unbalance of polarity of connection in some countries for the resultant d.c. component to cause corrosion problems in underground cables.

6.2 1960 to 1975

Phase-controlled dimmers for household lighting began to be marketed. These created high-frequency conducted emissions, thus initially drawing the attention of radio-spectrum protection authorities. Measures to limit these emissions could be made mandatory, but it was also noted that the dimmers produced harmonic currents and there was no practicable way of reducing the ratios of harmonic to fundamental current.

A system survey in Europe determined the 90th percentile value for supply impedance for residential customers (who were mostly fed by overhead LV distribution) as $(0,4 + jh0,25)$ ohms, where h is the harmonic order, and this value was included in IEC 60725. In addition it was determined that without some control of emissions from dimmers, the voltage distortion might grow to exceed acceptable levels (later to be called 'compatibility levels').

NOTE There is no direct relationship between compatibility levels and emission limits generally. Further information on this subject can be found in Annex A.

The first standard on this subject (according to its own text it is not based on any previous standard) was the European standard EN 50006 of 1975, implemented as various national standards including BS 5406:1976. This standard took burst-firing techniques into account and also covered voltage fluctuations, now the subject of IEC 61000-3-3 and IEC 61000-3-11. Limitation of harmonic current emissions was achieved by:

- prohibiting the use of phase control for heating loads over 200 W;
- applying limits for odd-harmonic emissions;
- applying limits for even-harmonic emissions to both symmetrical and asymmetrical control techniques.

The limits were expressed as voltage-harmonic percentages, produced with a supply system whose impedance (for single-phase loads) was $(0,4 + jh0,25)$ ohms. However, the test procedure actually required measurement of the harmonic currents, from which the voltage distortions were calculated. The standard does not include any explanation of the derivation of the limits, which are preserved as the Class A limits in IEC 61000-3-2, up to the 2000 edition. In fact, the numerical values were undoubtedly established piecemeal by negotiation between supply industry and equipment manufacturer experts. The retention of a strict mathematical rule for determining the values would not have been a priority for either group.

There was, however, a study that led to an approximate algorithm for determining the cumulative contribution of many dimmers set at different firing angles to a net voltage distortion level at the terminals of the LV transformer feeding the final distribution. (See also Annex A.)

6.3 1975 to 1982

During this period, a more comprehensive standard, IEC (60)555-2:1982, was developed. Still *effectively* restricted to 220(380) V-240(415) V 50 Hz European systems, it was adopted by CENELEC as EN (60)555-2 in 1987. It introduced three sets of limits; the original current limits unchanged from EN 50006, limits 1,5 times greater for products used only for short periods, such as portable tools, and special limits for television receivers, although an exemption for receivers whose input power was less than 165 W caused the limits to apply only to a small proportion of the receivers manufactured. The limits were expressed directly as currents, even for television receivers.

NOTE All IEC standards were renumbered in the 60000 series from 1998-01-01. To indicate the references of standards withdrawn before, or not reprinted after, that date, the '6xxx' prefix is here enclosed in parentheses. Hence 'IEC (60)555-2'.

Although this standard included an Annex that claimed to explain the derivation of the original current limits, in fact, it did not do so, merely citing the voltage distortion limits that were included in EN 50006 without explanation.

6.4 1982 to 1995

This period saw three profound changes; the great expansion of the use of switch-mode power supplies, both in business and in the home, the intimation that mandatory regulation of the electromagnetic compatibility (EMC) characteristics of electronic products would be introduced in Europe, and the further intimation that the European public electricity supply would be subject to 'product quality' requirements.

The early standards, EN 50006 and IEC (60)555-2, did not apply to professional equipment, but there is no relevant definition in either standard, although EN 50006 cites 'office machinery' as an example. Thus it was unclear whether the standards applied to desktop computers. This was clarified in Europe by a decision that such computers were 'household appliances', so that the original current limits applied. (But CISPR 14/EN 55014 was not applied for high-frequency emissions.) However the great expansion of single phase consumer electronics using direct on line switch mode dc power units, such as television receivers and desktop computers, led to significant peak flattening of the supply voltage waveforms due to near coincidence of the large current pulses drawn by these products. Although direct-on-line switch mode d.c. power units provided technology advantages (higher efficiency, lighter weight, smaller size), the near coincidence of the large current pulses being drawn can result in significant distortion of the supply voltage waveform. (Products with transformer-fed non-switching supplies have proportionally lower emissions because the series impedance of the transformer results in a larger conduction angle of the rectifiers.)

As a result, the development of the successor to IEC (60)555-2 was extremely controversial. It has been suggested that while the electricity supply industry continued to work in depth on the development of IEC 61000-3-2, the involvement of the equipment manufacturing industry was less structured. This may be true, but should be seen in the context that 'equipment manufacture' is a very diverse industry sector, whose sub-sectors have very different priorities in considering harmonic current emissions, while the supply industry has very little diversity in priorities, mainly deriving from differing infra-structure configurations in different countries.

IEC 61000-3-2:1995 introduced many new features. Most notably, it applies to '[***all***] electrical and electronic equipment having an input current up to and including 16 A per phase and intended to be connected to public low-voltage distribution systems.' (However, 'professional equipment', as defined in the standard, enjoys exemption from some requirements.)

The standard thus includes requirements and limits that apply to several different types of product, grouped into four classes. It *effectively* applies only to European systems, as for previous standards.

NOTE It is still not known whether the characteristics of 220V – 240 V, 50 Hz supply systems in other countries are sufficiently similar to the European for the standard to be applied, while it has been shown that 'scaling' operations, intended to make the provisions applicable to systems of other voltages and frequencies, are rather unreliable. Different distribution system configurations affect the effective supply impedance and the propagation of harmonic currents through the system.

Class A is a general class, applying to products within the scope that are not specifically included in another class. The limits are derived from the original voltage limits, dating effectively from before 1975, and the assumed supply impedances at the fundamental and harmonic frequencies. The limits are related to the current emissions of dimmers for incandescent lamps. See Annex B.

Class B is a specific class, applying to portable tools, which are assumed to be used for short periods only (a few minutes). The limits are 1,5 times the Class A limits. As far as can be determined, this factor of 1,5 is purely heuristic, although for the third harmonic, one piece of equipment that just meets the third-harmonic limit of 3,45 A thereby takes up almost all the allowable fraction (0,25) of the compatibility level of 5 % that can be allocated to the low-voltage network.

NOTE For an explanation of the 'allowable fraction of the compatibility level', see Annex A.

Class C is for lighting equipment, which has to be carefully defined. The limits are quite stringent and some of these originally appeared, with similar values, in the product standard IEC 60082, now withdrawn. See Annex C.

Class D applied originally to products drawing a current pulse from the supply that lay within a specified mask centred on the peak of the current waveform. The rectifier conduction angle of a typical high-efficiency direct-on-line d.c. power unit is 35°. The individual low-order odd harmonic currents emitted by a group of such products add nearly arithmetically, producing peak-flattening of the voltage waveform if single-phase supplies. This class was intended to apply to d.c. power units, separate or built into products, and was based, after considerable study (including the effect of supplying the rectifier with already peak-flattened sine waves), on a rectifier conduction angle of approximately 65°, with some heuristic adjustments to accommodate other products. See Annex D.

The Class D limits, which are proportional to the active power drawn and are thus expressed in milliamps per watt, were nominally aligned with the (fixed current) Class A limits at a power of 600 W, but because of rounding errors, the limits of the two classes for each harmonic become equal at significantly different powers, which caused some confusion initially. It was possible to determine that the expected effect on the supply system was that the compatibility limits would not be exceeded with these limits applied. The details of this prediction are given in [12] and [13][6].

It was also agreed that there should be a lower bound to Class D below which no limits would apply, because the impact on the network of a large variety of such products would be acceptable. The lower bound was set at 75 W, with a provision to reduce to 50 W 'after four years'. It was not realised that this is not a provision that could actually be implemented as stated. Consequently, those who relied on this provision have been disappointed that it has not been implemented.

NOTE There is no definite date from which to count the period of four years, because IEC standards are voluntary and can be applied, or not, at any time. Furthermore, IEC standards can only be amended by a voting process, which must be contemporaneous; National Committees cannot determine which way they should vote on a provision that would become effective many years in the future.

Unfortunately, the conduction angle of 65° required to meet the limits of Class D results in a rather unacceptably low efficiency of the power unit, manifesting as heat emission or the need for the inclusion of an inductor or an active power-factor correction circuit, at extra cost.

[6] Figures in square brackets refer to the Bibliography.

Consequently, this requirement was, and still is, by far the most controversial. It was introduced on the grounds that statistical evidence showed a rising level of voltage distortion on European networks, together with daily variations in the 5th harmonic levels that tracked with television viewing habits. The rate of rise determined in several European countries was about 1 % over ten years, although not all the data were measurements at the same sites or at the same times over the ten year period. But the 'background' level due to miscellaneous sources was about 3 % in some places and the compatibility level was 5 % for the fifth harmonic at that time, so an unchecked rise could have had serious consequences in about ten years. Considering the service lifetimes of the products concerned (3 to 10 years), it was clearly necessary to forestall any close approach to the compatibility level some years before it was forecast to occur.

A principle known as 'equal rights' was applied in the setting of limits at that time. This can be simply stated as, 'any product consuming X watts has an equal right to produce y % of harmonic currents'. Consequently, the classification and limits derived for television receivers were applied to ALL products with a d.c. power unit. However, this principle does not allow for the fact that there are, for example, far more television receivers in use than, say, some rare piece of scientific equipment, of which there may be only ten in any one country. So applying the limits to the ten rare units, at a cost, achieves nothing of any significance to the well-being of the supply network or its load equipment.

NOTE 'Equal rights' also suggests that the allowable harmonic emissions should be proportional to the power drawn by the product. From the equipment design point of view, this is entirely logical. Fixed current limits are very lax for low-power equipment and may be very stringent indeed for higher-power equipment.

The introduction in Europe of mandatory control of EMC characteristics effectively turned IEC 61000-3-2 into a quasi-legal document, and it was not editorially suited to such a role.

6.5 1995 to 2000

Amendment 1 to the First Edition was issued in 1997. It introduced the following changes:

- 'The designation shall be specified by the manufacturer.' was added to the definition of 'professional equipment'. (Unfortunately, a definition is not allowed to contain a requirement, so other committees have not been allowed to adopt this definition verbatim.)
- Test conditions for vacuum cleaners and air-conditioners were added to Annex C.

Amendment 2 was issued in February 1998. This introduced requirements for lighting equipment with active input power not greater than 25 W. The limits applying to Class D, without the lower bound of 75 W, can be applied, or, in addition to limits for low-order harmonic currents, the current waveform may meet shape requirements. In setting these requirements, note was taken of the fact that there can be partial cancellation of the 5th harmonic current produced by discharge lamps by the 5th harmonic current produced by d.c. power units with capacitive filter, such as in television receivers.

Amendment 3 resulted from a proposal to amend the CENELEC version of the standard unilaterally, which was changed to a request for SC77A/WG1 to prepare it. Additional amendments were consolidated with it, resulting in a combined text dealing with:

- limits for motor driven equipment with phase angle control;
- test conditions for kitchen machines;
- asymmetrical control methods;
- symmetrical control methods;
- test condition for arc welding equipment intended for non-professional use.

None of these involved fundamental changes to the standard.

In accordance with IEC publication procedures, this third amendment resulted in a second edition, dated August 2000.

6.6 The 'Millennium Amendment'

An initiative in CENELEC led to a reappraisal of the standard, with much discussion in a working group. The output document was referred to IEC SC 77A, and this resulted in further very extensive discussions. During this time, economic considerations were introduced as a specific subject (see Annex E). By the end of 1999, a somewhat reluctant consensus had been achieved, mainly on the grounds that further discussion would not produce significant improvement, and it had been agreed to begin work, immediately after finalizing the amendment, on a full revision of the standard, with documented rationales for all provisions. The resulting amendment became known as the 'Millennium Amendment', because it was substantially finalized at the beginning of 2000.

Unfortunately, Amendment 3 was also in process in IEC during 1998-99, and the IEC procedures resulted in a divergence of the editions of the IEC standard from those of CENELEC, which implemented the Millennium Amendment, but not the 3rd IEC amendment, in a consolidated edition, creating confusion that might have been avoided.

The Millennium Amendment eliminated many of the ambiguities and uncertainties that made the 1995 edition difficult to use in a regulatory situation. It also abandoned the mask for determining Class D membership, on the technical grounds that for some products it was impossible to be sure whether they should be in Class D or not. Instead, it substituted what was finally a rather short list, of high-volume products with high simultaneity of use, which contribute (in the absence of built-in mitigation measures) to *odd harmonic currents of little phase diversity* (rather than the overall harmonic content of the system voltage): personal computers, personal computer monitors and television receivers.

The amendment also included a clarification of the requirements for lighting equipment.

6.7 Future development of IEC 61000-3-2

A detailed consideration of this subject is a matter for IEC 61000-1-X (to be published). Initial considerations are described in Annex F.

7 History of IEC 61000-3-12 and its predecessor

7.1 1989 to 1998

IEC 61000-3-2 deals with equipment rated at up to 16 A/phase. A complementary document, dealing with equipment rated at over 16A/phase, was prepared as IEC 61000-3-4, a Technical Report type 2 ('prospective standard for provisional application'), by a team comprising experts from ES, FR, DE, IE, IT, UK and US. Some conclusions of the team were recorded:

- an arithmetic superposition law was used for harmonics up to the fifth and a geometric law for higher orders;
- approximately 75 % of the compatibility level (for the fifth harmonic, for example) is transmitted from the MV level and is present as a background disturbance throughout the LV network. Hence only 25 % of the compatibility level is left for the admissible additional voltage distortion due to non-linear loads connected to a specific LV supply. See Annex A.

Rough calculations, depending on different assumptions on the partition of distorting loads, yielded:

- $I_5/I_1 \leq 11$ % (UK)
- $I_5/I_1 \leq 15$ % (IT)
- $I_5/I_1 \leq 16$ % (CH)
- $I_5/I_1 \leq 9$ % to 16 % (DE)

It was decided that the limits should depend on the short-circuit ratio R_{sce}, with higher limits with higher R_{sce}, but remain in principle in the range of the rough calculations.

Further studies were made to find a justified relation between the R_{sce} values and the limits. The detailed calculations are lost. An attempt to 'recover' the basis of these studies, and relate it to the limits in IEC 61000-3-12, is presented in Annex G.

This rationale does not consider the provisions of IEC 61000-3-4 in detail, since all but one (relating to equipment rated at over 75 A/phase) will have been superseded by provisions of IEC 61000-3-12 by the time that the rationale is published.

The report was published in October 1998.

NOTE Technical reports type 2 are no longer produced by IEC.

Such reports were required to be reviewed within three years of publication, and IEC decided to convert the report into a standard, IEC 61000-3-12, which might also be adopted by CENELEC and could then be used to demonstrate compliance with the European EMC Directive.

NOTE This was seen to be helpful for manufacturers intending to export to Europe, as well as for manufacturers within Europe.

7.2 After 1998

As was expected, experience gained from applying IEC 61000-3-4 led to proposals for changes to be incorporated in IEC 61000-3-12. After a very great deal of discussion, a first voting document was circulated in 2003.

8 Economic considerations taken into account in setting limits in IEC 61000-3-2 before publication in 1995, and before the finalization of the text of the Millennium Amendment

Only passive mitigation was considered by IEC as economically practicable at that time, and only for single-phase equipment. Approximately €1 or $1 would be added to the production cost (not selling cost) for a TV-set, i.e. approximately 1 to 2 % for high volume, not low-price products (a self-ballasted lamp is a typical low-price product).

The cost-sharing idea was implemented by the lower power bound of 75 W:

- no harmonics limits up to this power value; costs only to the supply system;
- existing harmonics limits beyond this power value; costs to both, the product and the supply system (because the harmonic currents are not zero!).

This was considered in setting the limits in Table 3.

The limits of Tables 1 and 2 were taken from an older European standard (EN 50006) into IEC (60)555-2. No definite information on economics is available for the limits in these tables. In the European Standard, the scope was restricted to household appliances, and experts from that sector were actively involved in the work. It might be assumed, therefore, that the economic effects of the introduction of the limits were acceptable at that time, by the parties involved.

During the preparation of the Millennium Amendment, consideration of economic aspects was intensified. As a result, many products were re-allocated from Class D to Class A (see 6.6).

Annex A
(informative)

Compatibility level and compensation factor

A.1 Explanation of the allocation of only part of the total compatibility level to the low-voltage network

Harmonic distortion at LV-, MV- and HV-levels in the network is mainly produced by harmonic currents of non-linear loads installed in the LV-network. The resulting harmonic distortion in the LV-Network is the geometrical sum of the harmonic voltage drops in the LV network and in all superimposed MV- and HV-systems. According to IEC standards, the harmonic distortion in the LV-Network shall not exceed the compatibility level given in IEC 61000-2-2.

Harmonic currents of non-linear loads in the LV-network, in the MV-network and in the HV-network produce harmonic voltage drops at the harmonic impedances of the LV/MV-transformer, of the MV/HV-transformer and of the HV-network including generator respectively. The percentage harmonic voltage drops correspond approximately to the percentage transformer impedances which are given by the percentage short circuit voltage of each relevant transformer.

The typical percentage impedances in European networks are given in Figure A.1. The partition of the total compatibility level into the parts assigned to each voltage level reflects roughly the relation of these percentage impedances. In order to account for the geometric summation of the voltage drops, the value of 25 % for the LV-network is increased with respect to the value which can be derived from the ratio of the impedance values. 25 % of the total compatibility level is therefore used in IEC 61000-3-2 and IEC 61000-3-12 for the assessment of the maximum harmonic currents from non-linear loads in the LV-network for 230 V 50 Hz systems.

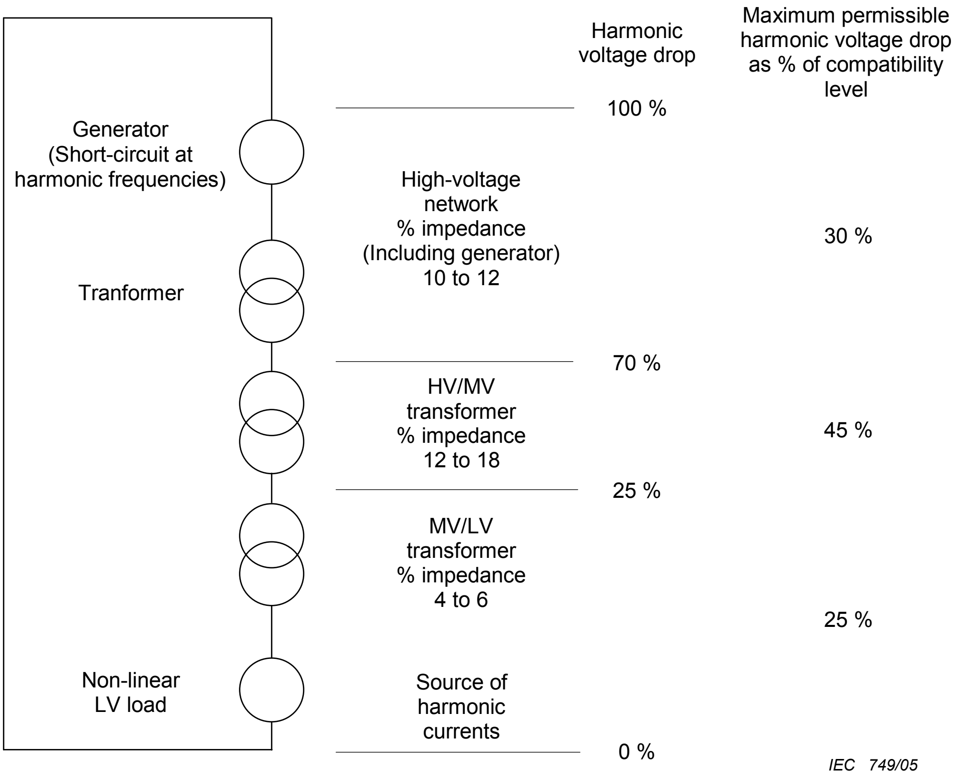


Figure A.1 – Allocation of harmonic voltage drops over the transformer impedances in a typical system

A.2 Compensation factor

A.2.1 Derivation from the model in Figure A.1

From the model, the maximum permissible current emission from equipment at each harmonic frequency can be shown to be:

$$i_{h,eq} = u_{h,CL} k_{N,LV} / Z_{LV,h} k_{p,h}$$

where

h is the harmonic order

$i_{h,eq}$ is the maximum permissible current emission from equipment at harmonic h;

$u_{h,\mathrm{CL}}$ is the compatibility level for voltage distortion at harmonic h;

$k_{N,\mathrm{LV}}$ is the sharing factor for the LV network;

$Z_{\mathrm{LV},h}$ is the network impedance at harmonic h;

$k_{p,h}$ is the compensation factor for harmonic h.

A.2.2 Detailed consideration

$k_{p,h}$ is composed of many sub-factors, and there is no generally-applicable analytic method for determining its values. The values used in the preparation of the first edition of IEC 61000-3-2 were as shown in Table A.1. The chance of compensation between different harmonic currents increases if the power drawn by the equipment emitting harmonic currents is small compared to the short circuit power R_{sc}. Therefore, $k_{p,h}$ depends on the factor R_{sce} (R_{sc} divided by the rated apparent power of the equipment, see IEC 61000-3-12) as given in Table A.1.

Table A.1 – Compensation factors $k_{p,h}$

R_{sce}	h=3	h=5	h=7	h=11	h=13
33	0,9	0,85	0,75	0,65	0,65
66	0,8	0,75	0,6	0,5	0,5
120	0,68	0,65	0,45	0,35	0,35
175	0,62	0,55	0,35	0,25	0,25
200	0,6	0,5	0,3	0,2	0,2
250	0,55	0,45	0,28	0,18	0,18

NOTE The above values were taken from Table 3 of IEC 61000-3-6 and were assumed to apply in the general case, being derived in part from published papers. For concentrations of equipment of the same type that produce harmonic currents with only small differences in phase (such as uncontrolled rectifiers with capacitive smoothing), values of $k_{p,h}$ nearer to 1,0 apply for low-order harmonics. See Table 4 of IEC 61000-3-6. New investigations are in progress to verify the above values or to improve them.

If proper account for actual system impedances is made, $k_{p,h}$ becomes the only term subject to estimation. The root cause for any discrepancies between modelling and survey results must then be isolated to this term alone. Table A.2, derived from [14], describes what might be considered a relatively complete set of sub-factors although it is possible to suggest others. The table also shows plausible ranges of values for these sub-factors, as well as for the composite compensation factor, $k_{p,h}$, which follows from combination of the individual sub-factors. As a first approximation, for Table A.2, the sub-factors are multiplied together to obtain the composite factor.

It should be clearly understood that, for some equipment and configurations, the listed factors may not be independent. The multiplication of the sub-factors to obtain the value of the composite factor is still valid if all but one member of a non-independent set of factors is set to the value 1.

Table A.2 – Sub-factors of $k_{p,h}$

Sub-factor	Estimated values for fifth harmonic factors		
	Low estimate	Typical value	High estimate
Non-linear load penetration factor [a]	0,1	0,14	1
Triplen factor [b]	1	1	1
System de-rating factor	0,75	1	1,5
Load diversity factor	0,5	1	1
L-L and L-N 3-phase factor [c]	0,23	1	1
Load phase diversity factor	0,4	0,44	1
System phase diversity factor	0,5	0,62	1
Voltage THD factor	0,85	1	1
Current division factor [d]	0,76	1	1
Resonance factor	1	1,6	4
3-phase unbalance factor	1	1,1	1,25
Composite factor $k_{p,5}$	0,01	0,64	7,5

[a] The mix of linear and non-linear loads is not considered for calculation of composite *kp,h*.

[b] Triplen cancellation in Δ-connected transformers is only applicable to the medium-voltage network.

[c] This factor may result in significant cancellation for the 5th and 7th harmonics, but may also be as high as 3,0 for triplen harmonics to account for summation in neutral conductors if all loads are connected L-N.

[d] This factor accounts for division of harmonic currents between the mains system impedance and the aggregate impedance of connected linear loads including capacitor banks.

Several conclusions may be immediately drawn from Table A.2. First, wide swings in the value of $k_{p,h}$ follow from reasonable selections of values for included sub-factors. At the extremes, substitutions of apparently defensible values for $k_{p,h}$ result in estimates for permissible 5th harmonic emissions ranging from greater than 400 % of the fundamental current at one extreme to less than 0,7 % at the other. Both results are clearly absurd. Secondly, a decision to ignore a particular sub-factor (i.e. to set the sub-factor to 1,0) can significantly impact the value derived for $k_{p,h}$. The fact that several ways of combining many sub-factors, especially simple multiplication, contributes greatly to the possibility of wide swings in the value of $k_{p,h}$ might tempt the dismissal of concerns that only a subset is typically considered, but this conclusion can be shown to be unrealistic.

Work is on-going to develop formally-defined sub-factors (which may or may not be those in Table A.2). The results of this work are intended to be reported in IEC 61000-1-X (to be published).

Annex B
(informative)

Comparison of Class A limits and the harmonic spectra of phase-controlled dimmers of incandescent lamps at 90° firing angle

The harmonic spectra of phase-controlled dimmers of incandescent lamps at 90° firing angle (at which the harmonic current emissions are greatest) vary very little from one product to another, and the Class A limits are specified as currents. It is therefore possible to deduce from each limit value the corresponding value of fundamental current. It can be shown (see Figure B.1) that the lowest fundamental current is determined by the limit for the 15th harmonic, and this corresponds to a full-load power of 745 W. Limits for the lowest harmonics are less stringent, no doubt due to changes to accommodate non-linear loads other than dimmers.

Figure B.1 illustrates this relationship, using a logarithmic vertical scale to show the high-order harmonic limits and levels clearly. For comparison, the measured spectrum of a typical dimmer of 1970s design (before conformity with EMC standards was mandatory) is shown, the load being a 230 V 150 W lamp and the firing angle 90°. It can be seen that for harmonics above the 13th, the correspondence between limit values and spectrum levels is quite good. The slightly higher levels of 19th and 27th harmonics from the measured dimmer may be due to distortion of the supply voltage or perhaps resonance between the 'rise-time' inductor in the dimmer and the capacitor for attenuating conducted emissions.

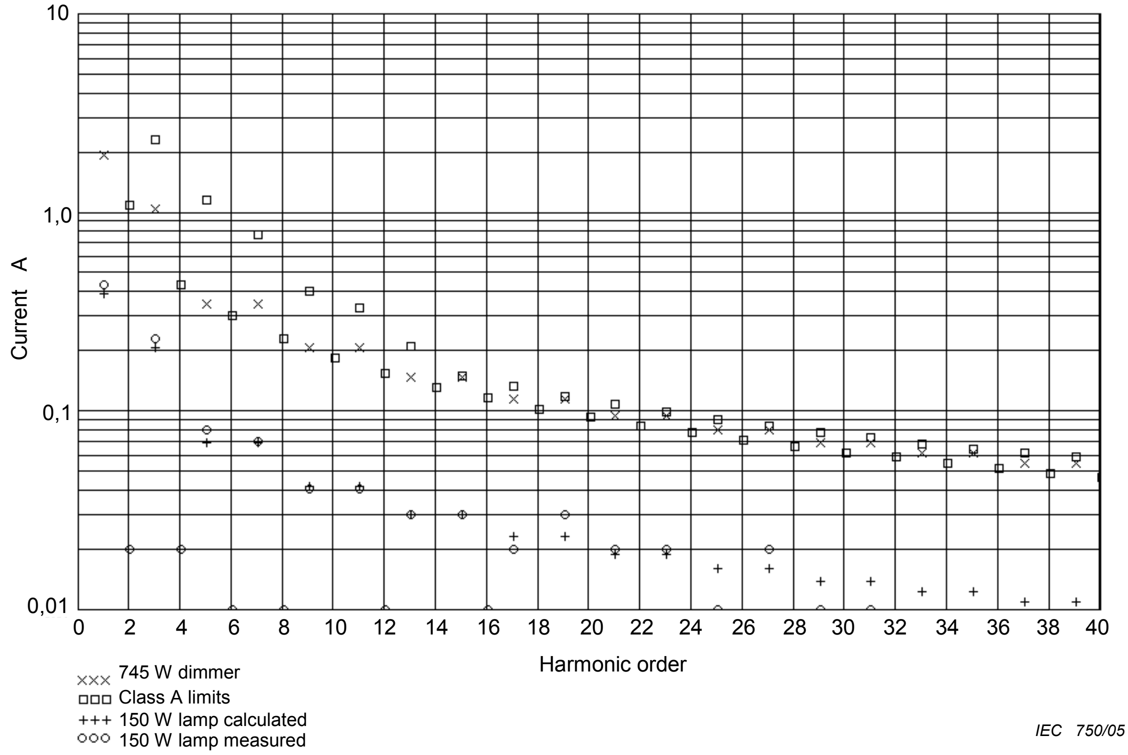


Figure B.1 – Comparison of Class A limits and spectra of dimmers

Annex C
(informative)

Comparison of Class C (Table 2 of IEC 61000-3-2) limits and the harmonic spectrum of a discharge lamp with inductive ballast

Figure C.1 is self-explanatory.

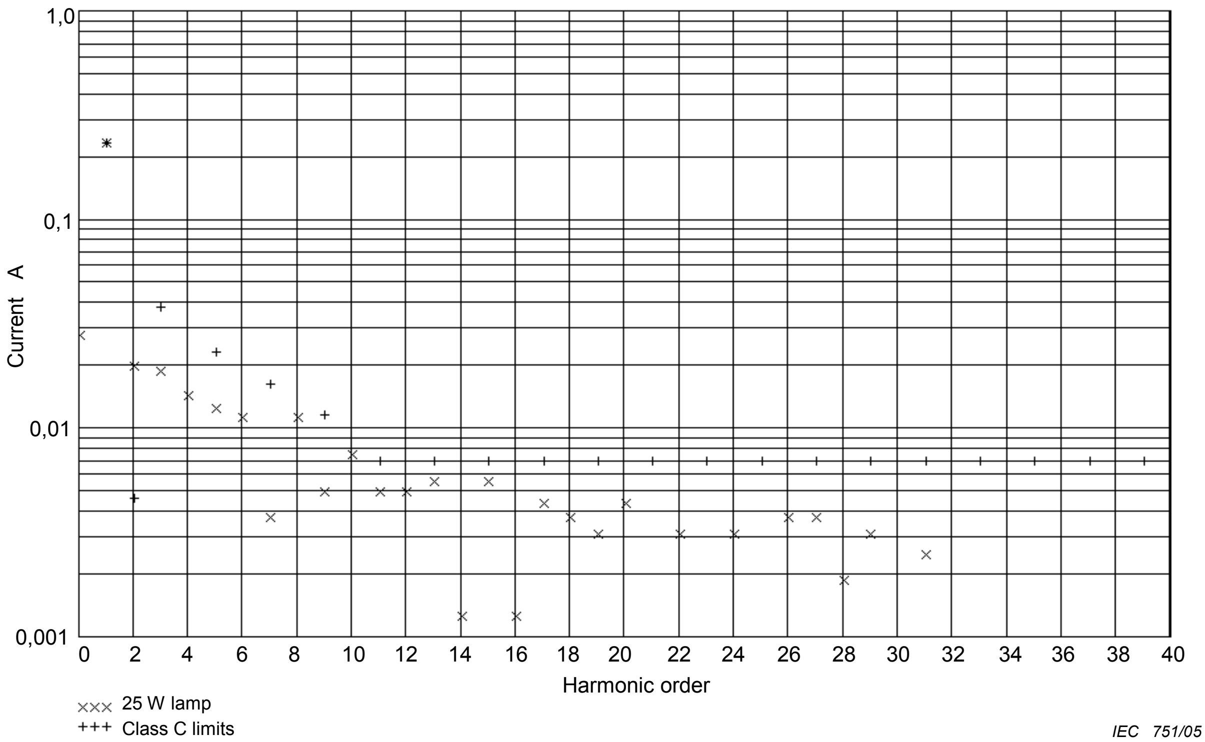


Figure C.1 – Comparison of Class C limits and the harmonic spectrum of a discharge lamp

Annex D
(informative)

Comparison of Class D limits and the harmonic spectra of capacitor-filtered single-phase rectifiers with 35° and 65° conduction angles

Figure D.1 is largely self-explanatory. Note that the 3rd and 5th harmonic levels for the 65° conduction angle coincide with the limits.

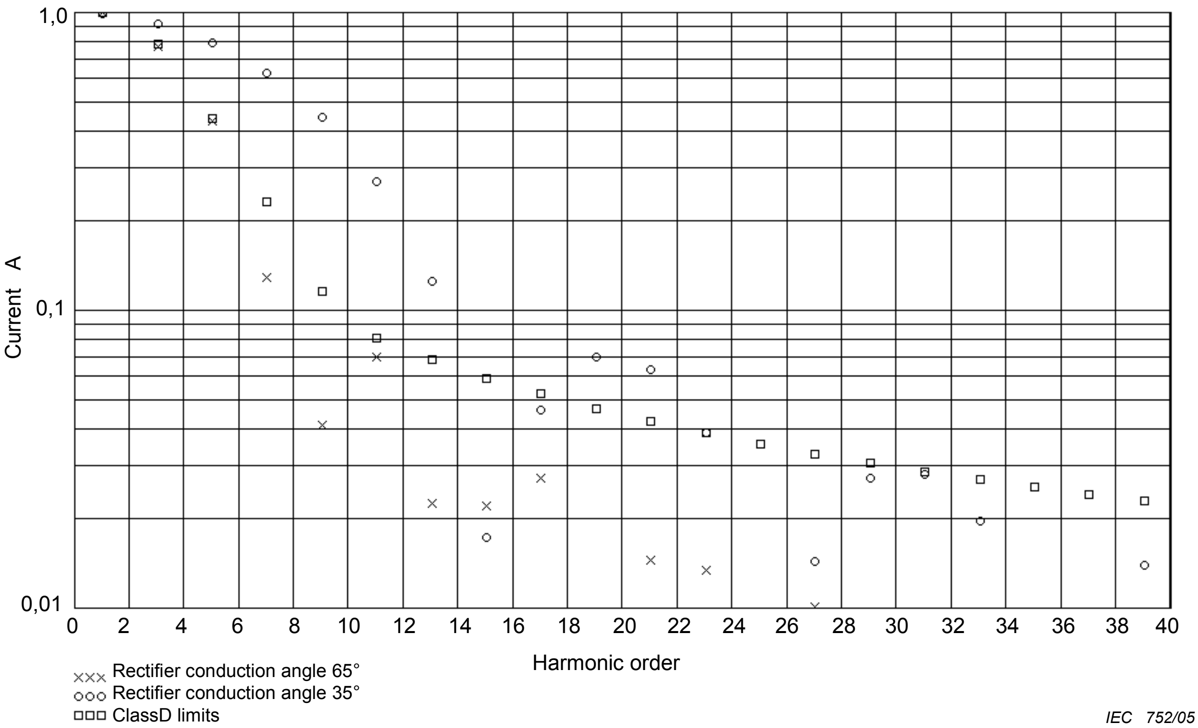


Figure D.1 – Comparison of Class D limits and harmonic spectra of single-phase 230 W rectifiers with capacitor filters

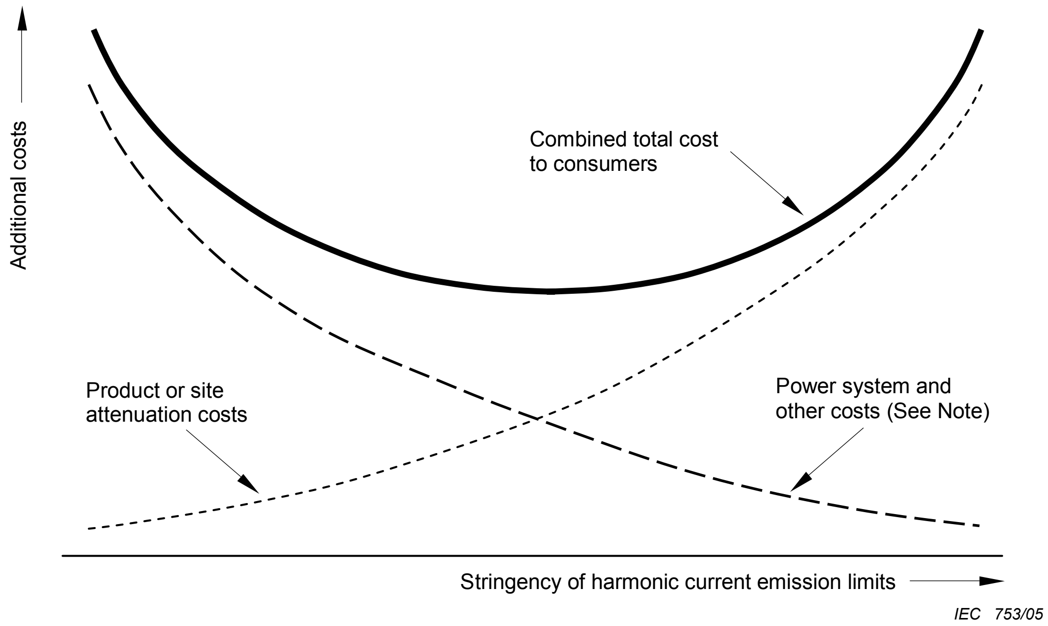
Annex E
(informative)

Economic considerations taken into account in setting limits, before finalization of the text of the Millennium Amendment to IEC 61000-3-2

Passive mitigation techniques typically yield less complete mitigation of harmonic emissions, but generally are less costly to implement compared with active methods. Until very recently, passive filtering was the only feasible method for high-power applications from a cost standpoint. Recent advances in power semiconductor devices and digital signal processing have made the use of active mitigation techniques more cost effective. Considered in aggregate, the average cost for implementing high performance, active mitigation using present-day techniques in a wide variety of high volume products (except low-cost products such as lamps) is estimated to be between 1 % and 2 % added to the end user's purchase price. It is not expected that these percentages will change substantially in the foreseeable future. Actual costs vary widely by product type. For example, incremental costs are a small percentage added to the purchase price for personal computers, but 60 % or more added to the purchase price of three- phase variable speed drives.

Experts from the product manufacturing sector estimate aggregate costs for implementing high performance active mitigation for all electrical and electronic products to be a very large sum annually. The consequence of this would be that harmonic voltage level be reduced very significantly. Experts from the electricity supply industry, for their part, have estimated that annual costs attributed to the effects of harmonic emissions would be comparable in future, if there were no harmonic emission limits at equipment or site level. With substantial sums at stake, it becomes very desirable to carefully consider how best to optimise the selection of mitigation options in order to rationally minimise total aggregate costs. Figure E.1 captures the basic concept of optimising a trade-off between excessive costs arising from attempts to address the problem in a single dimension. It is widely recognized that it is inappropriate to rely entirely on product mitigation or, conversely, on making the supply system capable of sustaining any level of emissions from equipment by, for example, reducing the system impedance to a negligible level. It is also widely recognized that it is inappropriate to attempt to reduce a phenomenon, for example voltage distortion, to a unnecessarily low level. In some countries, due to problems related to fair cost-sharing, the incremental cost associated with system-level mitigation is accepted only if it enables a much greater reduction in incremental costs which would otherwise be associated with mitigation at the equipment or site level.

NOTE In some countries, the electricity supply industry places reliance on IEC 61000-3-2 to control emissions at the equipment level. This is said to eliminate a need to install mitigation equipment at the site or system level, thus allocating the cost of mitigation to the origin of the harmonic distortion.



NOTE Most of the 'power system and other costs' are power system costs.

Figure E.1 – Illustration of the concept of total aggregate cost trade-offs for meeting compatibility levels

Annex F
(Informative)

Concept plan for the full revision of IEC 61000-3-2

NOTE This concept plan is intended to be used also for Edition 2 of IEC 61000-3-12.

F.1 Introduction

NOTE The rationale for the full revision of IEC 61000-3-2 is given in IEC 61000-1-X (to be published).

It was agreed to base the study on the allocation of limits based on a composite 'impact factor' of a product on the voltage distortion of the supply network. A number of components of this factor were identified and are listed below. This is not a new concept, a 'saturation factor' and a 'simultaneity factor' were used in [13].

F.2 Density

The density impact factor is intended to take into account the equipment impact related to the total number of pieces of equipment that are in the field. The density impact factor is assessed for each type of equipment. It is defined as the ratio of the number of pieces of equipment to the number of households.

NOTE Consideration of density allows the burden of strict limits to be removed from rare equipment.

F.3 Usage factor

The usage impact factor is intended to take into account differences of the impact on the network, related to the usage of equipment. Basically it can be calculated from the ratio of the electrical energy consumed per year to the maximum active power during normal use.

Additional correction factors consider the simultaneity of use, e.g. per day or per season of the year.

NOTE Consideration of usage allows the burden of strict limits to be removed from little-used equipment.

F.4 Contribution

The harmonic contribution factor attempts to capture the potential impact of the entire spectrum of the harmonic emissions from a particular type or general class of equipment. The ratio of the non-linear portion to the fundamental current is used to define the harmonic “contribution” factor with sufficient accuracy to define the potential impact of a particular type or general class of equipment.

For the purposes of assessing the impact of harmonic “contribution” where measurements are employed, any reasonably accurate and repeatable method should be suitable. However, it is generally preferred that methods as defined in IEC 61000-3-2, Ed. 2 are employed to obtain average emission values.

F.5 Phase angle factor

The phase angle of the harmonic current has been selected as a relevant impact factor, because this has an influence on the network voltage distortion. For example, considering two pieces of equipment connected on the same network, there is a cumulative or a cancellation effect on the distortion of the network voltage, depending on the relative phase angles of their harmonic currents.

Equipment with a phase angle factor less than 1 should have more relaxed limits, as their impact on the network distortion is lower.

F.6 System and site mitigation

In order to achieve an optimum economic accommodation of non-linear loads on the low-voltage electricity supply network, all possible technical measures should be assessed. Mitigation of the effects of harmonic currents at system level is technically very complex and can involve high capital costs, but some measures (such as the reduction of system impedance) are employed where justified. Mitigation at site level, where the interface with the public electricity supply is a medium- or high-voltage, may have economic advantages over mitigation at equipment level, but its introduction depends on the practicability of ensuring that agreed emission limits are respected, and the co-operation of electricity suppliers and government agencies. It has been introduced in some countries. Site level mitigation is extremely unlikely to be practicable for small and residential sites.

F.7 Network factors

Network factors are included within the impact factor assessment to take into account the electrical characteristics of the network, operation of the network, and the interaction of the loads on the network. Network factors are a function of the network design, network operation, interaction of the network loads, and the restraints imposed upon the network operators.

NOTE Consideration of these factors allows the burden of strict limits to be removed from some types of equipment.

Annex G
(informative)

Derivation of the limits in IEC 61000-3-12

G.1 Formulae connecting the voltage drop and the short-circuit ratio

In this document, the rated single phase voltage U_p is written V, and the rated interphase voltage U_i is written U. The line impedance Z of the network is written Z_L and the neutral impedance of the network is written Z_N.

Short-circuit power:

$$S_{sc} = \frac{U^2}{Z}$$ (U = phase to phase voltage; Z = network phase impedance)

Short-circuit ratio:

Single phase: $$R_{sce} = \frac{S_{sc}}{3.S_{equ}}$$ with: $S_{equ} = V.I_{equ}$

Three phase: $$R_{sce} = \frac{S_{sc}}{S_{equ}}$$ with: $S_{equ} = \sqrt{3}.U.I_{equ}$

Voltage drop per phase:

Single phase: $$\Delta V \leq \left|\overline{Z}_L + \overline{Z}_N\right|.I_{equ} = \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot Z_L \cdot I_{equ} = \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{U^2}{S_{sc}}.I_{equ}$$

$$\Delta V \leq \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{U^2}{3.S_{equ}.R_{sce}}.I_{equ} = \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{V}{R_{sce}}$$

$$\boxed{\frac{\Delta V}{V} \leq \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{1}{R_{sce}}}$$

Three phase: $$\Delta V \leq Z_L \cdot I_{equ} = \frac{U^2}{S_{sc}} \cdot I_{equ}$$

$$\Delta V \leq \frac{U^2}{S_{equ}.R_{sce}}.I_{equ} = \frac{U^2}{\sqrt{3}.U.I_{equ}.R_{sce}}.I_{equ}$$

$$\boxed{\frac{\Delta V}{V} \leq \frac{1}{R_{sce}}}$$

It is assumed that the maximum voltage drop at the fundamental frequency is 3 %.

For single phase equipment $\Delta V/V \leq 3$ % if $R_{sce} \geq 55$ (assuming that $\left|\overline{Z_L} + \overline{Z_N}\right| / Z_L = 5/3$).

For three phase equipment, $\Delta V/V \leq 3$ % if $R_{sce} \geq 33$.

As most of equipment with input current above 16 A is three phase equipment, the minimum R_{sce} value is chosen equal to 33.

G.2 Approximate formula connecting harmonic current, harmonic voltage and short-circuit ratio R_{sce} at the PCC level

Assuming that Z_L or Z_N is purely inductive: $Z_5 = 5.Z_1$

For single phase:

The 5th harmonic voltage (per phase) is:

$$V_5 = 5.\left|\overline{Z_L} + \overline{Z_N}\right|.I_5$$

$$V_5 = 5 \cdot \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot Z_L \cdot I_5 = 5.\left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{U^2}{3.S_{equ}.R_{sce}}.I_5 = 5.\left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{3.V^2}{3.V.I_{equ}.R_{sce}}.I_5$$

$$\frac{V_5}{V} = \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{5}{R_{sce}}.\frac{I_5}{I_{equ}}$$

Using percentages: $v_5(\%) = \frac{V_5}{V}$ $i_5(\%) = \frac{I_5}{I_1}$

And assuming $I_{equ} \approx I_1$, we obtain:

$$\boxed{v_5(\%) = \left|\frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L}\right| \cdot \frac{5}{R_{sce}}.i_5(\%)}$$

For three-phase:

The 5th harmonic voltage (per phase) is:

$$V_5 = 5.Z_L.I_5$$

$$V_5 = 5.\frac{U^2}{S_{equ}.R_{sce}}.I_5 = 5.\frac{U^2}{\sqrt{3}.U.I_{equ}.R_{sce}}.I_5 = 5.\frac{V}{R_{sce}}.\frac{I_5}{I_{equ}}$$

With the same assumptions as for single phase, we obtain:

$$\boxed{v_5(\%) = \frac{5}{R_{sce}}.i_5(\%)}$$

For any harmonic order h:

Single phase:

$$v_h(\%) = \left| \frac{\overline{Z}_L + \overline{Z}_N}{\overline{Z}_L} \right| \cdot \frac{h}{R_{sce}} .i_h(\%)$$

Three phase:

$$v_h(\%) = \frac{h}{R_{sce}} .i_h(\%)$$

G.3 Total and partial weighted harmonic distortion

These concepts are used in IEC 61000-3-12. For an explanation of their purpose, see Annex H.

G.4 Emission limits for R_{sce} = 33

The limits have been established using the following assumptions:

a) proportional limits are adopted;

b) ¼ of the compatibility level is not exceeded when one single piece of equipment is connected;

c) consequently, the maximum value for the 5^{th} harmonic voltage v5 is 1,5 % (compatibility level = 6 %);

d) for three phase equipment, using the above formula with R_{sce} = 33 gives a limit for i5 equal to 9,9 %;

e) in order to avoid discontinuity with the existing standards, the limit for the 5^{th} harmonic has been aligned with the class B limit of IEC 61000-3-2 at 16 A, which is 10,7 %;

f) the limits for single phase equipment have been aligned on those for three phase equipment;

g) the limits for all harmonic orders for R_{sce} = 33 have been aligned on the class B limits of IEC 61000-3-2 at 16 A (see Tables G.4 to G.6).

G.5 Emission limits for R_{sce} greater than 33

G.5.1 Assumptions for the LV-system

a) A transformer feeds into a busbar with n outgoing identical feeders of the same length.

b) The feeders have the same cross section over the total length; the feeder impedance increases linearly with the distance from the busbar.

c) The maximum 3-phase impedance is that at the far end of each feeder. It corresponds to the minimum short circuit ratio $R_{sce,\mathrm{min}}$ = 33. Loads with higher power may not be connected at this “far end” point. The “far end” impedance may be considered as the 3-phase reference impedance: $Z_{\mathrm{ref,3p}}$ = |0,24 + j 0,15| Ω = 0,283 Ω.

d) The “far end” impedance for the harmonic order h is $Z_{\mathrm{max},h}$ =|0,24 + jh 0,15| Ω, e.g. 0,79 Ω for h = 5.

e) The harmonic impedance at the busbar, $Z_{B,h}$, corresponds to h times the transformer short circuit impedance. Example: h = 5, transformer data: $U_{n,Tr}$ = 400 V; $S_{n,Tr}$ = 400 kVA; Z_{Tr} % = 4 %, $Z_{B,h} = Z_{Tr,h} = h\ Z_{Tr}\ U_n^2 / S_{n,Tr}$ = 5 × 0,04 x (400V)²/(400kVA) = 0,08 Ω.

f) The busbar impedance, $Z_{B,h}$, is the fraction x_{min} of the "far end" impedance: $x_{\text{min}} = Z_{B,h} / Z_{\text{max}\,h} \approx 0{,}1$. The same fraction x_{min} is assumed to be valid also for the fundamental, i.e. the busbar impedance corresponds to $R_{sce,\text{max}} = R_{sce,\text{min}} / x_{\text{min}} \approx 330$.

g) The busbar is considered as a node on a fictitious feeder at the distance x_{min} from an ideal source with $Z_{sc} = 0$, see Figure H.1b. The total length of the fictitious feeders is "1". The total length of the real feeders corresponds to $(1 - x_{\text{min}})$ on the fictitious feeder. The node at x_{min} is common for all fictitious feeders and represents the busbar.

h) A disturbing load is connected to one of the fictitious feeders at the point x ($x_{\text{min}} \le x \le 1$) and injects a constant harmonic current I_h at this point.

i) Customers installations are connected in uniform distribution along each feeder.

G.5.2 Description of the physics

The caused harmonic voltage increases linearly from the ideal source ($U_{x=0} = 0$) up to the connection point "x" (U_x) and remains then constant up to the end "1" of the fictitious feeder to which the load is connected, see Figure H.1b. The highest voltage U_{max} is reached if the load is connected at the far end. The voltage at the point "x" is $U_x = x\, U_{\text{max}}$, and the busbar voltage is $U_B = x_{\text{min}}\, U_{\text{max}}$. The busbar voltage is impressed to the remaining (n – 1) feeders and remains constant along these feeders.

G.5.3 Total distorting weight (TDW)

The following equations are used in order to calculate the "total distorting weight (TDW)" of the disturbing load depending on the point "x" where it is connected. The TDW describes the total impact of the disturbing load to all installations in the network. The TDW can be considered as the sum of all "voltage • length" – areas over all feeders in the network, see Figure H.2. Three areas of different shape exist (see Figure H.1b):

– Identical area for each of the n fictive feeders:

  $A_1 = U_B \bullet (1 - x_{\text{min}}) = x_{\text{min}} \bullet U_{\text{max}} \bullet (1 - x_{\text{min}})$

– Area of linear increase from x_{min} to x on the feeder with the load:

  $A_2 = (x - x_{\text{min}}) \bullet U_{\text{max}} \bullet (x - x_{\text{min}}) / 2 = U_{\text{max}} \bullet (x - x_{\text{min}})^2 / 2$

– Area of constant voltage from x to "1" on the feeder with the load:

  $A_3 = (x - x_{\text{min}}) \bullet U_{\text{max}} \bullet (1 - x)$

The TDW as a function of x is given by

$$\text{TDW}(x) = n \bullet A_1 + A_2 + A_3$$

$$= U_{\text{max}} \bullet [n \bullet x_{\text{min}} (1 - x_{\text{min}}) + (x - x_{\text{min}})^2 / 2 + (x - x_{\text{min}}) \bullet (1 - x)]$$

$$= U_{\text{max}} \bullet [n \bullet x_{\text{min}} (1 - x_{\text{min}}) + (x - x_{\text{min}}) \bullet (1 - (x + x_{\text{min}}) / 2)] \qquad (1)$$

The maximum value of $\text{TDW}_{x=1}$ is reached if the load is connected to the far end $x = 1$:

$$\text{TDW}_{x=1} = U_{\text{max}} \bullet [n \bullet x_{\text{min}} (1 - x_{\text{min}}) + (1 - x_{\text{min}})^2 / 2] \qquad (2)$$

The TDW_x at the point x can be related to the maximum $\text{TDW}_{x=1}$ and gives the relative $tdw(x) = \text{TDW}_x / \text{TDW}_{x=1}$:

$$tdw(x) = \frac{n \bullet x_{\min} + \dfrac{x - x_{\min}}{1 - x_{\min}} \bullet (1 - (x + x_{\min})/2)}{n \bullet x_{\min} + \dfrac{1 - x_{\min}}{2}} \qquad (3)$$

The parameter x can be expressed by R_{sce} using the following equation if always the same load at different points x is considered:

$$R_{sce} = 33 / x \tag{4}$$

The relative total distortion weight "*tdw*", depending on the connection point x, is calculated for $x_{\min}$ = 0,1 and n = 3, 4 and 5 feeders in the following Table G.1 and shown in Figure H.2.

Table G.1 – Relative total distortion weight depending on the point x where the distorting load is connected

x	R_{sce}	*tdw*		
		n = 3	n = 4	n = 5
0,1	330	0,400	0,471	0,526
0,2	165	0,526	0,582	0,626
0,3	110	0,637	0,680	0,713
0,5	66	0,815	0,837	0,854
0,7	47	0,933	0,941	0,947
1,0	33	1,000	1,000	1,000
x = 0,1: connection at the busbar; x = 1: connection at the far end of a feeder R_{sce} is valid for the point x n: number of feeders outgoing from the busbar				

G.5.4 Approximation for the relative total distortion weight

The curves in Figure H.2 can be approximated by the function

$$tdw = 1 / (R_{sce} / 33)^{\alpha} \tag{5}$$

The exponent α depends on the number n of the feeders:

α = 0,40 for n = 3

α = 0,33 for n = 4

α = 0,28 for n = 5

G.5.5 Relation between the relative total distortion weight and the limits

The distortion in a total LV system, produced by a load, is proportional to the harmonic current of the load, I_h, and to the relative total distortion weight tdw_x depending on the connection point x. Two loads at different connection points x_1 and x_2 should not exceed the same "total distortion":

$$I_{h,x1} \bullet tdw_1 = I_{h,x2} \bullet tdw_2$$

The equation can be rewritten into:

$$I_{h,x2} / I_{h,x1} = tdw_1 / tdw_2 \tag{6}$$

If $I_{h,x1}$ denotes the harmonic current limit for a load connected to the „far end“ (x_1 = 1 or R_{sce} = 33) then the harmonic current limit for a load connected to a point $x_2 = x < 1$ (or $R_{sce} /x > 33$) is given by:

$$I_{h,\mathrm{lim},x} = (tdw_{x=1} \,/\, tdw_x) \bullet I_{h,\mathrm{lim},x=1} = (1 \,/\, tdw_x) \bullet I_{h,\mathrm{lim},x=1} \qquad (7)$$

Using the approximation (5), the equation (7) can be rewritten into:

$$I_{h,\mathrm{lim},x} = (R_{sce} /33)^{\alpha} \bullet I_{h,\mathrm{lim},x=1} = (R_{sce} /33)^{\alpha} \bullet I_{h,\mathrm{lim,Rsce}} = 33 \qquad (8)$$

Equ. (8) relates the limits of the harmonics, depending on R_{sce}, to the limit value at R_{sce} = 33.

G.5.6 Limits in IEC 61000-3-12, Table 2 depending on R_{sce}

The limits in IEC 61000-3-12 related to single-phase equipment are taken for comparison with Equation (8). Table G.2 contains, as an example, the limits for the orders 5 and 7 and the result of Equation (8) for α = 0,3.

This value α = 0,3 is the average for LV-systems having 4 or 5 main feeders which reflects the reality. Original limits and approximated limits fit well together, see Table G.2.

Table G.2 – Comparison of limit values of IEC 61000-3-12 (columns 2 and 4) with the approximation by equation (8) (columns 3 and 5)

R_{sce}	I_5 Table 2	I_5 Equ.(8) α = 0,3	I_7 Table 3	I_7 Equ.(8) α = 0,3
33	10,7	10,7	7,2	7,2
66	13	13,2	8	8,9
120	15	15,8	10	10,6
250	20	19,6	13	13,2
350	24	21,7	15	14,6

The higher exponent α for higher harmonic orders takes the phase angle diversity between different loads into account; the limits for high R_{sce} values increase stronger. This is especially true for balanced three phase equipment where the phase angles normally differ from those of single-phase equipment.

G.5.7 Summary

It is shown that the assumed condition 'equal total distortion weight in a LV-system' leads to a relation between limit values and R_{sce} values which can be found in the existing report IEC 61000-3-4 and IEC 61000-3-12.

The limits have been established using the other following assumptions:

a) proportional limits are adopted;

b) higher limits are admissible for three-phase equipment than for single phase equipment (see tables G.4 and G.5), as the network impedance is lower for three phase equipment (Z_L) than for single phase equipment ($Z_L + Z_N$);

c) higher limits are admissible for special types of three-phase equipment (see tables G.5 and G.6), to take into account the compensation effect due to these types of equipment;

d) for simplification, linear functions of R_{sce} with rounded numbers have been adopted.

G.6 Voltage distortion

G.6.1 Voltage distortion produced by one piece of equipment at the PCC level:

In Tables G.4 to G.6, all the harmonic voltages are given, calculated from the formulas given in G.2, for different values of R_{sce}.

For single phase equipment, it is assumed that: $\left|\overline{Z_L} + \overline{Z_N}\right| / Z_L = 5/3$

G.6.2 Voltage distortion produced by *n* pieces of equipment at the LV busbar level (transformer level)

Two cases are considered:

- linear addition of harmonic currents;
- quadratic addition of harmonic currents.

It is assumed that:

- the MV/LV transformer is fully loaded by n identical non-linear loads;
- all non-linear loads comply with emission limits related to the R_{sce} value;
- the short-circuit voltage u_{sc} of the MV/LV transformer is equal to 5 %.

Only the harmonic voltage drop across one phase of the MV/LV transformer is considered here. Harmonic voltage drops due to harmonic currents flowing trough LV feeder impedances are not taken into account.

Notations:

I_1:	fundamental current of one piece of equipment;
I_h:	harmonic current produced by one piece of equipment;
n:	number of pieces of equipment;
S_{equ}:	power of one piece of equipment;
V_{Th}:	harmonic voltage across one phase of the MV/LV transformer;
S_T:	transformer power;
I_T:	nominal transformer phase current;
Z_L:	fundamental impedance of one phase of the transformer;
Z_h:	harmonic impedance of one phase of the transformer.

- Linear addition:

All the harmonic currents are in phase and add linearly.

Then: $V_{Th} = Z_h.(n.I_h) = (h.Z_L).(n.I_h)$

And: $u_{sc} = \dfrac{Z_L.I_T}{V}$ with: $I_T = n.I_1$

So: $u_{sc} = \dfrac{Z_L.n.I_1}{V}$ => $Z_L = u_{sc}.\dfrac{V}{n.I_1}$

$$V_{Th} = h.\left(u_{sc}.\frac{V}{n.I_1}\right).(n.I_h) = h.u_{sc}.V.\frac{I_h}{I_1} \quad => \quad \frac{V_{Th}}{V} = h.u_{sc}.\frac{I_h}{I_1}$$

Using percentages: $v_h(\%) = h.u_{sc}.i_h(\%)$

With u_{sc} = 5 %, the general formula for linear addition is:

$$\boxed{v_h(\%) = 0{,}05.h.i_h(\%)}$$

See Tables G.7 to G.9.

- Quadratic addition:

For n pieces of equipment, the total harmonic current of order h is: $\sqrt{n}.I_h$

Then, $V_{Th} = Z_h.(\sqrt{n}.I_h)$

$$V_{Th} = h.\left(u_{sc}.\frac{V}{n.I_1}\right).(\sqrt{n}.I_h)$$

$$v_h(\%) = \frac{h}{\sqrt{n}}.u_{sc}.i_h(\%)$$

The MV/LV transformer is fully loaded by the non-linear loads, so:

$$n = \frac{S_T}{S_{equ}}$$

$n = \dfrac{S_T}{S_{sc}}.\dfrac{S_{sc}}{S_{equ}} \approx u_{sc}.R_{sce}$ if the short-circuit power is almost similar at the Pcc and at the transformer level.

Then:

$$v_h(\%) = \frac{h}{\sqrt{(u_{sc}.R_{sce})}}.u_{sc}.i_h(\%) = \frac{h.i_h(\%)}{\sqrt{\frac{R_{sce}}{u_{sc}}}}$$

With u_{sc} = 5 %, the general formula for quadratic addition is:

$$\boxed{v_h(\%) = \frac{h}{\sqrt{(20.R_{sce})}}.i_h(\%)}$$

See Tables G.10 to G.12.

G.7 Voltage distortion produced by one piece of equipment at the PCC level

Table G.3 – Compatibility levels

n	**3**	**5**	**7**	**9**	**11**	**13**
Compatibility level (%)	5	6	5	1,5	3,5	3
1/4 of compatibility level (%)	1,25	1,5	1,25	0,375	0,875	0,75

Table G.4 – Maximum harmonic currents and voltages for one piece of single phase equipment (from Table 2 of IEC 61000-3-12)

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33	21,6	10,7	7,2	3,8	3,1	2
66	24	13	8	5	4	3
120	27	15	10	6	5	4
250	35	20	13	9	8	6
350	41	24	15	12	10	8
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33	3,27	2,70	2,55	1,73	1,72	1,31
66	1,82	1,64	1,41	1,14	1,11	0,98
120	1,13	1,04	0,97	0,75	0,76	0,72
250	0,70	0,67	0,61	0,54	0,59	0,52
350	0,59	0,57	0,50	0,51	0,52	0,50

Table G.5 – Maximum harmonic currents and voltages for one piece of balanced three phase equipment (from Table 3 of IEC 61000-3-12)

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
66		14	9		5	3
120		19	12		7	4
250		31	20		12	7
350		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		1,62	1,53		1,03	0,79
66		1,06	0,95		0,83	0,59
120		0,79	0,70		0,64	0,43
250		0,62	0,56		0,53	0,36
350		0,57	0,50		0,47	0,37

Table G.6 – Maximum harmonic currents and voltages for one piece of balanced three phase equipment (from Table 4 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
120		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		1,62	1,53		1,03	0,79
120		1,67	1,46		1,38	1,08

G.8 Voltage distortion produced by *n* pieces of equipment at the LV busbar level (Linear addition)

Table G.7 – Maximum harmonic currents and voltages for *n* pieces of single phase equipment (from Table 2 of IEC 61000-3-12)

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33	21,6	10,7	7,2	3,8	3,1	2
66	24	13	8	5	4	3
120	27	15	10	6	5	4
250	35	20	13	9	8	6
350	41	24	15	12	10	8
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33	3,24	2,68	2,52	1,71	1,71	1,30
66	3,60	3,25	2,80	2,25	2,20	1,95
120	4,05	3,75	3,50	2,70	2,75	2,60
250	5,25	5,00	4,55	4,05	4,40	3,90
350	6,15	6,00	5,25	5,40	5,50	5,20

Table G.8- Maximum harmonic currents and voltages for *n* pieces of balanced three phase equipment (from Table 3 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
66		14	9		5	3
120		19	12		7	4
250		31	20		12	7
350		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		2,68	2,52		1,71	1,30
66		3,50	3,15		2,75	1,95
120		4,75	4,20		3,85	2,60
250		7,75	7,00		6,60	4,55
350		10,00	8,75		8,25	6,50

Table G.9 – Maximum harmonic currents and voltages for *n* pieces of balanced three phase equipment (from Table 4 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
120		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		2,68	2,52		1,71	1,30
120		10,00	8,75		8,25	6,50

G.9 Voltage distortion produced by *n* pieces of equipment at the LV busbar level (Quadratic addition)

Table G.10 – Maximum harmonic currents and voltages for *n* pieces of single phase equipment (from Table 2 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33	21,6	10,7	7,2	3,8	3,1	2
66	24	13	8	5	4	3
120	27	15	10	6	5	4
250	35	20	13	9	8	6
350	41	24	15	12	10	8
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33	2,52	2,08	1,96	1,33	1,33	1,01
66	1,98	1,79	1,54	1,24	1,21	1,07
120	1,65	1,53	1,43	1,10	1,12	1,06
250	1,48	1,41	1,29	1,15	1,24	1,10
350	1,47	1,43	1, 25	1, 29	1, 31	1, 24

Table G.11- Maximum harmonic currents and voltages for *n* pieces of balanced three phase equipment (from Table 3 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
66		14	9		5	3
120		19	12		7	4
250		31	20		12	7
350		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		2,08	1,96		1,33	1,01
66		1,93	1,73		1,51	1,07
120		1,94	1,71		1,57	1,06
250		2,19	1,98		1,87	1,29
350		2,39	2,09		1,97	1,55

Table G.12 – Maximum harmonic currents and voltages for *n* pieces of balanced three phase equipment (from Table 4 of IEC 61000-3-12):

R_{sce}	i_3	i_5	i_7	i_9	i_{11}	i_{13}
33		10,7	7,2		3,1	2
120		40	25		15	10
R_{sce}	v_3	v_5	v_7	v_9	v_{11}	v_{13}
33		2,08	1,96		1,33	1,01
120		4,08	3,57		3,37	2,65

Annex H
(informative)

Explanation of the reasons for using the concepts of total harmonic distortion (THD) and partial weighted harmonic distortion (PWHD)

Two main impacts of harmonics on the supply system should be considered:

a) Harmonic currents produce additional ohmic losses e.g. in lines, cables and in the windings of transformers and generators. The total losses consist of one part due to the fundamental current and another part (the additional losses) due to the harmonic currents:

$$P_{\text{loss}} = R\, I^2 = R\, I_1^2 + R\, \Sigma\, I_h^2 = R\, I_1^2\, (1 + \text{THD}i^2),$$

where R is the resistance of the conductor, I is the total r.m.s. current, I_1 its fundamental component, $\Sigma\, I_h^2$ the harmonic content and THD_i the total harmonic current distortion.

It is obvious that the THD is an appropriate measure in order to evaluate the additional losses due to current harmonics.

b) Harmonic currents injected in a supply system produce harmonic voltages according to

$$U_h = Zh\, I_h,$$

where I_h is the harmonic current of order h and Z_h the system impedance at the frequency of the harmonic order h. For low order harmonics, the impedance may be approximated by $Z_h = h\, Z_1$, but for higher orders the impedance may increase less than linearly with the harmonic order. An approximation by $Z_h \sim \sqrt{h}\, Z_1$ is more realistic (see Note).

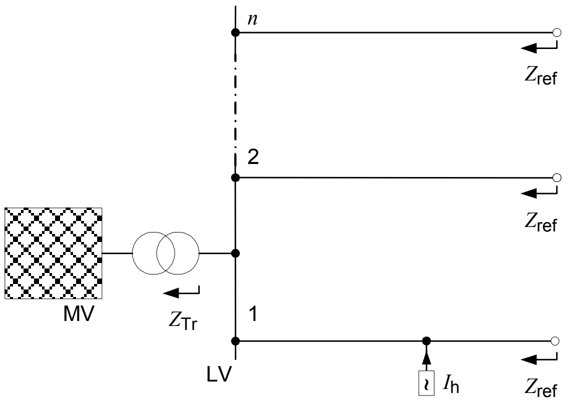
The comparison of each individual voltage harmonic U_h with the relevant compatibility or planning level may be replaced for high order harmonics by comparing only a global value with the relevant levels. Such a global value may be the partial harmonic distortion of the voltage, PHD_u, for high order ($h \geq h_{\text{min}}$) voltage harmonics

$$\text{PHD}_u = [\Sigma\, (U_h/U_1)\,^2]^{1/2} \sim [\Sigma\, (Zh/Z_1 \cdot I_h/I_1)^2]^{1/2} \sim [\Sigma\, h\, (I_h/I_1)^2]^{1/2} = \text{PWHD}_i \text{ for } h \geq h_{\text{min}},$$

NOTE The harmonic order h is thus not squared in the third summation.

where PWHD_i is the partial weighted harmonic distortion of the current.

The factor PWHD_i takes the realistic frequency dependent system impedance characteristic into account and reduces considerably the necessary effort to compare measured values with limits.



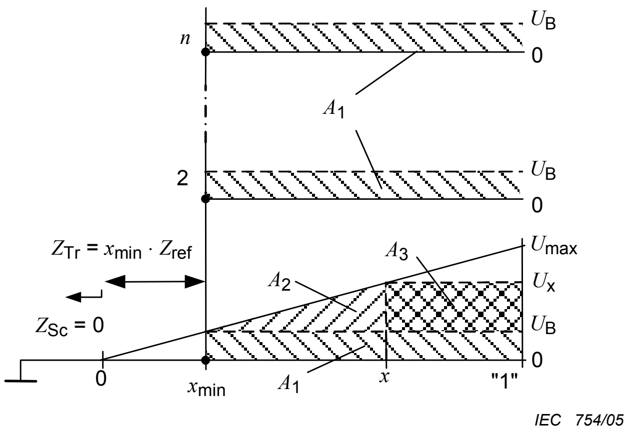


Figure H.1a – Diagram of a LV system consisting of a transformer, a busbar and *n* equal feeders

Figure H.1b – Equivalent circuit for the LV system with "fictitious" feeders

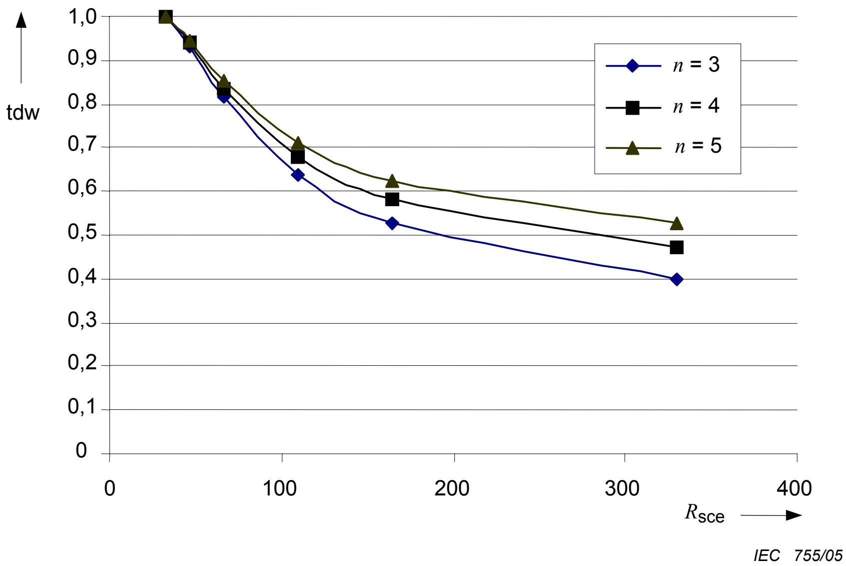


Figure H.2 – Relative total distortion weight "tdw" as a function of the short-circuit ratio R_{sce}

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