Implementation of IEC 1000-2-6:1995

Electromagnetic compatibility (EMC) —

Part 2: Environment —

Section 6: Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances

ICS 29.020

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee GEL/210, Electromagnetic compatibility, upon which the following bodies were represented:

Association of Control Manufacturers [TACMA (BEAMA Ltd.)]
Association of Consulting Engineers
Association of Manufacturers of Domestic Electrical Appliances
Association of Manufacturers of Power Generating Systems
BEAMA Ltd.
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The following bodies were also represented in the drafting of the standard through subcommittee GEL/210/8, EMC — Low frequency disturbances.

Electrical Contractors' Association
Heating, Ventilating and Air Conditioning Association
British Radio and Electronic Equipment Manufacturers' Association

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Contents

National foreword

This British Standard reproduces verbatim IEC 1000-2-6:1995 and implements it as the UK national standard.

This British Standard is published under the direction of the Electrotechnical Sector Board whose Technical Committee GEL/210 has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international committee any enquiries on interpretation, or proposals for change, and keep UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

NOTE International and European Standards, as well as overseas standards, are available from Customer Services, BSI, 389 Chiswick High Road, London W4 4AL.

Cross-references

Publication referred to	**Corresponding British Standard**
IEC 50(161):1990	BS 4727 *Glossary of electrotechnical, power, telecommunications, electronics, lighting and colour terms* Part 1 *Terms common to power, telecommunications and electronics* Group 09:1991: *Electromagnetic compatibilty*
IEC 146:1991	BS EN 60146 *Semiconductor converters. General requirements and line commutated converters* Part 1.1:1993 *Specifications of basic requirements* Part 1.3:1993 *Transformers and reactors*
IEC 1000-3-3:1994	BS EN 61000 *Electromagnetic compatibility (EMC)* Part 3 *Limits* Section 3:1995 *Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current less than or equal to 16 A*
IEC 1000-3-5:1994	BS IEC 1000 *Electromagnetic compatibility (EMC)* Part 3 *Limits* Section 5:1994 *Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 16 A*

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the IEC title page, pages ii to vi, pages 1 to 50, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

RAPPORT TECHNIQUE
TECHNICAL REPORT

CEI
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1000-2-6

Première édition
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Compatibilité électromagnétique (CEM) –

Partie 2:
Environnement –
Section 6: Evaluation des niveaux d'émission dans l'alimentation des centrales industrielles tenant compte des perturbations conduites à basse fréquence

Electromagnetic compatibility (EMC) –

Part 2:
Environment –
Section 6: Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances

IEC

Numéro de référence
Reference number
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Contents

Foreword

1) The IEC (International Electrotechnical Commission) is a world-wide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. 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. The IEC collaborates closely with the International Standardization Organization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of the IEC on technical matters, prepared by technical committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subject dealt with.

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- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 1000-2-6, which is a technical report of type 3, has been prepared by subcommittee 77A: Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

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

Committee draft	Survey of comments	Report on voting
77A(Secretariat)94	77A(Secretariat)103	77A/130

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

Annex A, Annex B, Annex C, Annex D and Annex E are for information only.

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Introduction

IEC 1000 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 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 9: Miscellaneous

Each part is further subdivided into sections which are to be published either as International Standards, or as Technical Reports.

These standards and reports will be published in chronological order and numbered accordingly.

This section is a technical report.

1 Scope

This technical report recommends the procedures to assess the disturbance levels produced by the emission of the devices, equipment and systems installed in non-public networks in industrial environment as far as the low-frequency conducted disturbances in the power supply are concerned; on this basis, the relevant emission limits can be derived. It applies to low and medium voltage a.c. non-public supply at 50/60 Hz. Networks for ships, aircraft, off-shore platforms, and railways are out of the scope of this report.

This technical report deals with the low-frequency conducted disturbances emitted by equipment connected to the power supply. The disturbances considered are:

- harmonics and interharmonics;
- unbalances;
- voltage changes;
- voltage dips.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this technical report. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this technical report are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEV 50(161):1990, *International Electrotechnical Vocabulary (IEV) — Chapter 161: Electromagnetic compatibility.*

IEC 146, *Semiconductor convertors.*

IEC 1000-3-3:1994, *Electromagnetic compatibility (EMC) — Part 3: Limits — Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current^{2} 16 A.*

IEC 1000-3-5:1994, *Electromagnetic compatibility (EMC) — Part 3: Limits — Section 5: Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 16 A.*

3 General

To achieve electromagnetic compatibility, the total disturbance level at the different points of coupling should be limited; this implies a control of the emission of the disturbing loads connected to the power supply.

As far as the LV public networks are concerned, the control of the disturbance level is obtained by means of a strict limitation of the emission of equipment absorbing up to 16 A to be installed in the networks. These limitations are fixed on the basis of statistical consideration on:

- wide diffusion of the equipment in the network;
- type of utilization (simultaneity effect);
- characteristics of the network.

Any equipment absorbing up to 16 A can be connected, provided it satisfies the emission limits given by the relevant standard.

This approach reflects the fact that in the public network, a strict co-ordination between different users and utility is not possible.

As regards the industrial plants and non-public networks, the compliance of compatibility levels must be achieved in different locations:

A. **At the Point of Common Coupling (PCC) to the public network.** The total emission of the plant into the public networks is subject to relevant limitation on the basis of the utility's requirements, and on the network conditions of the power supply.

B. **At the Internal Point(s) of Coupling (IPC).** The total disturbance level as produced by the emission of the inplant equipment and the disturbance level of the incoming supply is to be limited to the selected compatibility levels at the concerned IPCs.

Compliance with the above stated requirements can be achieved by imposing limitations on the emission of single pieces of equipment, taking into consideration the following:

- the actual impedance of the network where the equipment is to be connected;
- the mix of equipment actually present in the plant;
- the actual utilization of the equipment in relation to the organization of the production process;
- the possible control and mitigation of the disturbances obtained by provisions such as filtering or compensating devices, distribution of the loads on different supplies, segregation of disturbing loads.

This approach reflects the fact that in the industrial plant, the co-ordination of the disturbing loads, both at the design and at the operation stage, is possible.

To achieve an overall economy, the following facts for the limitation of the emission of each piece of equipment are important:

- the actual emission of a piece of equipment can be largely dependent on the characteristics of the supply network;
- low power equipment, even if incompatible as far as the emission levels are concerned with the standards of public network, can have globally a negligible impact in industrial plants in the presence of heavily disturbing equipment;
- the pattern of summation of the disturbance caused by various sources depends widely both on the design of the equipment, and on the industrial process involved;
- the user can, to a certain extent, select the applicable electromagnetic compatibility levels at the IPC. In fact, this choice is a trade-off between the costs to limit the level of the emission, and the costs to reduce the level of the disturbance by mitigation, or to increase the immunity.

4 Co-ordination of the emission limits with the compatibility levels

The allowable emission limit of an equipment can be stated through a three steps procedure:

a) Information between utility and user, and between user and manufacturer.

The utility is asked to provide the user with the minimum information following:

- the total emission limit applicable to the plant;
- the expected present and future disturbance level at the PCC, neglecting the disturbance produced by the plant under consideration;
- the range of values of the source impedance at the point of coupling as necessary for the disturbance evaluation; this range is related both to the network configuration and to the frequency characteristics.

The user is asked to provide the utility with information regarding:

- the characteristics of the equipment to be installed, and its mode of operation;
- the characteristics of power factor compensation devices;
- the characteristics of possible filters for harmonic current compensation.

The user is asked to provide the manufacturer with the minimum information following:

- the plan of the installation, and the characteristics of the connected equipment;
- emission levels of the other equipment in the installation, and the disturbance conducted by the supply network;
- characteristics of the process.

The manufacturer is asked to provide the user the minimum information following:

- expected emission levels of the concerned equipment or system in the specified operating conditions;
- the sensitivity of the emission levels to changes such as the supply impedance, the operating voltage, and so on.

b) Selection of the proper summation rule to account for the presence in the plant of various disturbance sources.

c) Evaluation of the expected total emission level of the plant at the PCC, and evaluation of the expected total disturbance level at the IPCs.

If either the total emission of the installation, or the expected disturbance level, exceed the relevant compatibility level, taking into account also the future network development, and the possible increase of the number of the disturbance sources in the plant, the following provisions should be considered:

- modification to the network configuration;
- changing the characteristics of the disturbing equipment;
- applying filters or compensating devices;
- tolerating the resulting disturbance and increasing the immunity levels of the involved equipment (this provision does not apply to PCC but to IPCs only).

The process is repeated until all the requirements are satisfied.

5 Definitions

All terms are according to IEV 161, to IEC 146 and to IEC 1000-3.

6 Survey of conducted emission of industrial equipment

Table 1 presents a survey on the sources of low-frequency conducted emission and their effects on the mains.

Table 1 — Sources of low-frequency conducted disturbances

Classification	Examples	Produced disturbance
Non-linear characteristics	Saturable magnetic devices, gas-discharge lamps	Harmonics
	Arc furnace, a.c. arc welders	Harmonics, interharmonics, voltage changes, unbalance
	Switching-on transformers	Harmonics, voltage dips
Electronically switched load	Convertors, a.c. controllers	Harmonics, Interharmonics, voltage changes, unbalance
	Multicycle control devices	
Switched load	Switching-on capacitors, filters, and induction motors	Interharmonics, voltage dips

7 Harmonics

7.1 Description of the disturbing phenomena and sources

The harmonic components in the line current are mainly generated in the ways described in the following subclauses; additional load characteristics are presented in Annex A.

7.1.1 ***Switching the line current with line frequency or its multiple by means of electronic switches such as in semiconductor convertors***

This function may be either controlled, as by thyristors, or uncontrolled as by diodes. The function in most cases is obtained by switching a series connection of impedance and voltage sources periodically either on and off, or from phase to phase. In principle, three characteristics for harmonic generation in convertors may be found:

a) The load is periodically switched on and off, for example an a.c. controller switches its load on at discrete phase angles, and switches off when the current drops to zero. Figure 1 a) shows the schematic arrangement. Amplitude and phase angle of the harmonic current depends on the angle at which the line voltage is connected to the load, the difference between line and load voltage, and the resulting series connection of load and line impedance.

Typical applications are:

- conductive heating, welding, melting;
- high-voltage d.c. supply for electrostatic precipitators or transmitter valves;
- high-current d.c. supply for galvanizing or metal pickling;
- static VAR compensator;
- a.c. motor starter.

b) An impressed current is cyclically switched from phase to phase (high d.c. inductance).

Figure 1 b) shows the schematic arrangement.

Typical devices in this category are:

- convertor feeding d.c. load (such as d.c. drive; d.c. supply for traction, for electro-chemical and electro-thermal processes; d.c. excitation for machines or magnet coils; d.c. welding convertor);
- convertor with direct current link (such as a.c. drive with current source inverter (CSI) or sub-synchronous convertor cascade; d.c. supply for medium-frequency convertor feeding metal glowing or induction furnace);
- bi-directional convertor, cycloconvertor (such as a.c. drive, low frequency supply for electrothermal melting and refining) as shown in Figure A.7 of Annex A.

c) A d.c. voltage is periodically switched on and off into the line via impedances. A convertor connected to a three-phase line switches the d.c. side at discrete phase angles from phase to phase with low d.c. inductance. Figure 1 b) shows an equivalent circuit. The harmonic current generation corresponds to that of the a.c. controller. Here the current drop to zero is either initiated at the latest by closing the switch of the following phase, or occurs previously in cases of low current or low d.c. inductance, because of current dropping voltage polarity.

Typical devices in this category are:

- convertor with direct voltage link (such as a.c. drive with voltage source inverter (VSI); uninterruptable power supply (UPS); d.c. voltage supply for resonant convertor applied to metal heating or soldering);
- self-commutated convertor (convertor type for drives and compensators that do not require reactive power or compensation for it).

7.1.2 ***Non-linear impedances such as current dependant resistances***

[see Figure 1 c)]

Typical devices in this category are:

- arc furnace (a.c. arc for melting and refining metal);
- a.c. welding machine (welding arc supplied via high-reactance transformer);
- fluorescent lamp, gas discharge lamp in mass applications for illumination.

7.1.3 ***Switching on saturable inductance (for example switching on induction motor or transformer)***

The magnetic saturation may produce transient current components. Switching on a resonant circuit with inductance and capacitance oscillating transiently to the mains (for example when switching on filter or capacitor, a transient oscillations is produced between filter capacitance and inductances of filter and line).

Figure 1 c) shows the equivalent circuit.

7.2 Typical emission data

A range of typical emission data is presented in Annex A for the most common loads generating harmonic line currents. They are given for guidance purpose only. Reliable data for the disturbance evaluation should be obtained by the manufacturer on the basis of the actual design parameters, and by his experience with similar equipment.

7.3 Influence of operating and installation conditions on emission

For the resulting emission of several loads (such as convertors), the amount and the phase angle of the harmonic current is to be estimated. The connection of the convertors and transformers (if any), as well as simultaneous and homogeneous load condition for the convertors, or their operation at random, have to be taken into consideration; this problem is dealt with in **6.4**.

The disturbance in the supply system may be defined by the presence of harmonic components in the line voltage, resulting from voltage drops of the harmonic currents across the line impedance. This line impedance is determined by the parallel and series connection of all impedances to the superimposed high voltage grid, and to all loads, compensating and filter components, considering the values which apply to the respective frequencies (see Figure 2a). Therefore, possible resonances must be identified and taken into consideration. Further information is given in Annex B.

7.4 Summation of harmonics

When several devices producing harmonic currents are present in the same plant, the harmonic currents in the lines, and the harmonic voltage at the point of concern (IPC or PCC) depends on the superposition effect caused by the different amplitudes and phase angles of the currents emitted from different sources.

An exact calculation of the resulting harmonic voltage (vectorial sum) is restricted to a few special cases. Taking the algebraic sum of the contributions by each harmonic source may represent the worst case, but this method often leads to unrealisticly high values, especially at high harmonic orders.

An approximate evaluation is sufficient in most of the cases. Several methods exist for the approximate evaluation of the resulting harmonics; see [4], [5] and [6] in Annex E for the relevant literature.

7.4.1 *Harmonic voltage at the point of concern*

The harmonic voltage $\underline{U}_h$ of order h at the point of concern (IPC or PCC) results from the equation (see Figure 2b):

$$\underline{U}_h = \underline{U}_{ho} + \Sigma\, \underline{U}_{hi} \qquad (1)$$

where

$\underline{U}_{ho}$ is the harmonic voltage of order h of the supply network not considering the effect of the sources of concern (background disturbance);

$\underline{U}_{hi}$ is the harmonic voltage of order h produced by the injection of the source i.

Assuming that all the transfer impedances between the point of connection of the disturbing sources and the point of concern are equal for all the disturbing sources (see Figure 2b); $\underline{U}_h$ results from:

$$\underline{U}_h = \underline{U}_{ho} + \underline{Z}_h\, \Sigma\, \underline{I}_{hi} \qquad (2)$$

where

$\underline{Z}_h$ is the equivalent harmonic impedance as seen from the point of concern.

7.4.2 *Summation of harmonic voltages*

7.4.2.1 *Principles of the evaluation*

The summation problem arises when studying the connection of a new industrial load producing harmonics, because the emission levels which may be allowed are a consequence of the pattern, the harmonics will add up to the ones generated by other existing and future loads. The lack of information, and the inherent variability concerning all the individual loads which generate harmonics, leads to the necessity of using a statistical approach for the evaluation of the resulting harmonic vectors. In such an approach, each harmonic source is represented by a randomly time-varying vector. Both magnitude and phase angle of these vectors are modelled by means of distribution laws.

In order to obtain a simple rule for practical applications, the diversity factor K is adopted:

$$K = \frac{\left| \Sigma\, \underline{U}_{hi} \right|}{\Sigma \left| \underline{U}_{hi} \right|} \qquad (3)$$

K is defined as the ratio between the vectorial sum (actual or expected) and the arithmetic sum of the individual contribution of all harmonic sources. This contribution is caused by the emission relevant to the design operational characteristic of the equipment concerned.

With the aid of the diversity factor K, the total disturbance $\underline{U}_h$ can be evaluated as:

$$|\underline{U}_h| \approx |\underline{U}_{ho}| + K\, \Sigma\, |\underline{U}_{hi}| \qquad (4)$$

The value of the diversity factor is influenced, among others, by:

— type of disturbing load, for example in the case of convertors
- controlled or uncontrolled convertor;,
- inductive or capacitive smoothing;
- type of load (ohmic, inductive, motor);
- number of convertors operating simultaneously;

— the kind of operation of the various disturbance sources (co-ordinate duty cycles, or independently from each other);

— variability of the load;

— harmonic order under consideration.

7.4.2.2 *Practical application of the evaluation*

Two methods for evaluating the diversity factor K are proposed, depending on the knowledge of the harmonic contribution of all devices in the industrial network, and the required accuracy of the resulting harmonic voltage at the point of concern. In particular, method 1 refers to special groups of equipment, while method 2 refers to overall statistical considerations.

Method 1

This method gives applicable diversity factors. It holds good for a first approximation, or for resulting harmonic voltages at the point of concern, with a considerable safety margin in relation to the compatibility level. It applies to low order harmonics $h \leq 7$.

The diversity factor K is obtained by the following:

$$K = \frac{\sum K_i |U_{hi}|}{\sum |U_{hi}|} \tag{5}$$

Several different K_i may be applicable in one plant.

Based on [13] of Annex E, the diversity factors K_i for individual loads and for different harmonic orders are given in Table 2.

Table 2 — Diversity factor K_i for various values *x* and harmonic orders, *x* being the ratio between the load of the device being considered and the total disturbing load of the plant

h	3	5	7	11	13	> 15
$x < 0,05$	0,6	0,5	0,3	0,2	0,2	0,1
$x = 0,1$	0,7	0,7	0,6	0,4	0,4	0,3
$x = 0,2$	0,9	0,8	0,7	0,6	0,6	0,5
$x > 0,5$	1,0	1,0	1,0	1,0	1,0	1,0

NOTE If the multi-unit installation is made up of several uncontrolled rectifier convertors, $K_i = 0,9$.
In addition, if the uncontrolled rectifiers have the same load cycle, $K_i = 1,0$.

The diversity factors in the table take into consideration the increasing variation of the phase angle $\Delta\phi$ towards higher harmonics (see figures relevant to method 2).

Method 2

This method is based on a statistical approach, considering that the compatibility level has to be met with a probability of 95 % or better.

A certain knowledge concerning the variation of magnitude and phase angle of the individual harmonic contributions is required:

$$K = \frac{S\left(\underline{U}_{hi}(p)\right)}{\sum\left|\underline{U}_{hi}\right|} \tag{6}$$

where

S ($\underline{U}_{hi}$ (P)) is the statistical sum vector having 95 % probability of not being exceeded.

Diversity factors K depending on the variation of magnitude and phase angle of the harmonic voltages and the number of sources N are obtained following the approach [4] of Annex E:

$$K \sum \left| \underline{U}_{hi} \right| = b \left(\sum \left| \underline{U}_{hi} \right|^{a} \right)^{1/a} \tag{7}$$

Typical relevant values for a and b are shown in the following Table 3; they are applicable to values having 95 % probability of not being exceeded:

Table 3 — Values a and b applicable to uniform statistical distribution of amplitudes and phase angles. Maximum amplitudes are all equal

Range of distribution of phase angle	Range of distribution of the amplitude	N = 2		N > 2	
$\Delta\phi$	$\Delta U/U_{max}$	b	a	b	a
0 – 360	0 – 1	1,0	2,0	1,0	2,0
	0,5 – 1	1,3	2,0	1,3	2,0
	1	1,0	1,0	1,7	2,0
0 – 270	0 – 1	0,9	1,6	0,9	1,6
	0,5 – 1	1,0	1,4	1,0	1,4
	1	1,0	1,0	1,3	1,4
0 – 180	0 – 1	0,8	1,3	0,8	1,3
	0,5 – 1	0,9	1,2	0,9	1,2
	1	1,0	1,0	1,2	1,2
0 – 90	0 – 1	0,9	1,2	0,9	1,2
	0,5 – 1	0,9	1.1	0,9	1,1
	1	1,0	1,0	1,0	1,0

NOTE The equation given above can only be used when no harmonic source provides more than 50 % of the algebraic sum of the harmonic voltage being considered. Otherwise refer to method 1.

Generally, the following applies:

- harmonic orders 3, 5 and 7 phase angle up to 90°
- harmonic orders 11 and 13 phase angle up to 270°
- harmonic orders above 13 phase angle up to 360°

For vectors with different maximum magnitudes, the factors can be used with sufficient accuracy. If the result exceeds the arithmetic sum, then the arithmetic sum will be used instead. In special cases, when the result may be lower than the greatest individual components, then the latter applies.

If in an installation some convertors are connected via phase-shifting transformers (Y/D group), and some others via non-phase-shifting transformers (Y/Y or D/D groups); the 5th and 7th harmonic currents generated tend to cancel, provided that the convertors are operated in similar conditions.

8 Interharmonics

8.1 Sources of interharmonic currents and voltages

The large majority of the interharmonic voltages and currents on the power supply are generated by static frequency convertors. Rotating machines without convertors may also generate interharmonic voltages; but, in relation to convertor borne interharmonics, their magnitude is very small, and for to this reason they are neglected here. Intended injection of interharmonic voltages into the mains, for example for ripple control, is not discussed here, since the emission is known perfectly.

The mechanism of the generation of interharmonic frequencies is dependent on the type of the convertor. Table 4 gives an overview of common applications of static frequency convertors acting as sources of interharmonics.

Table 4 — Overview of interharmonic current generation by convertors

Convertor arrangement		Typical applications
Supply side	**Load side**	
Line-commutated convertor and d.c. link	Line commutated inverter	Variable speed drive, power exchange between networks, sub-synchronous cascade
	Self-commutated inverter	Variable speed drives, UPS
	Resonant inverter	Induction heating
Self-commutated convertor and d.c. link		Variable speed drive
		Energy storage
Direct convertors (cycloconvertors)		Frequency conversion for traction and for electro-thermal processes, over-synchronous cascade, variable speed drive at low rotation speed

AC arc furnaces also are sources of interharmonics. In addition, any convertor or nonlinear device in non-stationary operating conditions can generate interharmonic currents.

8.2 Interharmonic line currents of indirect convertors

The indirect convertors are composed of a line-commutated convertor at the a.c. supply connected via a d.c. link to a second convertor, either motor — or resonance —, or self-commutated.

The following frequencies are present in the ripple current of the d.c. link:

$$f_{\mathrm{Ih}} = \mathrm{n}\, p_{\mathrm{L}}\, f_L \quad \text{and} \quad f_{\mathrm{Ih}} = k\, p_{\mathrm{A}}\, f_{\mathrm{A}} \qquad (8)$$

where

f_{Ih} is the frequency of the harmonic component in the current of the intermediate link (Hz)

p_{L} is the pulse number of the convertor at the a.c. supply

f_{L} is the line frequency (Hz)

n, k is the integer 0, 1, 2, 3, ...

p_A is the pulse-number of load side inverter

f_A is the load frequency (Hz); when the load is a motor, this frequency is related to the actual motor speed

In steady state, the following frequencies in the line-current are found:

$$f_{\mathrm{hh}} = f_{\mathrm{L}}\,(1 \pm \mathrm{n}\, p_{\mathrm{L}}) \pm k\, p_{\mathrm{A}}\, f_{\mathrm{A}} \qquad (9)$$

where

f_{hh} is the line current frequency components (Hz)

When $k = 0$ (corresponding to the d.c. component in the d.c. link current), the formula gives the characteristic harmonic in the line current. With k not equal to 0, the formula gives the interharmonic frequencies.

The interharmonic frequencies with highest amplitude are:

$$f_{mh} = (f_L \pm p_A f_A) \quad (10)$$

Figure 3 a) and Figure 3 b) give an overview of the frequency components. The number beneath the frequency traces is the factor G, that is the ratio between the line current and the corresponding link-current for each individual harmonic component.

Annex C gives the formulae to be applied in first approximation for the interharmonic current, and also an example of the application of Figure 3 b).

The manufacturer can provide more specific information.

8.3 Interharmonic current generated by direct convertors

Direct convertors are frequency changers with no intermediate link and no energy storage device. They convert the line frequency into a range from zero (d.c.) and up to about 40 % of the line frequency.

Three-phase to three-phase convertors, called cycloconvertors, control both the frequency and the voltage amplitude. Their main application is the speed control of large three-phase rotating machines, either by handling the total energy transfer, or by handling the transfer of the slip energy of the drive. In the second case, the convertor is connected to the induction motor via slip rings, the speed control is limited to narrow range close to the synchronous speed (cycloconvertor cascade).

The direct conversion from three-phase to single-phase is used in typical applications such as links between a public power supply and a single-phase railway supply, or as a.c. supply of some metallurgical processes which need very low frequencies. The spectrum of the supply current is dominated by the characteristic harmonics:

$$f_{ch} = (1 \pm n\, p_L)\, f_L \quad (11)$$

Moreover side band frequencies exist.

They are given by:

$f_{hh} = f_{ch} \pm 2k\, f_A$ in the case of single phase load (see Figure 4);

$f_{hh} = f_{ch} \pm 6k\, f_A$ in the case of three-phase load (cycloconvertors, see Figure 4);

f_{ch} characteristic frequencies according to the number of pulses of the supply convertor;

f_A output frequency of the cycloconvertor.

Figure 4, Figure 5 and Figure 6 show the influence of different load parameters such as:

— low and high load frequency;

— 6 and 12 pulse arrangement.

The amplitude of interharmonic current is largely dependent on:

— load current;

— load power factor;

— motor voltage (dependent on actual speed);

— convertor control philosophy, for example sine control, trapezoid control, etc.

8.4 Subsynchronous cascade

This kind of slip control, by a simple indirect convertor, is used for speed adjustment of induction motors in the medium power range, and within a speed range approximately from 60 % up to nearly the full synchronous speed. The rotor windings transfer energy (via a rectifier, a d.c. link, and an inverter) back to the a.c. supply. The harmonic currents generated by the rectifier and by the inverter, flow into the supply network. In addition, the harmonic currents generated from the rectifiers on the rotor side are transformed in frequency, by reason of the rotation of the winding.

Figure 7 shows the generated frequencies f_{hh} in the line current as function of speed.

The following equations hold:

$f_{hh} = (1 \pm k\ s\ p_r)\ f_L$ stator contribution

and

$f_{hh} = (1 \pm n\ p_L \pm s\ p_r)\ f_L$ rotor contribution

$$S = \frac{u_s - u_A}{u_s} \qquad (12)$$

where

p_L is the pulse number of the convertor connected at the a.c. supply;

p_r is the pulse number of rotor-side rectifier $p_r = 6$;

u_s is the synchronous speed;

u_A is the actual speed;

s is the slip-factor.

Figure 8 presents an example of a super- and subsynchronous cascade, where the slip energy is handled by a cycloconvertor.

8.5 Self-commutated convertors on the line side

Interharmonic voltages or currents can be generated if the beat frequency is not an integer multiple of the line frequency.

8.6 Arc furnaces

AC furnaces generate harmonic and interharmonic frequencies. While convertors generate a discrete frequency spectrum, arc furnaces generate a continuous spectrum. In that case, the harmonic spectral density should be considered.

Figure 9 gives an example of it.

8.7 Summation of components of interharmonic frequencies

Only in exceptional cases, and for a short period, interharmonic components have the same frequency; therefore, a summation of interharmonics is only possible in these exceptional cases.

9 Three-phase unbalance

9.1 Description of the disturbing source

9.1.1 *General*

Unbalanced three-phase voltage appears when an unbalanced load is connected to a power system. An unbalanced load takes a current that differs over the three phases in magnitude or phase.

Loads, such as three-phase a.c. motors, generators, and convertors, do not in principle contribute to the unbalance during normal operation. However, a small unbalance may occur, due to imperfect design, but this is normally quite negligible, and not possible to calculate by general rules.

Unbalanced voltages can also be caused by symmetrical currents in a power system with unbalanced line impedances, but this is outside the scope of this report.

In the general case, unbalanced harmonics can appear, but this is not treated here. This part only deals with the unbalance in the fundamental voltages and currents.

9.1.2 ***Examples of unbalanced loads***

All single-phase loads, either connected phase-to-neutral or phase-to-phase, are unbalanced.

Typical instances are:

— heating equipment;

— lighting;

— single-phase convertors and rectifiers;

— a.c. controllers;

— a.c. traction equipment;

— welding machines.

These loads should, as much as possible, be distributed equally over the three phases, to reduce the overall unbalance. Arc furnaces, even if they are three-phase equipment, present large unbalances.

9.2 Characteristics of the emission

9.2.1 ***Symmetrical components***

An unbalanced system can, with the use of symmetrical components, be divided into three components: positive sequence, negative sequence, and zero sequence.

NOTE The zero sequence components are outside the scope of this Report. They do not affect loads connected between phases.

The zero sequence components can exist in the line-to-earth voltages of any system. They can exist in the line currents even if the system has no available neutral point; the current can flow to earth through the line-to-earth capacitance.

9.2.2 ***Assessment of negative sequence currents***

The calculation of the negative sequence current component is equal for all single-phase loads listed above, individually or combined. With the no-load voltage of phase A, as reference direction for all phase angles, the following formulae can be used to determine the resulting negative sequence current, if the magnitude and phase displacement of the individual currents in the three phases, A, B and C, are known.

a) Three-phase loads connected phase-to-neutral

$$\underline{I}_{neg} = \frac{1}{3}\left(\left|I_a\right| \angle\varphi_a + \left|I_b\right| \angle\varphi_b - \frac{2}{3}\pi + \left|I_c\right| \angle\varphi_c + \frac{2}{3}\pi\right) \quad (13)$$

b) Three-phase loads connected phase-to-phase

$$\underline{I}_{neg} = \frac{1}{\sqrt{3}}\left(\left|I_{ab}\right| \angle\varphi_{ab} + \frac{\pi}{6} + \left|I_{bc}\right| \angle\varphi_{bc} - \frac{\pi}{2} + \left|I_{ca}\right| \angle\varphi_{ca} + \frac{5}{6}\pi\right) \quad (14)$$

In the case of a single-phase load connected between two phases:

$$\left|\underline{I}_{neg}\right| = \frac{1}{\sqrt{3}} I_{1\phi} \quad (15)$$

For more details, see Annex D.

9.2.3 ***Assessment of negative sequence voltage***

The contribution to the negative sequence voltage from a load can be calculated as:

$$\underline{U}_{neg} = \underline{I}_{neg}\ \underline{Z}_{neg} \quad (16)$$

The negative sequence impedance, $\underline{Z}_{neg}$, can be taken as equal to the positive sequence impedance of the network; this refers to the subtransient impedances of the rotating machines.

The formula can be transformed to:

$$u_{neg} = \frac{|\underline{I}_{neg}|}{I_{sc}} \tag{17}$$

where

u_{neg} is the relative negative sequence voltage $\underline{U}_{neg}/\underline{U}_{nom}$;

$\underline{I}_{neg}$ is the negative sequence current;

I_{sc} is the three-phase short-circuit current at the IPC.

9.3 Summation of several sources

The negative sequence current resulting from a number of unbalanced loads under steady state operation can be calculated using the formulae given in **6.4**.

If the loads vary, in magnitude or phase, the same rules of statistical summations as were given for harmonics can be used. In fact, the negative sequence component can be regarded as a harmonic component with order number 1. Therefore, if method 1 is used, the approximate values for K are similar to those of order 3 in Table 2.

10 Voltage changes, flicker and voltage dips

10.1 Voltage changes

10.1.1 *General*

Voltage changes are caused by changes in reactive and active current taken by the loads connected to the network, and thus causing a change of voltage drop in the network impedance (see Figure 10).

In certain cases, they may also be caused by changes in the short-circuit power of the network, due to changes in generation, or due to changes in the network configuration. These changes lead to changes in network impedance. They will be neglected in this report and the network impedance will be taken as constant and known.

In general, the voltage remains in a steady state with the mass of existing loads.

The individual changes or emissions are to be limited in such a way that the steady-state operational voltage U_c remains within the agreed-upon voltage band (Figure 11) for proper performance of all the applications connected to the IPC or PCC.

A relatively large dynamic change ΔI causing ΔU_c, due to the connection or disconnection of a relatively large load, or a large change of load impedance, such as with motor starting or arc furnace operation, even within an agreed voltage band, is considered as a disturbing phenomenon.

This relative voltage change is considered in the following.

10.1.2 *Examples of loads causing relatively large voltage changes*

Typical examples are:

— operation of arc furnaces;

— operation of welding machines;

— starting of motors;

— switching of capacitors.

Figure 11 shows how the starting of a motor could change the operational voltage. The starting of several motors may also be represented by the same figure by vectorial sum of the individual starting currents.

10.1.3 ***Assessment of dynamic or relative voltage change due to a single load at the point of coupling***

A simple assessment of the relative voltage change may be made as follows (see Figure 11):

$$\underline{\Delta I} = \Delta I_p - j\,\Delta I_q \quad \text{current change}$$
$$\underline{Z}_L = R_L + j\,X_L \quad \text{network impedance} \qquad (18)$$

For single-phase and symmetrical three-phase loads:.

$$\Delta U_{dyn} \approx \Delta I_p R_L + \Delta I_q X_L \qquad (19)$$

The emission limit at IPC of class 2 requires a limitation of $\underline{U}_{dyn}/\underline{U}_{nom}$ according to the flicker assessment procedure.

The emission limit at IPC of class 3 shall consider the actual voltage:

$$U_o - \Delta\underline{U}_c \pm \Delta U_{dyn} \qquad (20)$$

10.1.4 ***Summation of the voltage fluctuations***

The following rules are applied to class 3 IPCs to consider the presence of various disturbing sources:

- the average active and reactive currents of the fluctuating loads are added algebraically, this provides the equivalent ΔU_c;
- the largest dynamic change provides the value ΔU_{dyn}; in some special case only the coincidence of disturbance is to be considered.

$$\Delta U_c \approx \sum_i \left[I_q X_L\right]_i + \sum_i \left[I_p R_L\right]_i$$
$$(21)$$
$$\Delta U_{dyn} \approx \underset{i}{\mathrm{MAX}} \left(\left|\Delta I_q X_L + \Delta I_p R_L\right|_i\right)$$

10.2 Flicker

10.2.1 ***General***

Flicker is the subjective impression of fluctuating luminance, and is caused by rapidly changing loads from:

— arc furnaces;

— welding machines;

— starting and stopping of motors (if the frequency of relative change of voltage lies between 0,1 and 3 000 changes per minute).

Detailed description of the phenomenon is given in UIE guide [15] cited in Annex E.

10.2.2 ***Assessment of flicker emission***

IEC 1000-3-3 gives methods of assessment by analytical tools, simulation, and direct measurement.

Limits of IEC 1000-3-3 and IEC 1000-3-5 are valid for IPC class 2 and PCC.

As IPC class 3 has generally no lighting load, no flicker assessment is required. When the contrary applies, the flicker assessment is to be made according to the rule of IPC class 2.

10.3 Voltage dips

10.3.1 ***General***

Voltage dip is a sudden reduction of the voltage at a point in the power supply system, followed by a recovery after a short period of time, from half a cycle to a few seconds.

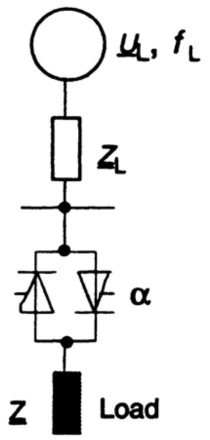
Voltage dips are caused by faults in the network and installations, or by a sudden large change of load.

10.3.2 ***Assessment of the disturbance***

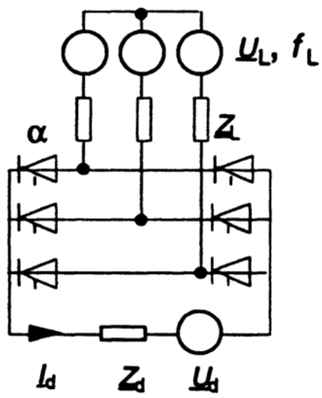
Statistics classified with regard to depth, duration and frequency of occurrence per year for MV public power supply networks are available for Europe. Statistics from industrial systems are not yet available.

On the basis of the above statistics, it will be possible to assess the magnitude of the disturbance in industrial systems.

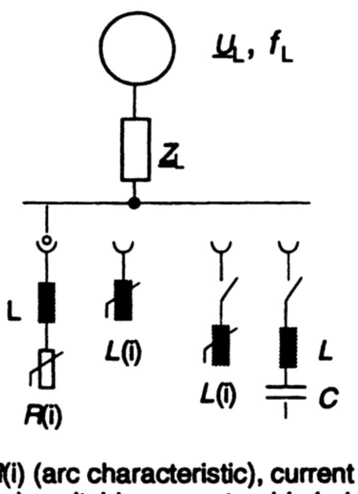
Sudden large changes may be evaluated for any point of coupling as shown in **9.2**.



a) a.c. controller, load periodically switched on and off

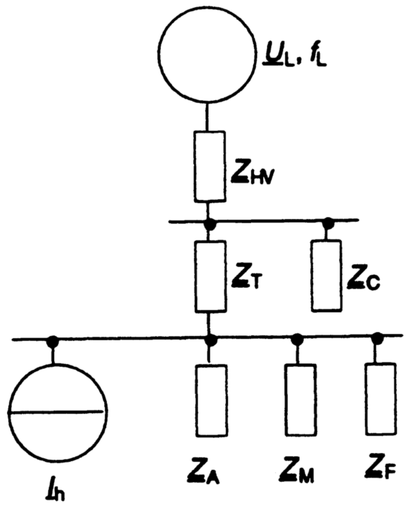


b) Convertor in three-phase bridge connection (B6), d.c. voltage $\underline{U}_d$ and d.c. current $\underline{I}_d$, with impedance $\underline{Z}_d$ cyclically switched from phase-to-phase



c) Current dependent resistance *R*(i) (arc characteristic), current dependent inductance *L*(i) (magnetic saturation), switching on saturable inductance *L*(i)

Figure 1 — Examples of convertors or loads producing harmonic or interharmonic a.c. currents



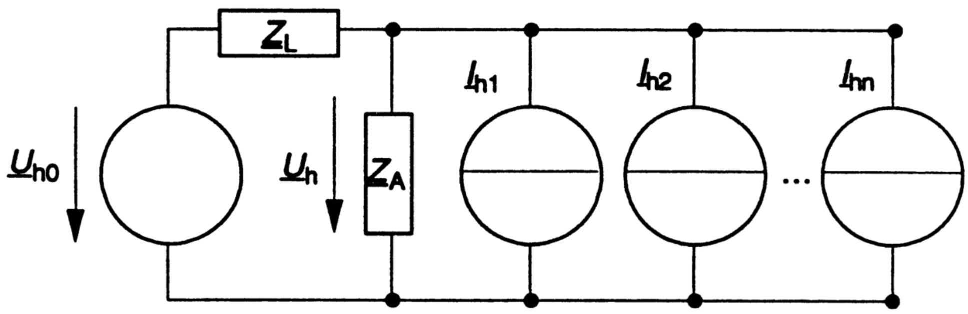
Examples of impedances $\underline{Z}$:

$\underline{Z}_A = R_A + jh\, X_A$	passive load
$\underline{Z}_M = R_M + jh\, X_M$	leakage impedance of an induction machine
$\underline{Z}_F = jh\, X_{LF} - jh^{-1}\, X_{CF}$	reactance of filter
$\underline{Z}_T = R_T + jh\, X_T$	leakage impedance transformer
$\underline{Z}_C = -\, jh^{-1}\, X_C$	cable capacitance
$\underline{Z}_{HV} = jh\, X_{HV}$	reactance of the high voltage grid

Figure 2a — Assessment of the resulting supply side impedance $\underline{Z}_L$ effective for an harmonic source $\underline{I}_h$

$$\underline{Z}_L = \underline{Z}_A \,//\, \underline{Z}_M \,//\, \underline{Z}_F \,//\, (\underline{Z}_T + (\underline{Z}_C \,//\, \underline{Z}_{HV}))$$

With / / for parallel connection; all impedances are referred to one voltage level and depend on the harmonic order h.



$$\underline{U}_h = \frac{\underline{Z}_A}{\underline{Z}_A + \underline{Z}_L}\underline{U}_L + \frac{\underline{Z}_A \cdot \underline{Z}_L}{\underline{Z}_A + \underline{Z}_L}\sum_{i=1}^{n}(\underline{I}_{hi})$$

$$= \underline{U}_{h0} + \underline{Z}_h \sum_{i=1}^{n}(\underline{I}_{hi})$$

$$\approx \underline{U}_{h0} + \underline{Z}_L\, \underline{I}_h$$

$$\text{if } \left|\underline{Z}_A\right| >> \left|\underline{Z}_L\right| \text{ and } \measuredangle\,(\underline{Z}_A, \underline{Z}_L) < 120°$$

Figure 2b — Assessment of the resulting harmonic voltage $\underline{U}_h$ at the inplant point of coupling IPC regarding several harmonic current sources $\underline{I}_{h1}$... $\underline{I}_{hn}$, the harmonic level $\underline{U}_{h0}$ of the supply, the harmonic impedances $\underline{Z}_A$ of the load side, and $\underline{Z}_L$ of the supply side

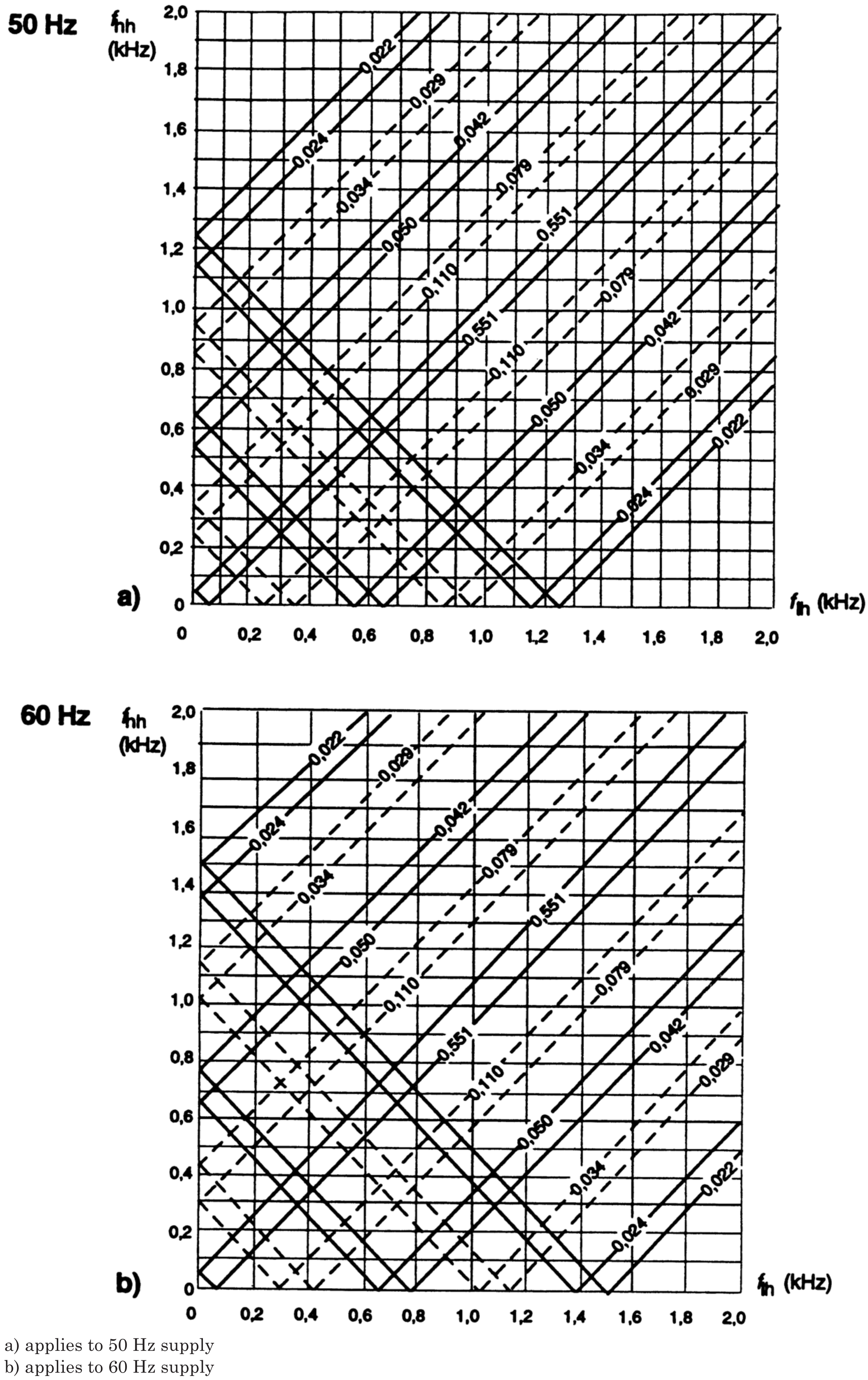


Diagram a) applies to 50 Hz supply
Diagram b) applies to 60 Hz supply
Solid lines apply to 6 pulse convertors
Broken lines apply to 6 and 12 pulse convertors

Figure 3 — Diagrams of the interharmonic frequencies in the line current I_{hh} of the a.c. supply produced by harmonic current I_{Ih} in the d.c. link. The parameter G is the ratio between I_{hh} and I_{Ih}

A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
...			...			...			...			...		
30	*	-	230	*	-	330	*	-	530	*	-	630	*	-
35	*	*	235	*	*	335	*	*	535	*	*	635	*	*
40	*	-	240	*	-	340	*	-	540	*	-	640	*	-
45	*	-	245	*	-	345	*	-	545	*	-	645	*	-
50	*	*	250	*	*	350	*	*	550	*	*	650	*	*
55	*	-	255	*	-	355	*	-	555	*	-	655	*	-
60	*	-	260	*	-	360	*	-	560	*	-	660	*	-
65	*	*	265	*	*	365	*	*	565	*	*	665	*	*
70	*	-	270	*	-	370	*	-	570	*	-	670	*	-
...			...			...			...			...		

A frequency in Hertz

B single-phase load $p_A = 2$

C three-phase load $p_A = 6$

Figure 4 — Interharmonic frequencies generated by a direct convertor $f_L = 50$ Hz, $f_A = 2{,}5$ Hz, $p_L = 6$

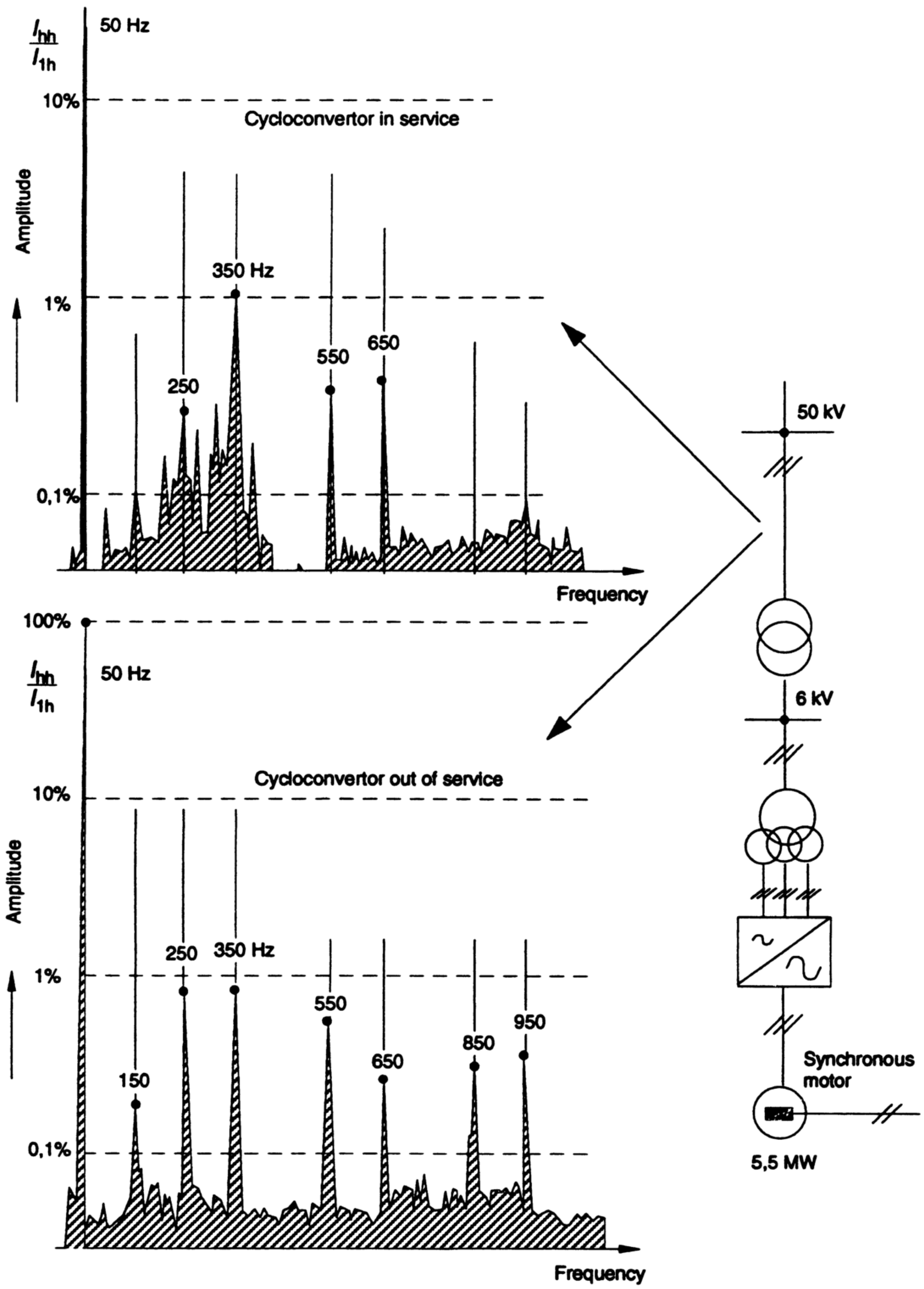


Figure 5 — Measurement of harmonic and interharmonic voltages at the point of common coupling of a 5,5 MW cycloconvertor drive

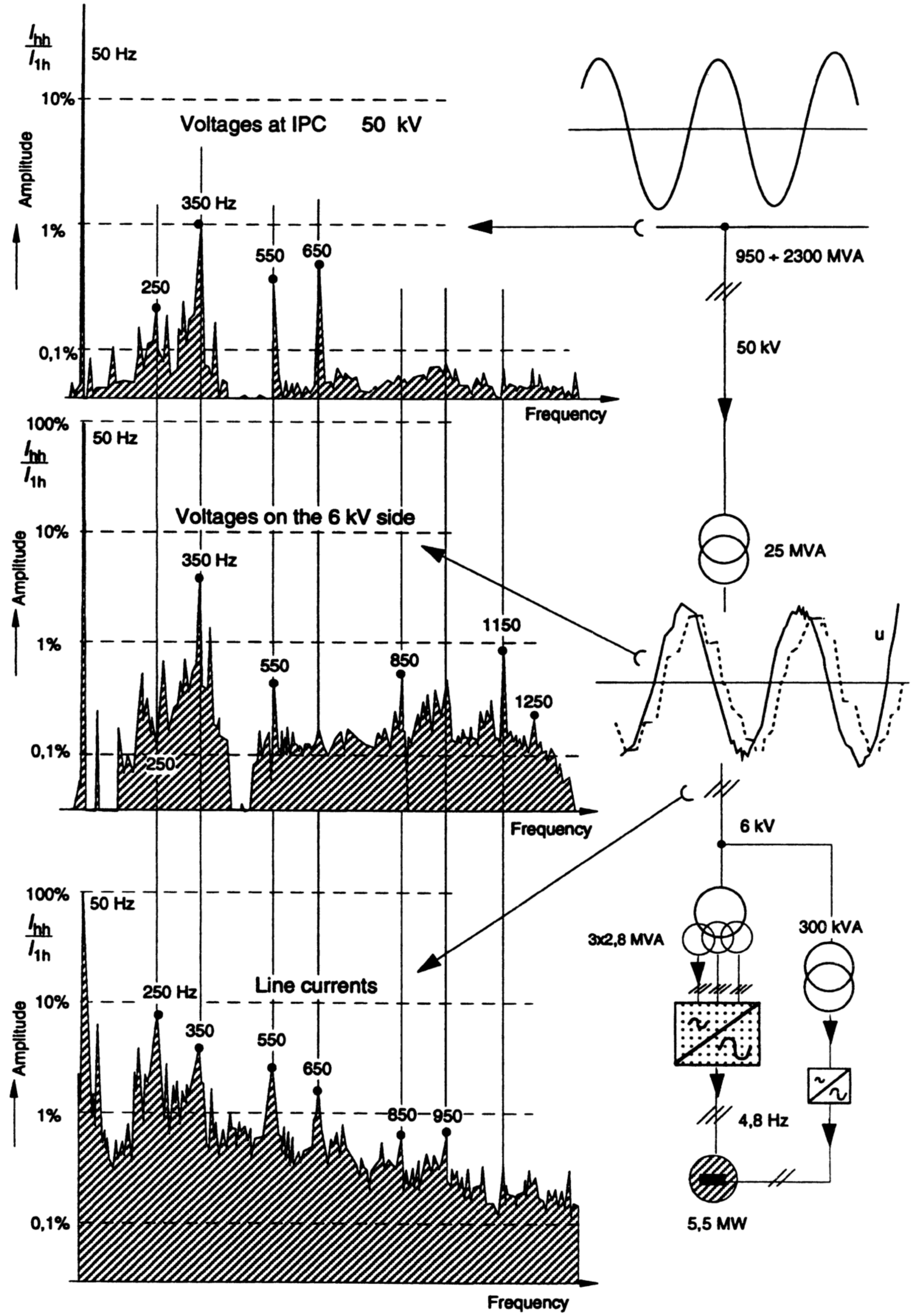
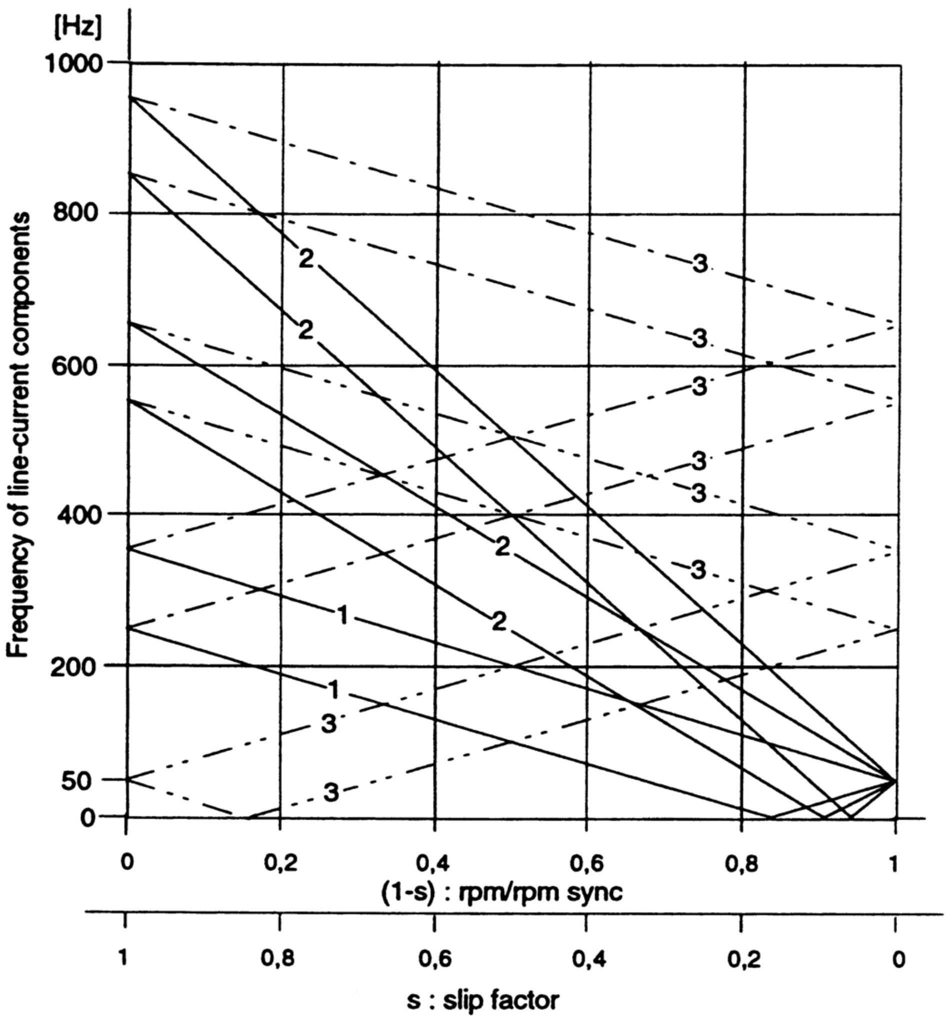


Figure 6 — Measurement of harmonic and interharmonic voltages and currents at the point of common coupling and the 6 kV terminals of the transformer. Same system as in Figure 5

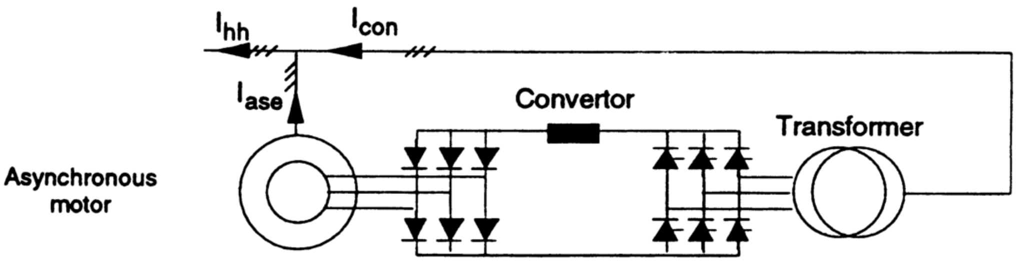


a) Spectral components in the line current as a function of the slip factor s, or of the speed ratio (1-s)

1) Frequency components common to I_{ase} and I_{con}

2) Frequency components of I_{ase} only

3) Frequency components of I_{con} only



b) Schematic diagram

Figure 7 — Subsynchronous cascade

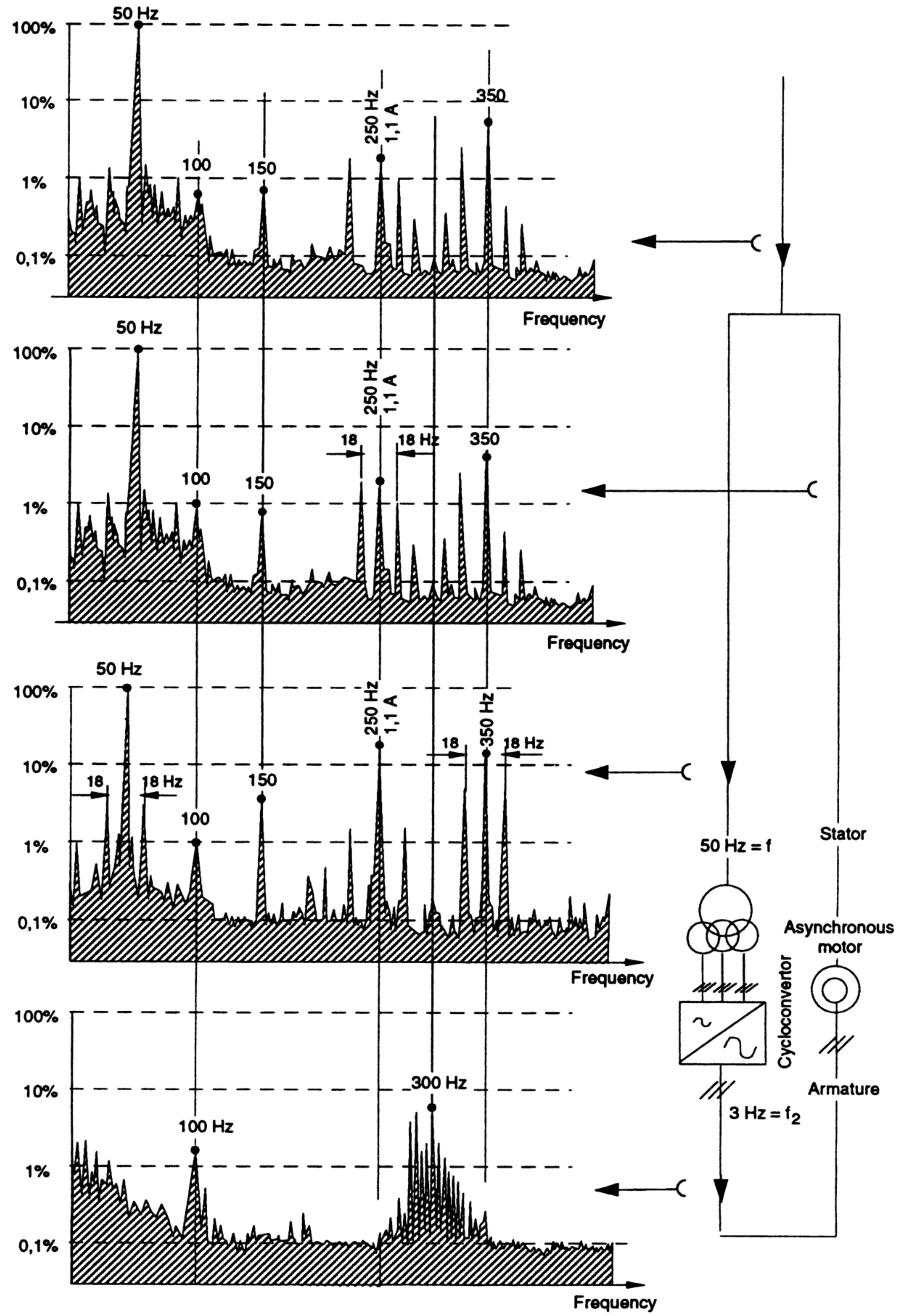


Figure 8 — Harmonic and interharmonic currents measured on a super/sub-synchronous cascade drive

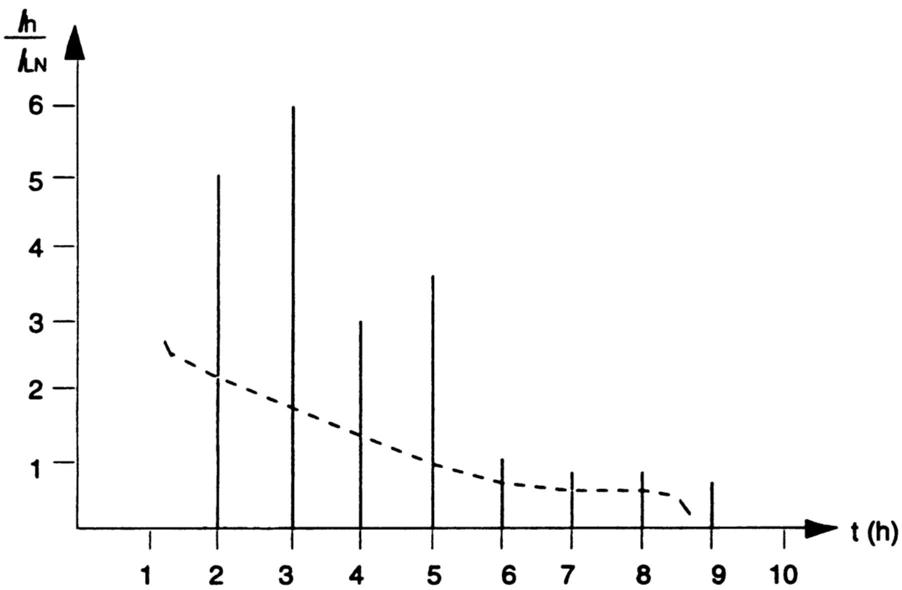


Figure 9 — Example of line and continous spectra for arc furnace (amplitude I_h/I_{LN} with respect to the nominal furnace current as a function of harmonic of 50 Hz, bandwidth 1 Hz)

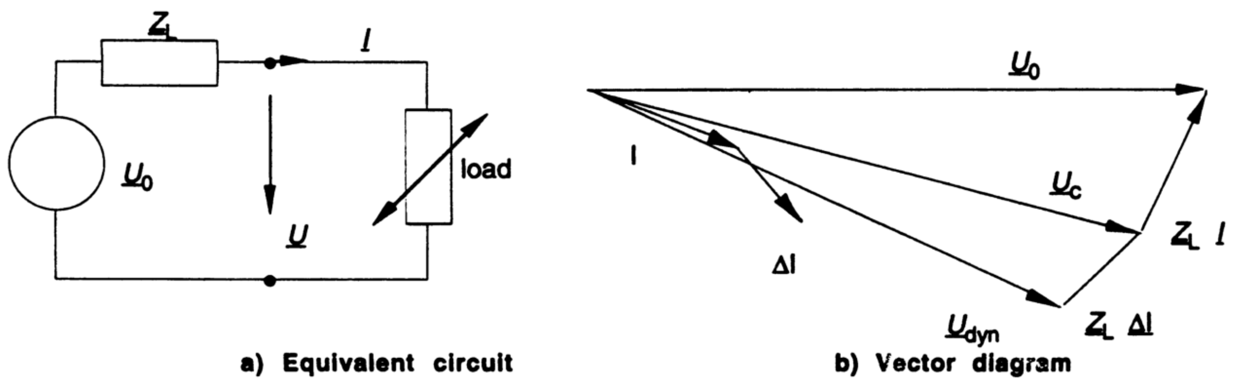


Figure 10 — Steady state and dynamic voltage changes

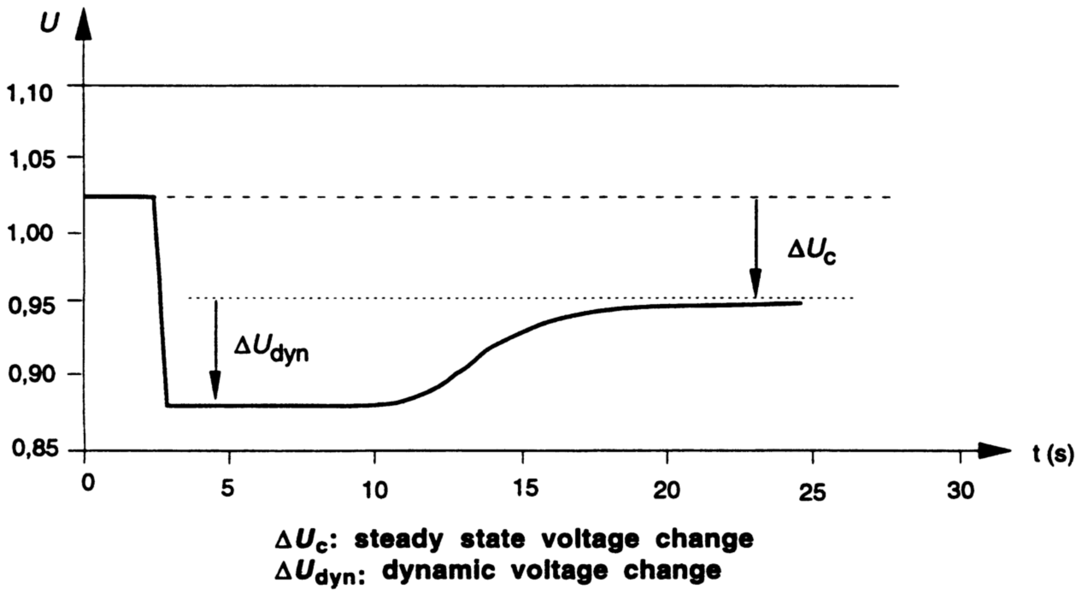


Figure 11 — Steady state and dynamic voltage changes

Annex A (informative)
Harmonic emission

A.1 Load characteristic and harmonic emission

Typical time dependent variation of different types of load and the disturbances mainly emitted are as follows.

— Drives and traction supplies, convertors as for a.c. arc furnace and for d.c. welding convertors, form a load which varies between steady state, and frequent as well as rapid changes. The peak current may rise up to three times the rated curent. Besides harmonic currents, voltage fluctuation and transient interharmonics may be introduced.

— Some of these applications produce a repetitive high short time current, for example in spot welding, or suffer from more or less frequent short-circuits on the load side, as in precipitators, thus causing voltage fluctuation.

— Slowly changing loads are electro-thermal processes for refining, heating and the excitation of machines or magnet coils emitting harmonic currents where convertors are applied. In these cases, the rated current is normally not exceeded.

— Rather constant load is given by electro-chemical processes, such as for electrolysis, galvanization and metal pickling, by high voltage supplies for transmitter valves, by UPS, and by illumination devices emitting continuously harmonic currents.

— Electro-thermal processes using arcs such as in d.c. arc furnaces, for welding, or melting are strongly changing loads. They produce a band of harmonic and interharmonic currents, voltage fluctuation, and unbalance, all randomly altering. In the case of a shorted arc, the current may increase to between 1,5 and 2 times its rated value.

— AC controllers as static compensators are normally associated with arc furnaces to compensate for their unbalance and reactive power fluctuation. In addition, heavily fluctuating harmonic and interharmonic currents are produced. AC controllers as motor-starters may produce high harmonics transiently.

— Switching on induction machines or transformers produces transient harmonics, voltage dips and unbalance, switching on capacitors or filters produces transient interharmonic currents and voltage dips. In all cases, the peak current can be far beyond the peak of the rated value.

A.2 Typical emission data of convertors

The basic data are found in IEC 146-1 and IEC 146-2.

As a first approach, the following considerations may apply.

A.2.1 Three-phase bridge convertors feeding a d.c. load where the d.c. current is smoothed inductively, as shown in Figure A.1 a) and Figure A.2 a).

Mostly controlled convertors in three-phase bridge connection (B6) are used and operating with non-intermitting d.c. current, therefore a range of their values for B6 arrangement is given. They depend on the trigger delay angle α or relative d.c. voltage U_d/U_{di}, on the short-circuit ratio r, and on the ripple of the d.c. current. The degree of the d.c. current smoothing is represented by the ratio:

$$\left(X_d + 2\,X_L\right)\frac{I_d}{U_{di}} \qquad \text{(A.1)}$$

where

X_d is the d.c. side reactance at line frequency, including load side reactance;

X_L is the a.c. side reactance in each phase at line frequency, including the reactance of the line and of a transformer or a commutating reactor (see Figure A.1.1 and Figure A.1.3);

I_d is the d.c. current (mean value);

U_{di} is the ideal no load d.c. voltage at $\alpha = 0$.

$$U_{di} = \frac{3}{\pi}\sqrt{2}\ U_L \quad \text{(A.2)}$$

where

U_L is the actual line-to-line voltage (r.m.s value);

U_d is the actual d.c. voltage (mean value).

$$\frac{U_d}{U_{di}} \approx \cos\alpha - d_x \quad \text{(A.3)}$$

where

α is the trigger delay angle;

d_x is the inductive direct voltage regulation.

$$d_x = \frac{3}{\pi}\frac{I_d X_L}{U_{di}} \quad \text{(A.4)}$$

R_{sc} is the short-circuit ratio, ratio of the short-circuit power at the valve side, and the d.c. power of the convertor at the ideal operating point (α = 0).

$$R_{sc} = \frac{U_L^2}{X_L}\ \frac{1}{U_{di}\ I_d} = \frac{\pi}{6}\frac{1}{d_x} \quad \text{(A.5)}$$

where

I_{d6} is the harmonic component of order 6 (r.m.s value) of current ripple;

I_1 is the fundamental component of the current (r.m.s value) of the a.c. supply.

$$I_1 \approx \frac{1}{\pi}\sqrt{6}\ I_d \quad \text{(A.6)}$$

where

I_h is the harmonic component of current (r.m.s value) of the a.c. supply;

h is the harmonic order, h = 6 n ± 1 = 1, 5, 7, 11, 13...;

n is the natural number, n = 0, 1, 2, 3....

Neglecting any d.c. current ripple (I_{d6} = 0) and commutation phenomena the relative harmonic currents amount to:

$$\frac{I_h}{I_1} = \frac{1}{h} \quad \text{(A.7)}$$

The neglected factors influence the results in deviations from the formula as follows.

- The line side relative harmonic component is shown in the Figure A.4 a) and Figure A.4 b) for the harmonic orders h = 5 and 7 depending on the trigger delay angle α. Parameters are the smoothing degree = 2, 0,4, and 0,1 for relative short-circuit power R_{sc} = 20 and 10. Values for higher harmonics are given Table A.1, Table A.2 and Table A.3.

  For exact values with smoothing degree > 2, see IEC 146-1-2, Figure 7.

- A lower relative short-circuit causes somewhat less harmonic components I_h/I_1, due to an increased overlap angle.

• With increasing d.c. current ripple, that is a lower smoothing degree, the relative 5th harmonic content notably increases above the theoretical value of I_5/I_1 = 1/5. This applies especially to operation with pulsating d.c. current. Correspondingly, the relative content of the 11th order of the line current is increased above 1/11 in the case of a 12 pulse convertor with two B6 connections in series, but it is nearly constant in case of two B6 connections in parallel.

• Non-characteristic harmonics of integer order, but:

$$h \neq 6n \pm 1 \qquad \text{(A.8)}$$

may appear because of unbalance in the line voltages, or impedances or in the trigger delay angles.

• 12 pulse operation.

In the cases of parallel or series arrangement of two B6 connections fed with 30° phase-shift and equally loaded, 5th and 7th harmonics are partially cancelled; a residual harmonic content of 5th and 7th order of up to 4 % is to be expected, because of uneven d.c. voltage or current share between the bridges.

As regards the phase angle of harmonic currents on the line side, the harmonic currents I_h of the same order h are to be added vectorially for the calculation of the perturbation resulting from simultaneous operation of several convertors.

The phase angle ϕ_h is the difference between the positive-going zero crossings of the fundamental phase-to-neutral voltage, and the harmonic current referred to the harmonic frequency $h\omega_N$.

Positive ϕ_h means phase lag of the harmonic current I_h.

As a first approach applies $\phi_h \approx \pm h\alpha$ for h = 5 and 7; therefore the phase angles of higher harmonic orders are well spread. Thereby, the positive sign is valid for convertor transformer in Y/D or D/Y, negative sign applies for direct connection of convertors and for convertor transformers in Y/Y or Δ/Δ connection, respectively.

a) Relative harmonic current I_h/I_1 in the a.c. supply

Shown in Table A.1, Table A.2 and Table A.3 are three values of relative d.c. voltage U_d/U_{di}, corresponding trigger delay angles, and resulting d.c. current ripple I_{d6}/I_d for the 6th harmonic component of the direct current with a short-circuit ratio R_{sc} = 20.

The usual range of operation is:

$U_d/U_{di} \approx 0$ — $\alpha \approx 90°$: controlled low d.c. voltage

$U_d/U_{di} \approx 0{,}84$ — $\alpha \approx 30°$: controlled usual d.c. voltage

$U_d/U_{di} \approx 0{,}975$ — $\alpha \approx 0°$: uncontrolled d.c. voltage

a_1) In the case of a high smoothing of the d.c. current

$$\left(X_d + 2X_L\right)\frac{I_d}{U_{di}} = 2$$

Table A.1 — Relative harmonic current at low d.c. ripple. R_{sc} = 20

$\frac{U_d}{U_{di}}$	α	$\frac{I_{d6}}{I_d}$	h	5	7	11	13	17	19	23	25
0	90°	0,021	$\frac{I_h}{I_1}$	0,21	0,13	0,09	0,07	0,06	0,05	0,04	0,04
0,84	30°	0,012		0,21	0,13	0,09	0,07	0,05	0,04	0,04	0,03
0,975	0°	0,005		0,19	0,12	0,08	0,05	0,02	0,02	0,01	0,01

a$_2$) In the case of medium smoothing of the d.c. current

$$\left(X_d + 2X_L\right)\frac{I_d}{U_{di}} = 0,4$$

Table A.2 — Relative harmonic current at medium d.c. ripple. R_{sc} = 20

$\frac{U_d}{U_{di}}$	α	$\frac{I_{d6}}{I_d}$	h	5	7	11	13	17	19	23	25
0	90°	0,11	$\frac{I_h}{I_1}$	0,27	0,06	0,09	0,04	0,05	0,03	0,04	0,03
0,84	30°	0,06		0,24	0,10	0,09	0,06	0,05	0,04	0,03	0,03
0,975	0°	0,03		0,20	0,11	0,06	0,05	0,02	0,02	0,01	0,01

a$_3$) In the case of low smoothing of the d.c. current

$$\left(X_d + 2X_N\right)\frac{I_d}{U_{di}} = 0,1$$

Table A.3 — Relative harmonic component at high d.c. ripple. R_{sc} = 20

$\frac{U_d}{U_{di}}$	α	$\frac{I_{d6}}{I_d}$	h	5	7	11	13	17	19	23	25
0	90°	0,43	$\frac{I_h}{I_1}$	0,48	0,17	0,09	0,05	0,04	0,02	0,02	0,01
0,85	30°	0,23		0,35	0,04	0,09	0,01	0,04	0,01	0,03	0,01
0,98	0°	0,11		0,25	0,09	0,06	0,04	0,02	0,02	0,01	0,01

Intermediate values for a.c. supply harmonic current for:

$$0,1 \leq \left(X_d + 2X_L\right)\frac{I_d}{U_{di}} \leq 2$$

For more detailed evaluations, see [7] and [8] in Annex E.

b) Phase angle of harmonic currents on the line side

In the case of well smoothed d.c. current and with:

$$u_{L\text{-}N} = U_{L\text{-}N}\sqrt{2}\,\sin(\omega_L t) \qquad \text{(A.9)}$$

$$i_{Lh} = I_H\sqrt{2}\,\sin(h\omega_L t - \phi_h) \qquad \text{(A.10)}$$

$$\alpha + \frac{u}{2} \approx \arccos\left(\frac{U_d}{U_{di}}\right) \qquad \text{(A.11)}$$

where

- u is the overlap angle;
- $U_{L\text{-}N}$ is the phase-neutral voltage of the a.c. supply;
- i_{Lh} is the phase current in the a.c. supply;
- ω_L is the a.c. supply angular frequency.

The phase angle ϕ_h may be calculated approximately, depending on the winding connection of a convertor transformer with the following relations.

b_1) Convertor linked to the mains directly or via a transformer in Y/Y or D/D connection

(see Figure A.5 a) for the waveforms of the current and of the voltage)

$$\phi_h \approx (180° + \alpha + u/2)\, h \qquad \text{for } h = 5, 7, (17, 19)$$

$$\phi_h \approx (\alpha + u/2)\, h \qquad \text{for } h = 11, 13, (23, 25) \tag{A.12}$$

b_2) Convertor linked to the mains via a transformer in Y/D or D/Y connection

(see Figure A.5 b) for wave forms of current and voltage)

$$\phi_h \approx (\alpha + u/2)\, h \qquad \text{for } h = 5, 7, 11, 13, \ldots \tag{A.13}$$

NOTE These formulae apply for harmonic current of orders 5 and 11, even in presence of d.c. ripple. As regards the effect of the current ripple at the d.c. side on harmonic current of order 7 at the a.c. side, see [8] in Annex E.

A.2.2 ***Three-phase bridge convertor feeding a d.c. load through a L-C filter***

When a convertor with direct voltage link is fed by a controlled convertor via a filter with a sufficiently high smoothing reactor, as shown in Figure A.1 c), then the information relevant to indirect convertors apply. Sufficiently high smoothing is achieved when:

$$2\,\omega_L > \omega_r$$

$$\text{with} \quad \omega_r = \sqrt{\frac{\omega_L}{C_d\left(X_d + 2X_L\right)}} \tag{A.14}$$

where

ω_L is the a.c. supply angular frequency;

ω_r is the resonance angular frequency of the filter.

A.2.3 ***Three-phase bridge convertor feeding a d.c. load with a capacitor smoothing***

When a high smoothing capacitance is directly fed by a diode rectifier in B6 connection, as shown in Figure A.2 c), high harmonic currents occur in the case of low a.c. supply reactance.

The relative harmonic components in dependance on the relative short-circuit power R_{sc} are shown in the Table A.4.

Table A.4 — Relative harmonic current of a diode rectifier (B6) feeding a high capacitance

$\frac{U_d}{U_{di}}$	R_{sc}	h	5	7	11	13	17	19	23	25
1,02	500	$\frac{I_h}{I_1}$	0,86	0,70	0,35	0,22	0,09	0,09	0,07	0,05
1,00	100		0,64	0,40	0,09	0,09	0,05	0,04	0,02	0,02
0,97	20		0,30	0,09	0,06	0,04	0,02	0,02	0,01	0,01
0,94	10		0,24	0,07	0,04	0,03	0,014	0,01	0,01	0,01

Intermediate values for a.c. supply harmonics of order 5 and 7 are shown in Figure A.6. More detailed results concerning the behaviour of amplitude and phase are given in [8] of Annex E.

For more detailed evaluations regarding also d.c. voltage ripple, see [9] and [10] in Annex E.

Neglecting d.c. voltage ripple, the range of the phase angles of the lower order harmonic currents is approximately given for ϕ_5 = 70°...135° and for ϕ_7 = 90°...290°, where R_{sc} = 10...500 is assumed.

The level of the harmonics depends strongly on the filtering on the a.c. and d.c. side, and should be requested from the manufacturer.

The low order harmonics (in particular 3 and 5) have very similar phase angles, and therefore sum up almost arithmetically, when many of these devices are operating simultaneously in a network.

More details on this connection and its harmonic emission are given in [11] of Annex E.

A.2.4 ***Direct convertors consist of one or several pairs of convertors connected in antiparallel***

— a single-phase a.c. load is fed by one pair, as shown in Figure A.7 a);

— a three-phase a.c. load is fed by three pairs, as shown in Figure A.7 b), called cycloconverter.

For the resulting harmonic currents of the characteristic orders h = 5, 7, 11, 13 in the a.c. supply, Similar values to those of indirect convertors apply. Normally, these values are lower, but interharmonics of side band frequencies are increased.

For a more exact evaluation, see [1] in Annex E.

A.2.5 ***AC Controllers***

AC controllers regulate the a.c. voltage and current at the load by means of thyristors connected in antiparallel in the a.c. lines. There are single-phase and three-phase controllers.

Figure A.8 a), Figure A.8 b), and Figure A.8 c) show the connections usually used. The relative harmonic component of the line currents depend on the ratio *R*/*Z* in the circuit and the delay angle α.

Table A.5 shows the maximum values of the harmonic current within the control range.

$$\arccos\left(\frac{R}{Z}\right) \leq \alpha \leq 180° \qquad \text{(A.15)}$$

I_{hmax} is referred to the maximum of the fundamental load current.

I_{hmax}/I_{1max} for several ratios *R*/*Z* is given for single-phase connection, according to Figure A.8 a).

$$Z = \sqrt{R^2 + X^2} \approx \sqrt{R_A^2 + (X_A + X_L)^2} \qquad \text{(A.16)}$$

$$I_{1max} = \frac{U_L}{Z} \qquad \text{(A.17)}$$

Table A.5 — Values I_{hmax}/I_{1max} of a single-phase a.c. controller for several harmonic orders depending on the load ratio R/Z

I_{hmax} / I_{1max} α_w/ϕ_h	R/Z						
h values	1	0,9	0,8	0,7	0,6	0,5	0,0
3	0,318 90°/– 90°	0,227 95°/– 23°	0,193 100°/8°	0,174 103°/21°	0,161 106°/35°	0,153 109°/47°	0,138 120°/90°
5	0,138 60°/– 60° 120°/– 120°	0,078 67°/40°	0,067 75°/94°	0,061 80°/138°	0,058 87°/153°	0,056 90°/175°	0,050 105°/90°
7	0,106 90°/– 90°	0,041 102°/62°	0,032 110°/135°	0,030 – 20°/– 150°	0,029 78°/– 94°	0,028 100°/– 60°	0,026 105°/90°
9	0,076	0,026	0,020	0,018	0,017	0,016	0,016
11	0,064	0,016	0,014	0,012	0,011	0,011	0,011
13	0,052	0,012	0,010	0,009	0,008	0,008	0,008
15	0,046	0,009	0,007	0,006	0,006	0,006	0,006

$\alpha_w = \alpha$ in the worst case

The same values apply for the circuit shown in Figure A.8 b). Note that the neutral line is loaded with three times the triple n harmonics. The phase angle ϕ_h of the harmonic current depends on the ratio R/Z and the trigger delay angle α.

Further information is given in Table A.5; it contains the maximum relative harmonic currents of the single phase a.c. controller, and the relevant phase angle α_{worst} for the lower harmonic orders.

These values, as regards the amplitude, apply with good approximation also for three single-phase controllers of Figure A.8 c) with equal firing delay angles, but the harmonic orders 3, 9, and 15 are cancelled. The maximum fundamental current I_{1max} and the ratio R/Z are:

$$I_{1max} = \frac{U_L}{\sqrt{R_A^2 + \left(3X_L + X_A\right)^2}}$$

$$\frac{R}{Z} \approx \frac{1}{\sqrt{1 + \left(\frac{3X_L + X_A}{R_A}\right)^2}} \qquad \text{(A.18)}$$

For further details concerning the harmonic currents of a.c. controllers according to the connections in Figure A.8 a), Figure A.8 b) and Figure A.8 c), see [12] of Annex E.

Three-phase a.c. controllers are often applied to control the primary voltage of a transformer feeding a high voltage or high current d.c. load via a diode rectifier on the secondary side. The d.c. current usually is smoothed by a reactor. The harmonic currents depend on the connections of the a.c. controller and of the transformer, on the delay angle, and on the degree of smoothing. The values for the harmonic currents to be expected should be requested from the manufacturer.

A.2.6 *Self-commutated convertors*

Self-commutated convertors, connected on the line side, are able to avoid reactive power or to compensate for it, and to decrease harmonic currents. As the application of this new technique is still rare, it is not yet dealt with.

A.3 Arc furnaces

The amount of harmonic currents produced by a.c. arc furnaces and their fluctuation depends on several factors, such as the operating mode, kind of scrap, temperature, and condition of the electrodes. The values measured depend on the settings of the harmonic analyzer, as the harmonics vary at random.

Reference [2] in Annex E gives an example of a measured spectrum for an arc furnace (see Figure 10), but the spectra of other furnaces may deviate considerably.

The phase angles of the harmonics vary randomly over a broad range.

A.4 AC welding machines

AC welding machines for spot welding via high-reactance transformer do not create appreciable harmonics. Harmonic currents are produced when a welding arc is fed, or the welding current is controlled, by an a.c. controller. In both cases the harmonic currents are relatively low, because of the high reactance in the load circuit.

The values of Table A.5, with R/Z = 0,5, are appropriate to welding machines. However, the main disturbance produced by welding machines is voltage fluctuations.

A.5 Fluorescent lamps

Fluorescent lamps are mostly connected via a ballast inductance to the mains. They generate harmonic currents of constant amount and phase angle, because of the non-linear impedance of the discharge arc.

Modern fluorescent lamps intended to replace incandescent lamps are fed by a high frequency generator. Today, the a.c. supply is normally loaded by a single-phase diode bridge with smoothing capacitors connected on the d.c. side.

The increasing mass of fluorescent lamps in combination with computers, television sets, etc., having the same power supply, causes a high harmonic disturbance level in almost all networks, especially concerning the fifth harmonic. Additionally, a high third harmonic flowing in the neutral line can be expected.

A.6 Switching of saturable inductances

The inrush current of transformers and a.c. machines depends on the phase angle of the switching instant, and the remanent magnetization of the active iron parts. The inrush current contains all integer low order harmonics, including zero order for d.c. components. The harmonic components decay with a time constant between several seconds and a few minutes (high power transformers).

A.7 Switching of capacitor banks

Switching on capacitors excites an oscillation, the frequency of which is determined by the capacitance and all inductances feeding into it. In the case of filters, the resulting resonance frequency is somewhat lower than the frequency the filter is tuned to. This resonance oscillation decays within 10 to 20 of its periods, that is, in less than one second.

NOTE The design of a reactive power compensation should avoid capacitances without tuning reactors, as parallel resonance may be caused by one of the harmonics. Also overcompensation should be prevented in order not to increase the line voltage.

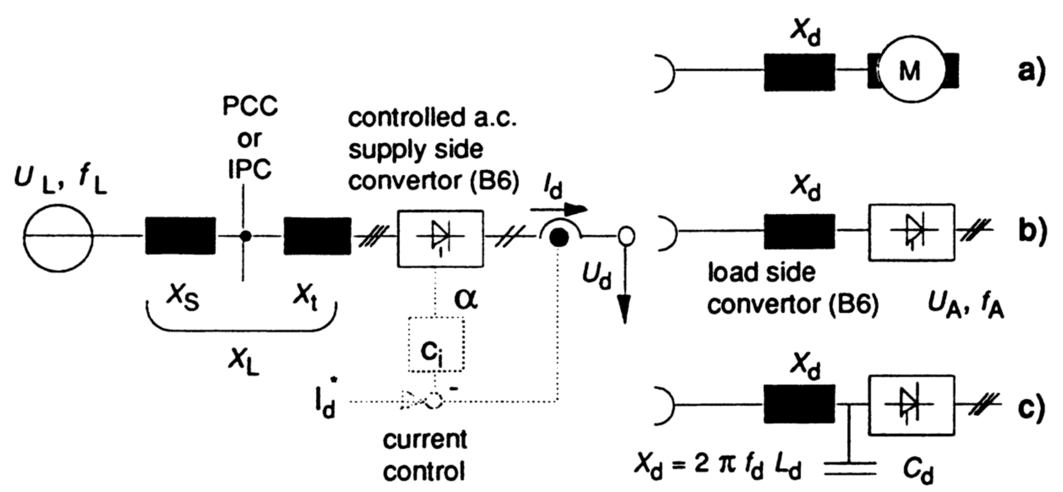
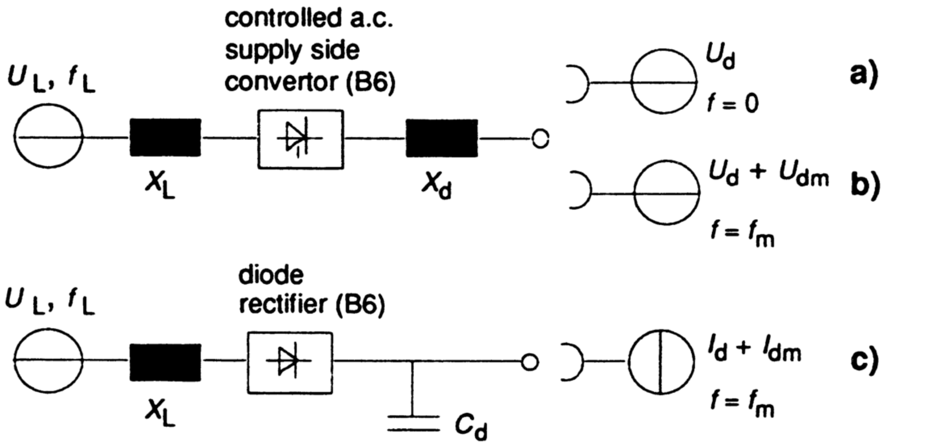


Figure A.1 — AC supply side thyristor convertor with inductive smoothing and
a) d.c. drive and static compensation
b) current source inverter
c) additional capacitive smoothing and voltage source inverter



a) d.c. voltage between 0 (static compensator) and 0,9 U_d (d.c. machine)
b) d.c. voltage U_d and superimposed a.c. voltages U_{dm} with frequencies f_m
c) d.c. current I_d and superimposed a.c. currents I_{dm} with frequencies f_m

Figure A.2 — Equivalent circuit for convertors producing harmonic and interharmonics current in the a.c. supply side

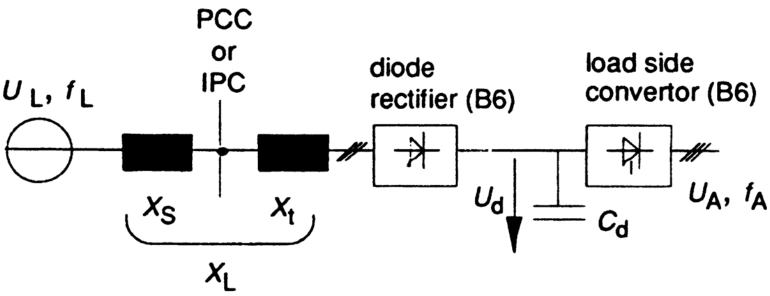


Figure A.3 — AC supply side diode rectifier with capacitive smoothing and voltage source inverter

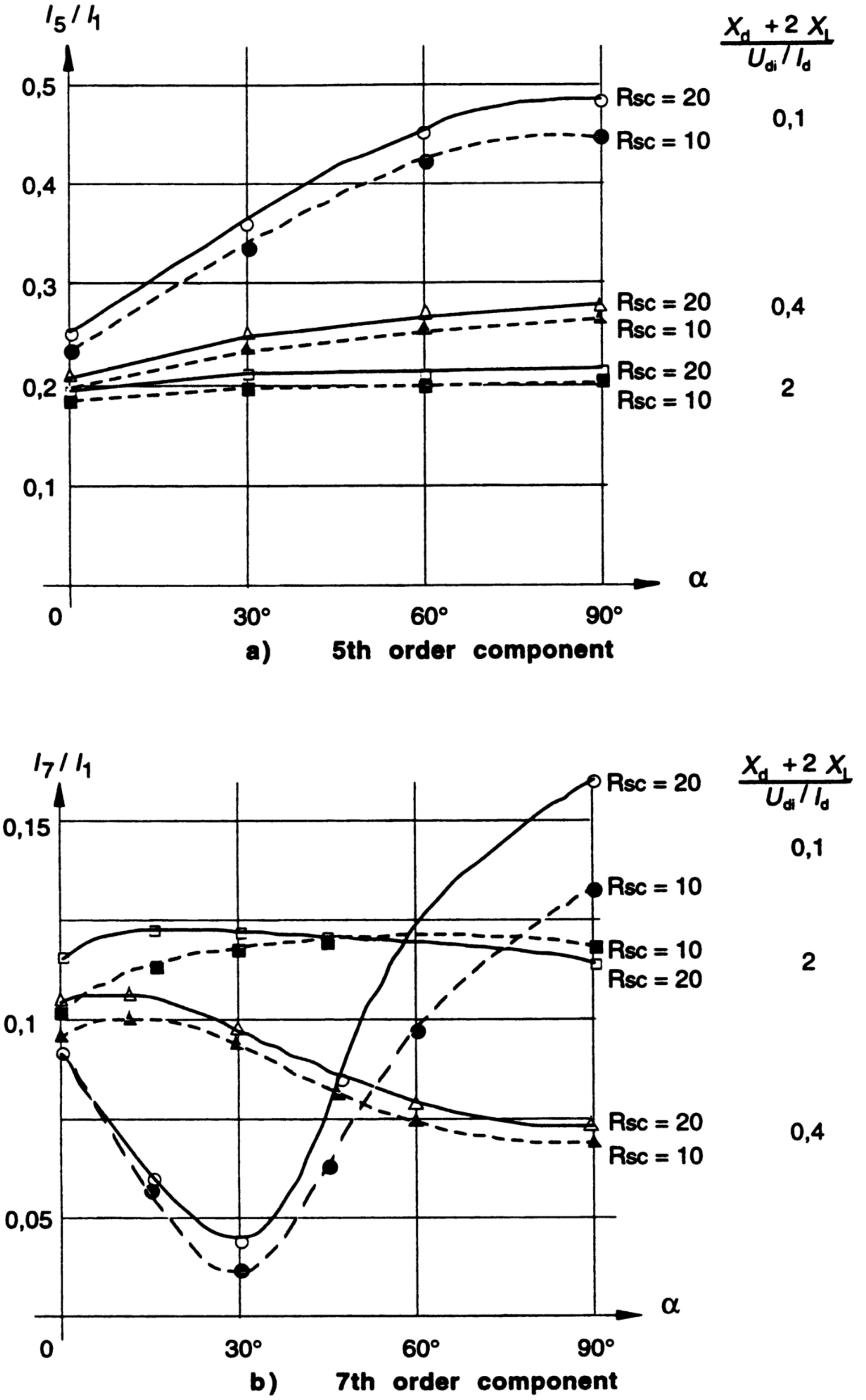
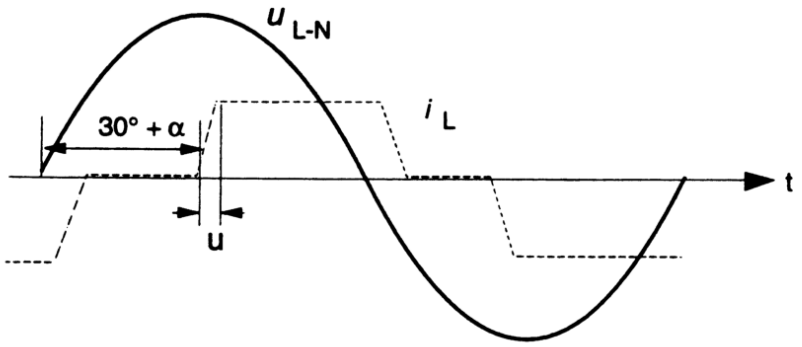
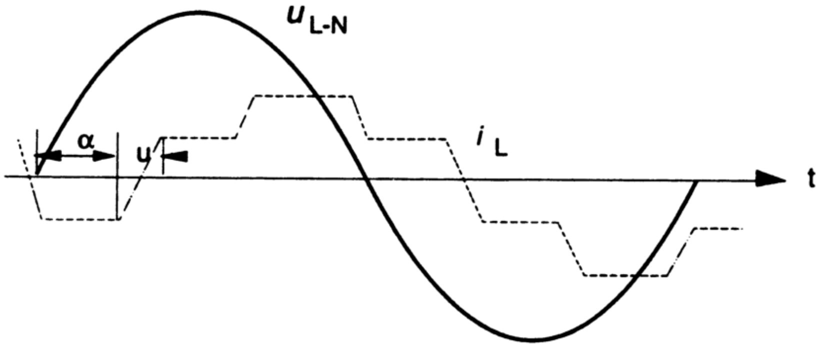


Figure A.4 — Relative harmonic line current of order h = 5 and 7 depending on the trigger delay angle α
Parameters: R_{sc} = 20 and 10

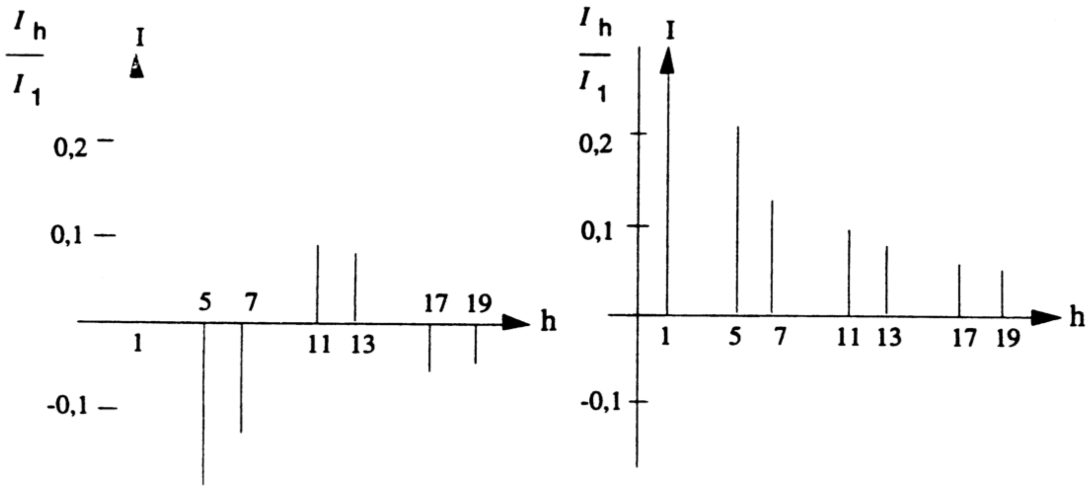
Smoothing degree $\frac{X_d + 2\ X_L}{U_{di}/I_d}$ **= 0,1, 0,4 and 2**



a) waveform of the voltage and current in case of a Y/Y or D/D connection of the transformer.



b) waveform of the voltage and current in case of a Y/D or D/Y connection of the transformer.



c) spectra of harmonic current in the supply current (referred to the zero crossing of the fundamental current); the left diagrams is relevant to the case a), the right one is relevant to the case b).

Figure A.5 — Primary voltage and current for a convertor linked to the mains via a transformer

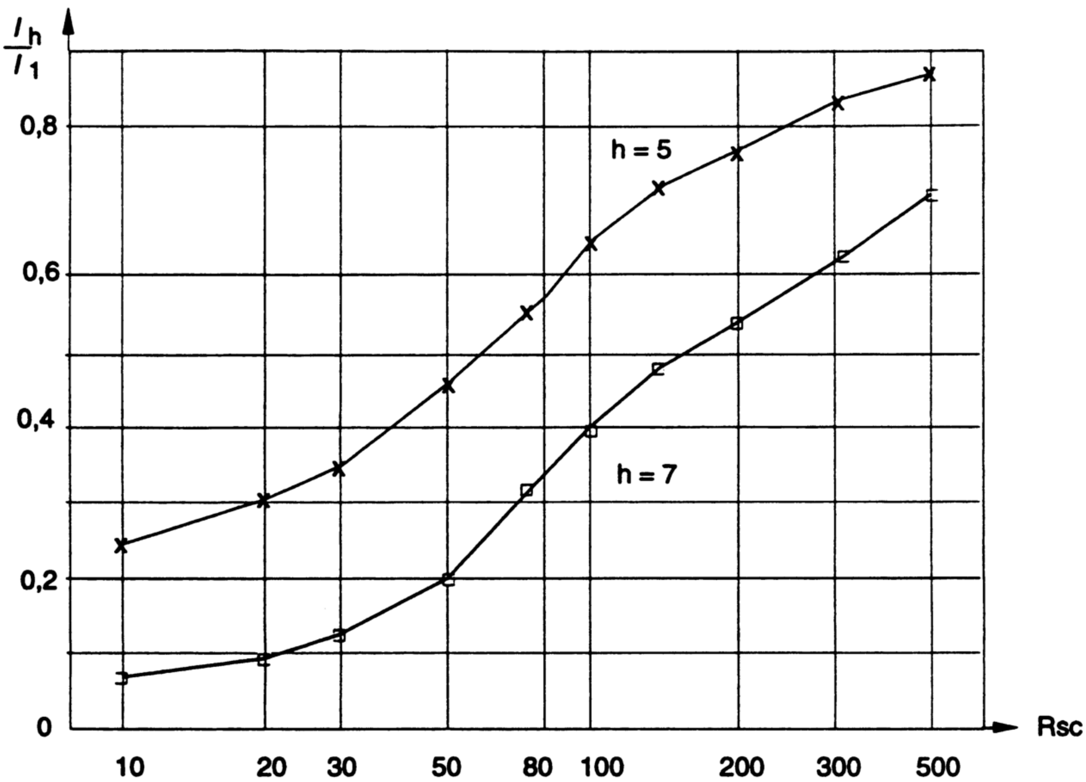


Figure A.6 — Relative harmonic a.c. supply side current of a diode rectifier in B6-connection feeding a ripple-free d.c. voltage

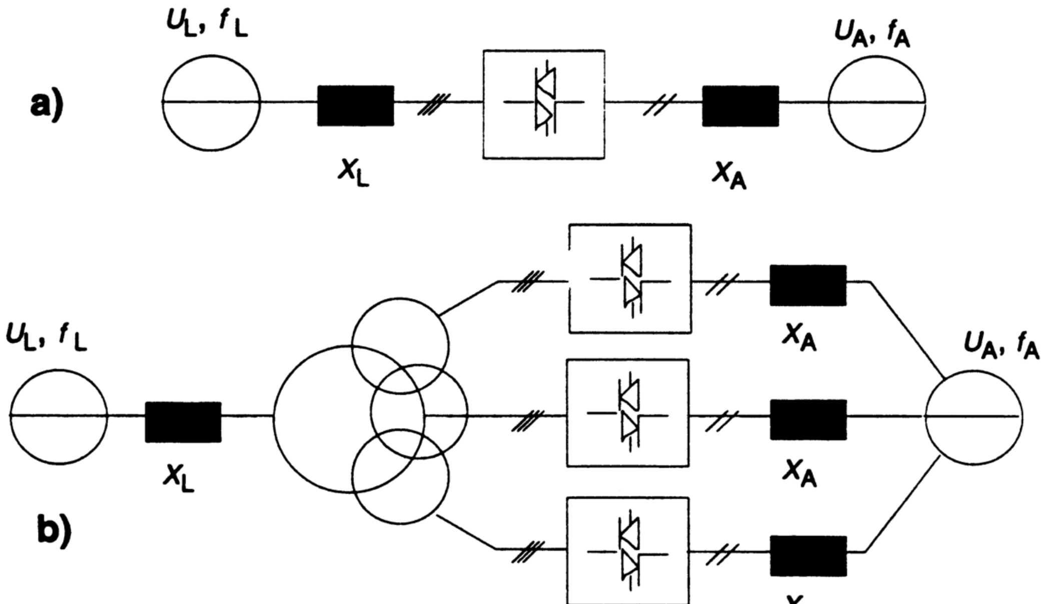


Figure A.7 — Direct convertor with:
a) single-phase output
b) three-phase output (cycloconverter)

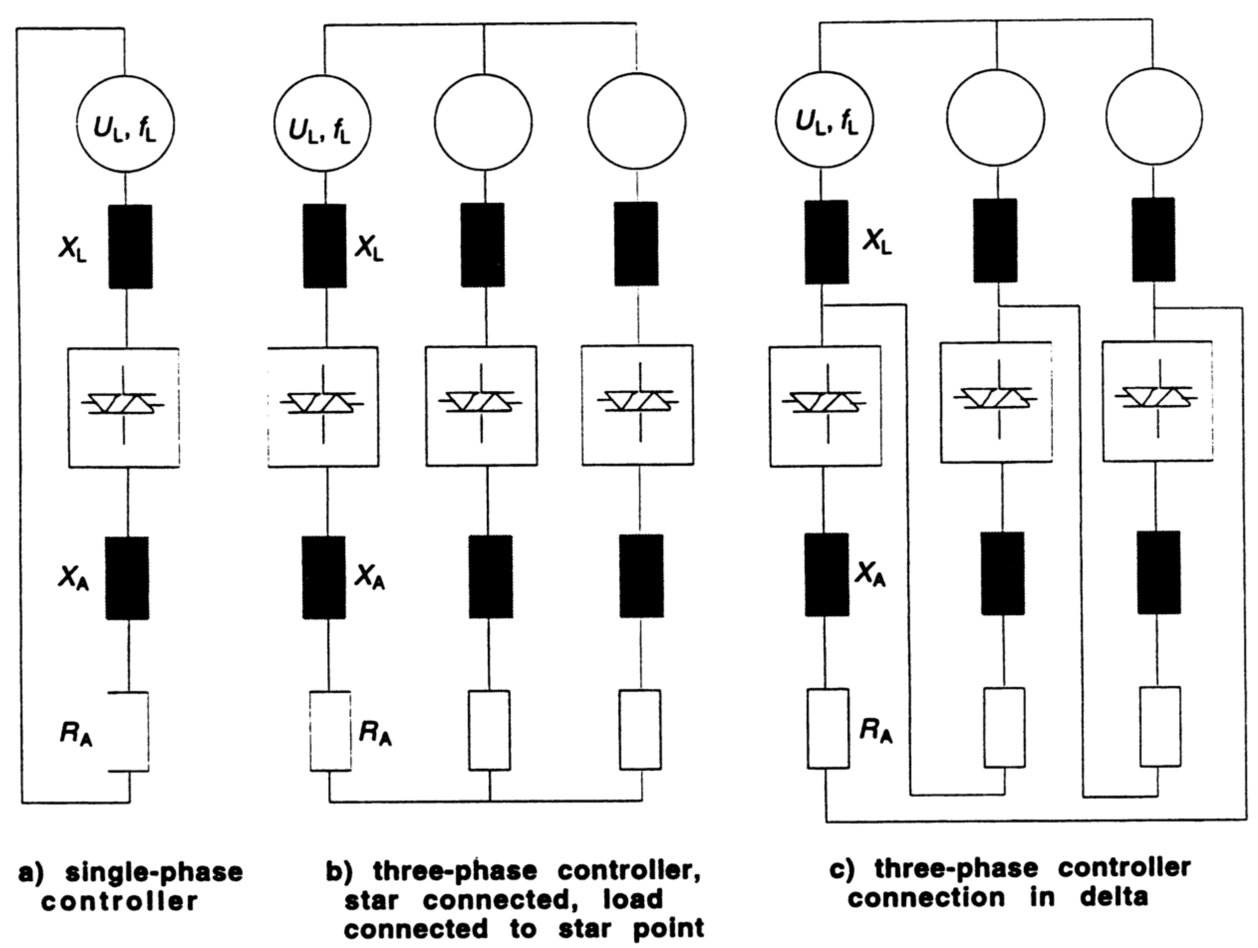


Figure A.8 — AC controller connections

Annex B (informative) Network impedances for calculation of harmonic propagation and evaluation of harmonic voltage components

B.1 Scope

This annex relates to the evaluation of the impedances necessary for the computation of the harmonic current distribution and the harmonic voltage components in electric power systems. A simple approach is also presented here; it is restricted to frequencies up to the 40th harmonic, and is applicable to industrial installations. The accuracy of the calculation diminishes with increasing frequency. Therefore, complementary measurements may be useful for critical cases.

The aim is to give guidance to the system designer on the evaluation of the network impedances at harmonic frequencies.

B.2 Introduction

A load connected to an electrical power supply network may produce harmonic currents, which flow through the different branches of the network. The harmonic currents cause voltage drops across the impedances of the various components of the system. Thus, the load under consideration produces harmonic voltages at the point where it is connected, and all through the system. The magnitude of these harmonic voltages, as well as the distribution of the harmonic currents in the network, is determined by the impedances, at harmonic frequency, of the different branches in the network, as well as the size and location of the harmonic sources.

B.3 Calculation methods

Calculation of the harmonic current distribution and the harmonic voltages should take into consideration the internal impedance of the power supply system all the way up to the infinite EMF of the network, and the impedances of all pieces of equipment connected to the same system in parallel. This may include the impedances of:

— the high voltage power supply network, to which the system to be studied is connected;

— transformers and current limiting reactors;

— a.c. rotation machines;

— cables and overhead lines;

— capacitors installed to correct the power factor;

— harmonic filters;

— large loads.

Loads with high internal impedance, such as line commutated convertors with inductively smoothed d.c. current, are normally considered as ideal harmonic current sources.

The network asymmetries are, in general, neglected when considering the distribution of harmonic currents in the network. Under this assumption, the study of harmonic distribution can be performed in a single-phase equivalent network. On the other hand, asymmetries are to be considered when evaluating the amount of harmonic currents injected by the disturbing loads.

NOTE Line-line voltages are considered only, therefore, zero sequence networks are not dealt with here.

In simple cases where the system to be studied is of relatively low complexity, it is possible to carry out the calculations manually, but in general, with more complicated network configurations, a manual calculation will be cumbersome, in particular if the harmonic voltage components are to be evaluated in various points of coupling, and for a large number of frequencies. In such cases, it is recommended to use a computer program for power system analysis. A number of such programs are available on the market.

B.4 Determination of harmonic voltages

As a first approximation, the harmonic voltage components in a system can generally be evaluated under the assumption that the harmonic currents/voltages injected by a load are not largely dependent on the particular characteristics of the network at harmonic frequency. The injected current depends mainly on the smoothing, on the operating conditions of the considered device, and to some extent, on the short-circuit power at the point of connection of the disturbing equipment.

NOTE Line commutated convertors with relatively large inductive loads act as harmonic current sources for frequencies up to the 40th harmonic. Other types of disturbing equipment may act either as harmonic voltage or current sources.

The harmonic voltage generated by a single load can in such a case be calculated as the injected harmonic current, multiplied by the network internal impedance at the point of connection. The internal impedance in this case is the equivalent impedance, Z_{eq}, as seen from the load terminals into the network, and is to be evaluated for each individual harmonic frequency. The evaluation takes into consideration the impedance of the feeding line, as well as the impedance of all pieces of equipment connected in parallel, including harmonic filters, if any.

An example of calculation of Z_{eq} for two different points in a system is shown in Figure B.1.

It should be noted that Z_{eq} may vary considerably under different network and/or load conditions. Thus, it is important for the designer of the plant to have all information about the whole range of variation of Z_{eq}.

B.5 Variation of the network impedance with frequency

In general, Z_{eq} is a complicated function of frequency. However, in some cases a simpler approach can be used, which makes manual calculation possible. This approach can be applied where the capacitance of the network is negligible, or a single capacitance plays a dominant role in the considered range of frequency.

NOTE 1 Often the impedances can be approximated by their reactive part only, when a capacitive impedance will have negative sign. In the following, the notation of complex quantity is omitted.

NOTE 2 In the case of particular resonance, harmonics with an order higher than 25 have to be considered.

B.5.1 Z_{eq} *directly proportional to frequency*

In simple installations, with no large capacitors for power factor correction, and no large cable networks, resonance conditions are not likely to occur for frequencies up to the 13th harmonic. In such cases, Z_{eq} can be considered to be mainly inductive, and approximated as:

$$|Z_{eq}| \approx |X_{eq}(h)| \approx h\,|X_{eq}(1)| \qquad \text{(B.1)}$$

where

X_{eq}(h) is the network reactance at the harmonic of order h;

X_{eq}(1) is the network reactance at fundamental frequency.

This approach can be used with a reasonable accuracy (normally better than ± 20 %) if:

a) The bus is fed through a transformer, and the impedance of the transformer, X_T, at fundamental frequency, is high compared to the impedance of the high voltage supply, X_{HV}.

$X_T/X_{HV} > 10$	if resonance in the high voltage supply is possible in the considered frequency range;
$X_T/X_{HV} > 4$	if resonance in the high voltage supply is unlikely to occurr in the considered frequency range.

b) The total capacitance connected to the secondary system is so low that the resonance frequency is at least 2,5 times the highest studied harmonic frequency.

The resonance frequency f_r is calculated as:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad \text{(B.2)}$$

Where L is the inductance per phase corresponding to Z_{eq} if the capacitance is omitted, and C is the capacitance per phase connected at the point where Z_{eq} is assessed, with both power factor capacitors and cable capacitances taken into consideration. The capacitance of a three-phase cable is typically 0,2 µF/km – 0,6 µF/km and phase.

f_r can be also obtained by:

$$f_r = f_N\sqrt{\frac{S_{sc}}{Q}} \qquad \text{(B.3)}$$

where

f_N	is the fundamental frequency;
S_{sc}	is the short-circuit power of the supply;
Q	is the total reactive power generated by capacitors and cables in the system.

The above rules are justified by the following considerations relevant to simple network configurations.

B.5.1.1 *Network impedance for simple networks*

a) Resonance in the high voltage network

Consider the network configuration and associated impedance diagram at a given frequency shown in Figure B.2. Z_{HV} is the internal impedance of the high voltage supply if no resonance is present. The resonance amplification, due to the presence of capacitance in the supply systems, is considered to be five times or less for most cases. Thus the impedance vector Z_{HV}, will fall within the shaded circle, with a diameter of 5 Z_{HV}, and the following expressions can be derived from the impedance diagram.

$$Z_{eq\,max} \approx \sqrt{\left(Z_T + 2{,}5\,Z_{HV}\right)^2 + \left(2{,}5\,Z_{HV}\right)^2}$$

$$Z_{eq} \approx Z_T + Z_{HV} \qquad \text{(B.4)}$$

$$Z_{eq\,min} \approx \sqrt{\left(Z_T - 2{,}5\,Z_{HV}\right)^2 + \left(2{,}5\,Z_{HV}\right)^2}$$

$$\text{if } Z_{HV} < \frac{Z_T}{10} \text{ then}$$

$$Z_T \leq Z_{eq\,max} \leq 1{,}27\ Z_T \tag{B.5}$$

$$Z_T \leq Z_{eq} \leq 1{,}1\ Z_T$$

$$0{,}79\ Z_T \leq Z_{eq\,min} \leq Z_T$$

$$0{,}72 \leq \frac{Z_{eq\,min}}{Z_{eq}} < \frac{Z_{eq\,max}}{Z_{eq}} \leq 1{,}15 \tag{B.6}$$

b) Resonance in the low voltage network

Consider a network with a single resonance, as schematically shown in Figure B.3.

The impedance at the point of coupling can be derived as:

$$Z_{eq} \approx \frac{2\pi\ f_N\ L}{\left(1 - \left(\frac{f_N}{f_r}\right)^2\right)} \tag{B.7}$$

where

f_N is the system frequency

f_r is the resonance frequency

$$\text{if } f_r > 2{,}5\ f_N \text{ then } Z_{eq} < 1{,}19\ Z_L \tag{B.8}$$

The inequalities demonstrate that in the considered cases a and b, the linear variation of the impedance with the frequency is a reasonable approximation.

B.5.2 Z_{eq} *with single resonance*

If the total capacitive components can be regarded as connected to the same electrical point, the resulting value of Z_{eq} can be calculated as L in parallel with C, where L and C are defined as in **B.5.1**.

This agrees with the principle explained in Figure B.1.

Close to the resonance point, however, this method will give a far too high value for the resulting impedance. In order to calculate the proper value, the resistive component of the network impedances should be taken into consideration. The resistive components, at harmonic frequencies, are, however, very difficult to determine in a practical situation. It is, therefore, recommended that the value of Z_{eq} is calculated with only L and C, neglecting the resistive component, and then limited so that the resonance amplification factor k:

$$K = \frac{Z_{eq}(h)}{h\ X_{eq}(1)}$$

does not exceed 3 to 10 times. The lower value is valid for heavily loaded networks, and the higher value for networks with extremely low load. Normally, the resonance amplification factor does not exceed 5 times in public networks, but can reach 8 to 10 times in some industrial networks under light load conditions.

B.5.3 Z_{eq} *in more complex systems*

If capacitive elements are connected to several points in the network, or if the capacitors are tuned with series reactors, several resonance points will occur. In these cases, as well as all other cases with more complicated networks, a manual calculation will be cumbersome, and hence a computer calculation is recommended.

An example of variation of the impedance Z_{eq}, with frequency at the point of coupling, is shown in Figure B.4. It shows the one-line diagram of an industrial plant fed by an 132 kV system and the relevant variation of supply impedance as seen from IPC1 and PCC. The effect of the installation of power factor capacitors is also shown.

A definite parallel resonance occurs in this case at IPC1.

B.6 Impedance of system components

The calculation of the harmonic current distribution and the harmonic voltages in the network requires the definition of the impedances that describes the behaviour at harmonic frequency of each network component. Basic information on the models to be considered, and on the values of the relevant parameters, is commonly available in handbooks. In the following, some comments are given on particular aspects, also taking into consideration that the studied frequency range is limited to 2nd to 40th harmonic.

B.6.1 *Synchronous generators, induction motors*

In a first approximation, the machine presents an inductive behaviour, the inductance to be considered is the negative sequence one for synchronous machines, and the locked rotor one for induction motors.

Series resistive losses increase considerably as the frequency increases. Some data has been collected by CIGRE reference [16] in Annex E. More complex models account also for the reduction of the inductance as the frequency increases. The possible presence of protective surge capacitors is to be considered.

B.6.2 *Power transformers*

Leakage impedance only is generally considered. The inductance is generally fairly constant, while the series resistance increases when the frequency increases. The actual position of the tap changer is also important. In the frequency range up to 2,5 kHz, it is normally not necessary to consider the influence of stray capacitances.

B.6.3 *Transmission lines*

Both for cables and overhead lines, the standard circuit can be adopted. The line constants for the calculation of the equivalent circuit can be found in standard handbooks.

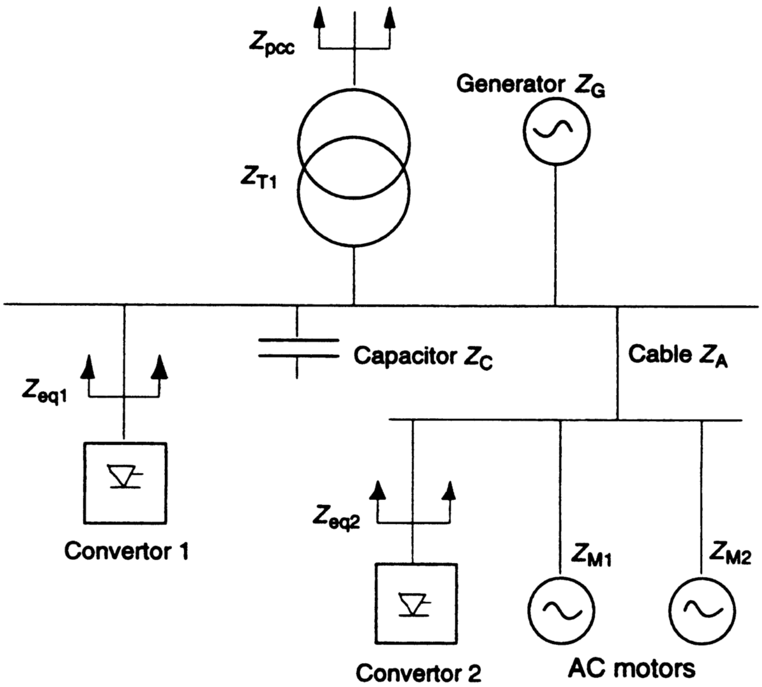
For short lines (less than 10 km for overhead lines and 3 km for cables), it is possible to disregard the fact that the line constants are distributed along the line.

B.6.4 *Capacitor banks and harmonic filters*

They are to be represented in detail. It is also necessary to take into account the presence of possible choke reactors. Capacitor losses are generally neglected, but losses in filter reactors and damping resistors are to be considered.

B.6.5 *Loads fed through line commutated convertors*

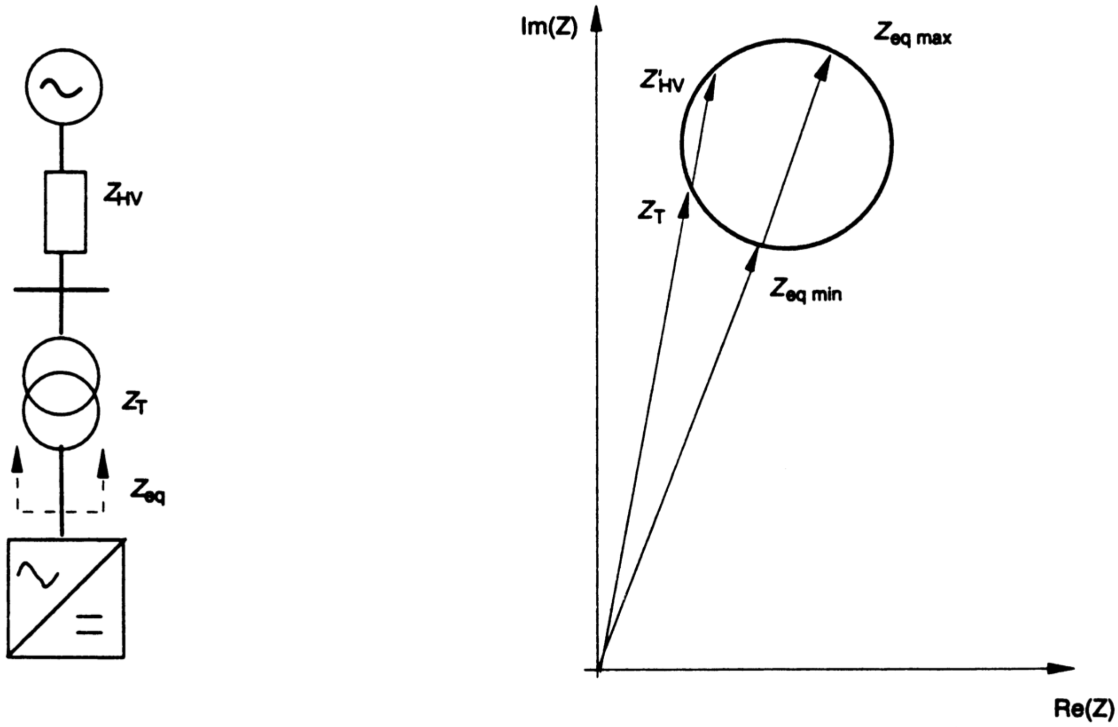
If they feed large inductive loads, they can normally be neglected for impedance calculations. Such a convertor may generally be considered as a pure current source, and is therefore not present in the bus admittance scheme.



$$Z_{eq1} = \frac{1}{\frac{1}{Z_{pcc} + Z_{T1}} + \frac{1}{Z_G} + \frac{1}{Z_C} + \frac{1}{Z_A + \left(\frac{1}{Z_{M1}} + \frac{1}{Z_{M2}}\right)}}$$

$$Z_{eq2} = \frac{1}{\frac{1}{\frac{1}{\frac{1}{Z_{pcc} + Z_{T1}} + \frac{1}{Z_G} + \frac{1}{Z_C}} + Z_A} + \frac{1}{Z_{M1}} + \frac{1}{Z_{M2}}}$$

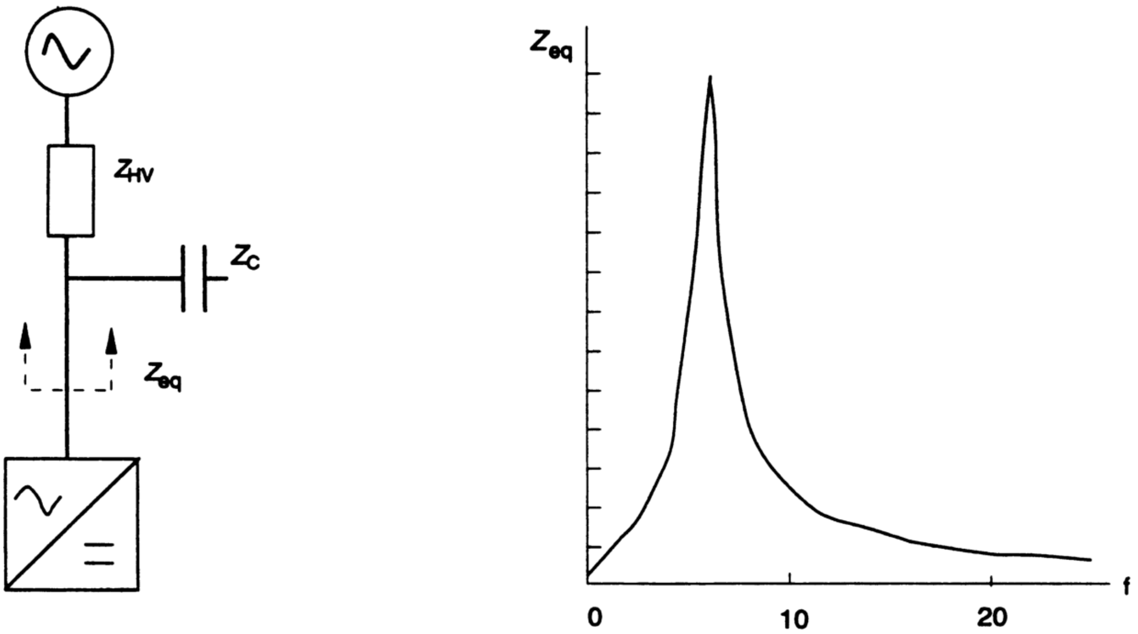
Figure B.1 — Example of calculation of the impedance seen from convertor 1 and convertor 2



a) Single line diagram of the a.c. supply for an industrial installation

b) Locus of the network impedance at a given frequency (depending on the characteristics of HV network)

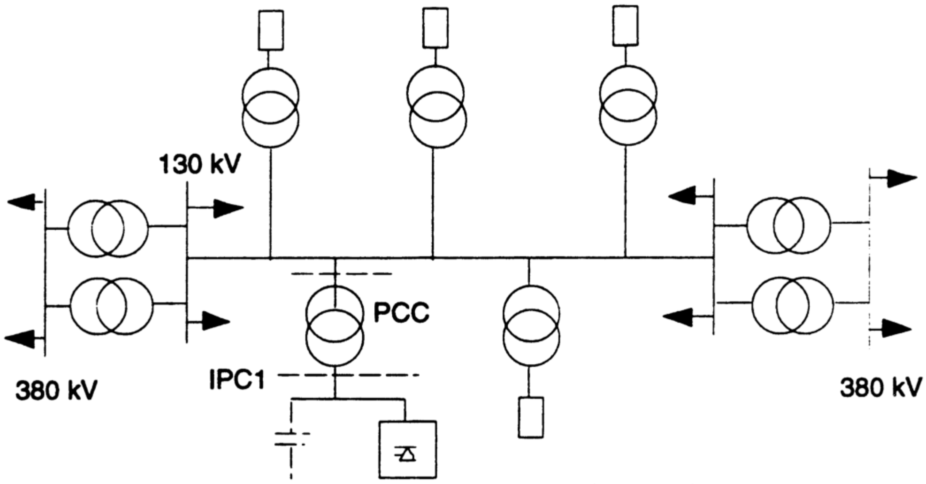
Figure B.2 — Harmonic impedance for a simple network. HV resonance



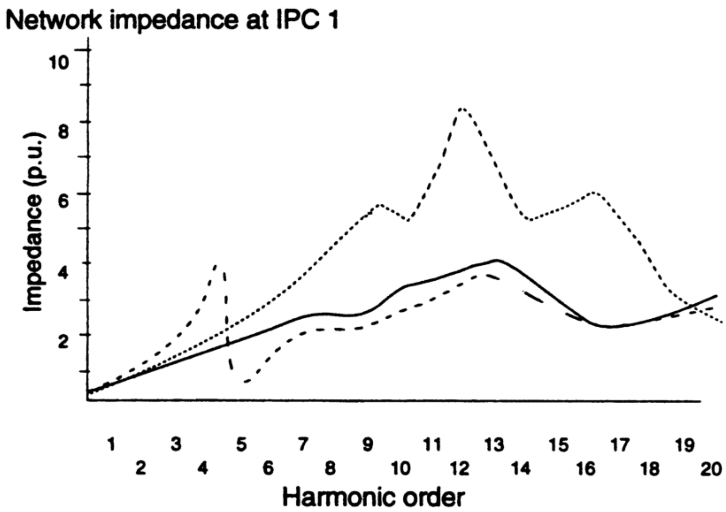
a) Single line diagram for the supply of an industrial installation

b) Network impedance versus frequency

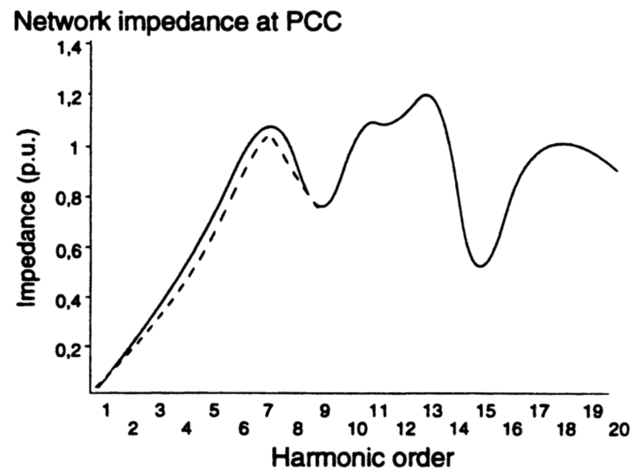
Figure B.3 — Example of resonance in a low voltage network



a) One line diagram of the HV supply of an industrial installation



b) Impedance as seen at IPC 1



c) Impedance as seen at PCC

Solid lines: no power factor capacitor at IPC 1
Broken lines: 3 Mvar capacitors at IPC1
Dotted lines: 3 Mvar capacitors with detuning series reactors

Figure B.4 — Harmonic impedance of complex network. Impedance p.u. based on 100 MVA

Annex C (informative) Interharmonic line current of indirect convertors

C.1 Calculation of RMS value of the link current I_{hi} of the line and the load commutated indirect inverter

C.1.1 *Three-phase load side convertor. Evaluation of the current in the filter (smoothing-reactor only)*

$$I_{Ih} = \frac{U_{Ih}}{4 \pi k p_A f_A \left(\frac{L_d}{2} + \frac{f_L e_{xL} P_{tL}}{f_A I_{tL}^2} + \frac{e_{xA} P_{tA}}{I_{tA}^2} \right)} \qquad \text{(C.1)}$$

where

f_{Ih}	is equal to 6 $k f_A$;
I_{Ih}	is the intermediate link current component (A r.m.s.);
f_L	is the a.c. supply frequency (Hz);
U_{Ih}	is the harmonic (or d.c.) voltage load side (V r.m.s.) see Figure C.1;
L_d	is the smoothing-reactance (H);
e_{xL}	is the relative short-circuit voltage at line side;
e_{xA}	is the relative short-circuit voltage at load side;
I_{tL}	is the rated current line side (A r.m.s.);
I_{tA}	is the rated current load side (A r.m.s.);
P_{tL}	is the rated power of the line connected transformer (VA);
P_{tA}	is the rated power of the load connected transformer (VA);
p_A	is the pulse-number of the load side invertor.

C.1.2 *Single phase load (for example convertor for inductive heating)*

Evaluation of the current in the inductive current filter neglecting the commutation overlap.

$$I_{Ih} = \frac{\frac{4 U_{di0}}{\pi \left(4 k^2 - 1\right)} \sqrt{\left(\cos \beta\right)^2 + 4 n \left(\sin \beta\right)^2}}{2 \pi k f_A \left(\frac{L_d}{2} + \frac{f_L e_{xL} P_{tL}}{f_A I_{tL}^2} + e_{XA} \frac{P_{tA}}{I_{tA}^2} \right)}$$

$$f_{Ih} = 2 k f_A \qquad \text{(C.2)}$$

where

n, k	are integers;
f_{Ih}	is the frequency of I_{Ih} component (Hz);
U_{di0}	is the no-load voltage of the load side convertor (V r.m.s.);
β	is the phase-control angle of the load side convertor;
f_A	is the frequency of the load side convertor.

For the other symbols see above.

C.2 Calculation of r.m.s.-value of the line current interharmonics

The following formula applies for the evaluation of the factor G given in Figure 3 a) and Figure 3 b):

$$G = \frac{I_{hh}}{I_{Ih}} = \frac{\sqrt{3}}{\pi\left(1 \pm n p_L\right)} \qquad (C.3)$$

The influence of commutation overlap is here neglected, it has no significant effect if n $\leq$ 2.

In absence of detailed information, use the following values for estimation:

$I_{Ih} \approx 0{,}3\ I_d$ for current source convertors in the intermediate link

$I_{Ih} \approx 0{,}1\ I_d$ for voltage source convertors in the intermediate link

C.3 Example of use of graph 3

This graph allows the calculation of the frequency and amplitude of the interharmonic component on the basis of the harmonic component in the intermediate link.

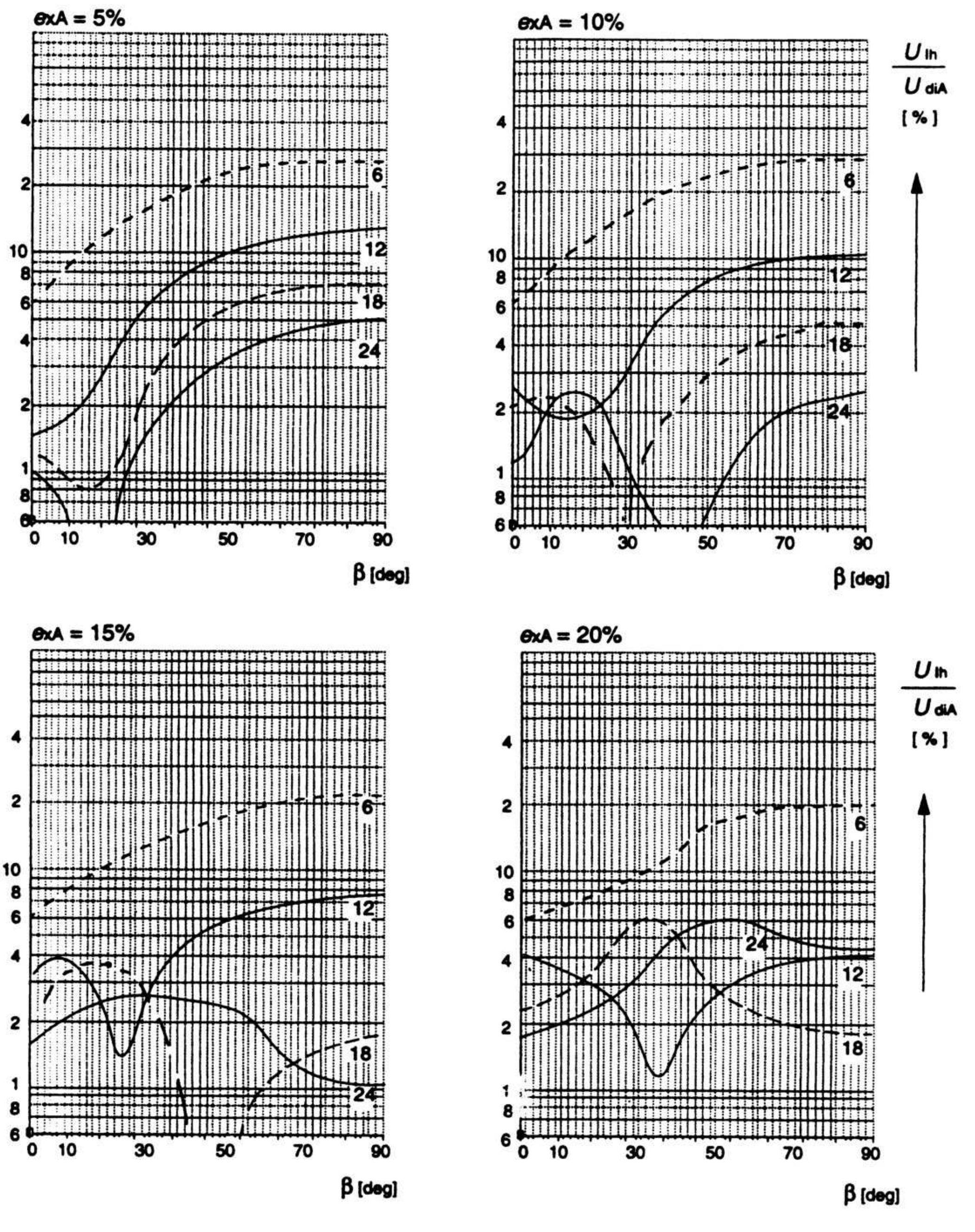
Let us assume that in the link the following current is present:

I_{Ih} = 100 A; f_h = 605 Hz; f_L = 60 Hz

(see the example in Figure C.2).

AC supply convertor		AC supply frequency	Line current amplitude
6 pulses	12 pulses	(Hz)	(A)
X	—	55	5,0
X	—	175	4,2
X	X	185	7,9
X	X	305	11,0
X	X	415	3,4
X	X	535	2,9
X	—	545	55,1
X	—	665	55,1
X	—	775	2,4
X	—	895	2,2
X	X	905	11,0
X	X	1 025	7,9

Evaluation of the interharmonic frequency in the a.c. supply current as caused by a harmonic current in the d.c. link.



U lh Harmonic voltage component of order h
U dIA Ideal no-load d.c. voltage (β = 0) of the load convertor
e xA Relative short-circuit voltage at the load a.c. side
β Phase control angle of the load convertor

Figure C.1 — Harmonic components of the d.c. voltage from a load-commutated convertor connected at the load side of a d.c. link

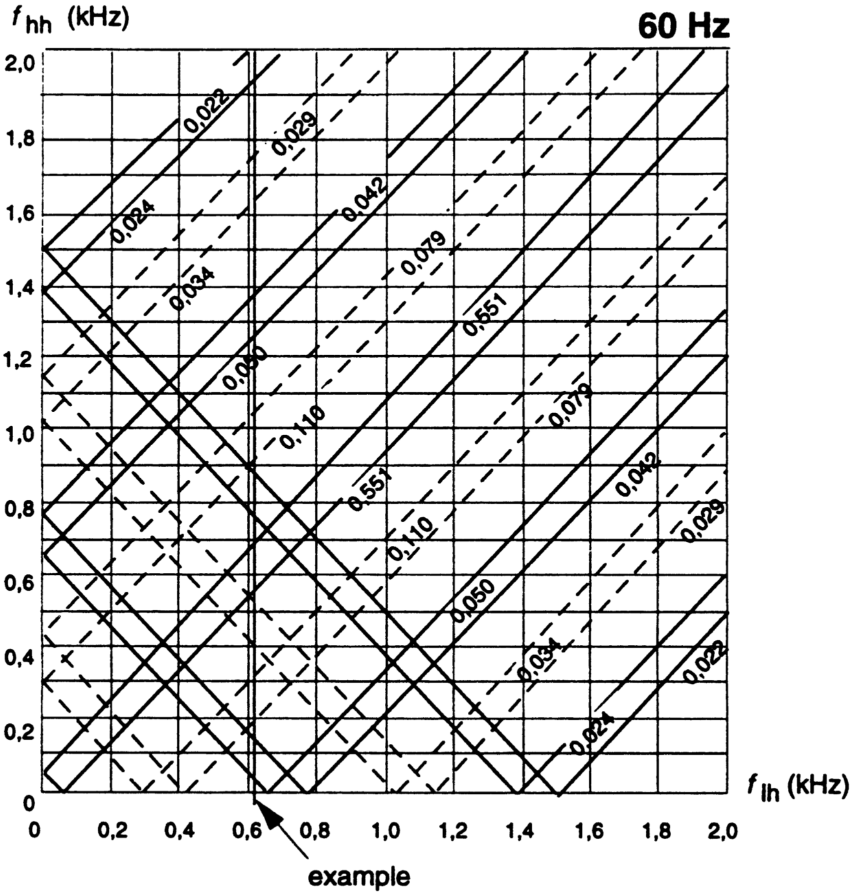


Figure C.2 — Evaluation of the interharmonic frequency in the a.c. supply current as caused by a 605 Hz current in the d.c. link

Annex D (informative) Three phase unbalance

D.1 Description of disturbance sources

D.1.1 *Single-phase loads*

The decomposition in symmetrical components of the current drawn by a single-phase load is further explained by the two vector diagrams in Figure D.1 and Figure D.2. For simplicity, a unity power factor is assumed.

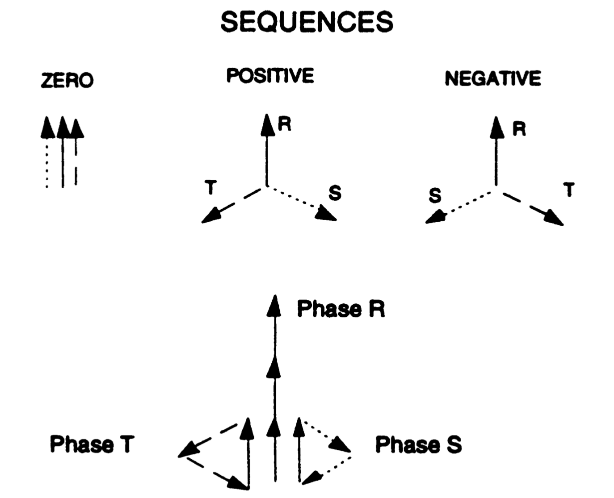


Figure D.1 — Single-phase load between phase R and neutral

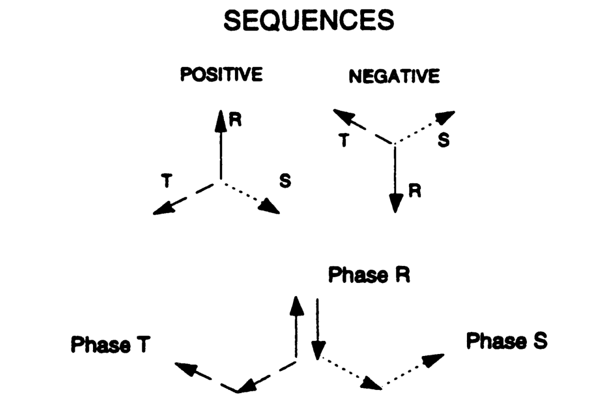


Figure D.2 — Load connected between phases S and T

D.1.2 ***Arc furnaces***

An arc furnace is in principle a three-phase load, but runs with individual phase control in a very unstable process. This makes the arc furnace a major source of unbalanced currents. Since it is connected only to the three phases, and not to the neutral, it draws only positive and negative sequence currents, and no zero sequence. During the meltdown period, the negative sequence current is highest, and is also rapidly varying. The average negative sequence current can, during this period, be as high as 20 % of the rated furnace current, with peaks up to 40 %, see example [14] of Annex E.

A typical registration of negative sequence current during meltdown is shown in Figure D.3.

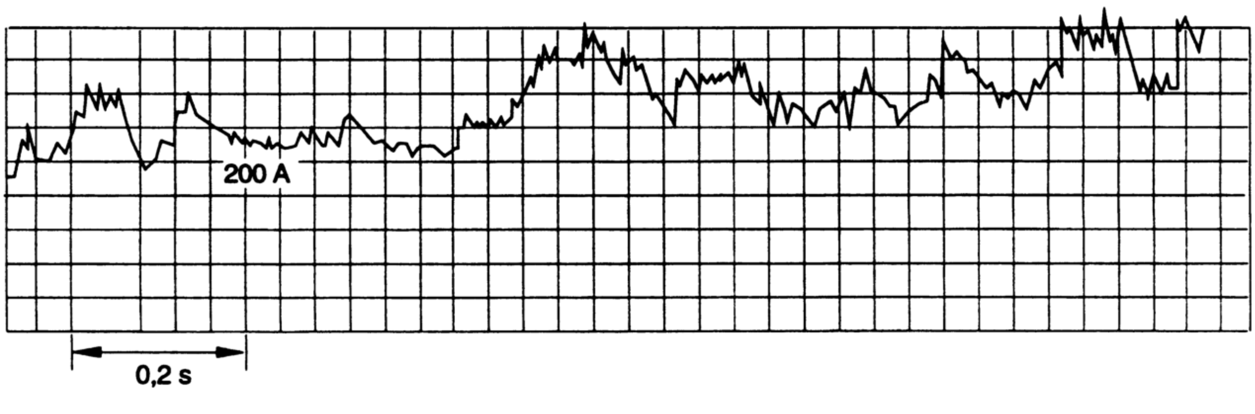


Figure D.3 — Negative sequence recorded on a 22 kV arc furnace feeder with rated current of 944 A

Annex E (informative) Bibliographic references

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