



BSI Standards Publication

Power electronics systems and equipment — Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz

National foreword

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Power electronics systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz

Systèmes et équipements électroniques de puissance – Conditions de fonctionnement et caractéristiques des convertisseurs à alimentation active (AIC), y compris les recommandations de conception pour leurs valeurs d'émission inférieures à 150 kHz

INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER ELECTRONICS SYSTEMS AND EQUIPMENT –

**Operation conditions and characteristics of active
infed converter (AIC) applications including design
recommendations for their emission values below 150 kHz**

FOREWORD

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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62578, which is a technical specification, has been prepared by IEC technical committee TC 22: Power electronic systems and equipment.

This second edition cancels and replaces the first edition published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) IEC TS 62578, in its revised version includes observed values out of practical applications for emission values below 150 kHz.
- b) Therefore the document has been extended compared to the first edition, several detailed analysis results are given in the extended Annexes.
- c) Design recommendations have been derived from the international working group by an assessment of the power supply impedances between 2 kHz and 9 kHz, a comprehensive analysis of the withstand capability of power capacitors against harmonic currents injected by AIC, immunity tests of equipment and considerations about shifted resonances in the power supply network with increased population of undamped filter capacitors.

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

Enquiry draft	Report on voting
22/235/DTS	22/239/RVC

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

The French version of this technical specification has not been voted upon.

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

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

This revision of the technical specification IEC TS 62578 is necessary because active infeed converters (AIC) are a state of the art technology in power electronic products and will be of major importance in order to realize the "smart grid" and the "energy efficiency" initiatives.

AICs in industrial and domestic use are necessary to feedback energy from an energy source (e.g. solar panels, fuel cells or wind turbines) or from a motor load to the power supply network and make it available for other consumers instead of dissipating it as a waste-heat to the environment.

Dispersed power generating equipment uses AICs to synchronise their voltages and currents to the power supply network or to exchange electrical energy between energy storage devices such as batteries and consumers.

Utilities will require information on how to correctly apply the AICs in order to mitigate harmonics in the power supply network.

AICs can also be used to mitigate pre-existing harmonics in the supply system – information on this is of interest to utilities.

Different possible topologies of AICs are described together with their specific advantages.

Warning: The recommendations of maximum emission values for conducted emissions <150 kHz defined in this document are based on observations and experience gained from state of the art AICs operating today in most power supply networks together with other equipment without creating intolerable interference and should lead to an increased acceptance of using AICs.

Nevertheless it has to be highlighted that electromagnetic environment is subject to changes e.g. because of smart grid deployment and that emission limits that are currently under development by the IEC EMC Committees may be different to the maximum emission values recommended in this document.

This document is being issued in the Technical Specification series of publications (according to the ISO/IEC Directives, Part 1, 3.1.1.1) as a "prospective standard for provisional application" in the field of power electronics because there is an urgent need for guidance on the design and use of active infeed converters (AIC) today and in "smart grid environments".

It remains unclear during revision of this document, how and when the smart grid vision will be realized and to what extent in the future. AICs will be the "key link components" if several electrical energy storage devices or storage technologies and energy users are to be connected together and will interact under "smart grid behaviour" conditions. The power supply network may adapt its future characteristics compared to the state of the art while increasing the installed density of AIC.

POWER ELECTRONICS SYSTEMS AND EQUIPMENT –

Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz

1 Scope

This Technical Specification IEC TS 62578 describes the operation conditions and typical characteristics of active infeed converters (AIC) of all technologies and topologies which can be connected between the electrical power supply network (lines) a.c. side and a constant current or voltage type d.c. side and which can convert electrical power (active and reactive) in both directions (generative or regenerative).

Applications with active infeed converters are commonly used with the d.c. sides of adjustable speed power drive systems (PDS), uninterruptible power systems (UPS), active filters, photovoltaic systems, wind turbine systems, battery backed power management systems etc. of all voltages and power ratings.

Active infeed converters are generally connected between the electrical power supply network (a.c. side) and a current or voltage d.c. side, with the objective to avoid emitting low frequency harmonics (e.g. less than 1 kHz) by synthesizing a sinusoidal a.c. current. Some of them can additionally compensate the pre-existing harmonic distortion of a given supply side voltage. They are moreover able to control the power factor of a power supply network section by moving the electrical power (active and reactive) in both directions (generative or regenerative), which enables energy saving in the system and stabilizes the power supply voltage or enables coupling of renewable energy sources or electrical energy storage devices to the supply.

A practical and analytical approach for emission values for AICs in power supply networks is given, which is based on the latest results for line impedance values between 2 kHz and 9 kHz and withstand capability of capacitors connected directly to the supply.

This results in design recommendations for emission values below 150 kHz.

The following is excluded from the scope.

- Requirements for the design, development or further functionality of active infeed applications.
- Probability of interactions or influences of the AIC with other equipment caused by parasitic elements in an installation or caused by poor electronic design as well as their mitigations.
- "Overhead line" power supply networks because of lack of information (measurements) of their three phase impedances. This could be the subject for future editions.

2 Normative references

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

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at www.electropedia.org)

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

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods*

IEC 61800-5-1, *Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*

IEC 62040-1, *Uninterruptible power systems (UPS) – Part 1: General and safety requirements for UPS*

IEC 62103, *Electronic equipment for use in power installations*

IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*
IEC 61000-4-7:2002/AMD1:2008

CISPR 16-1-1, *Radio disturbance and immunity measuring apparatus – Measuring apparatus*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60500 and the following apply

3.1

active equalization of the power supply network

AEP

ability of an AIC to enable and combine smart grid functionalities with a specific main application

Note 1 to entry: Specific main applications include:

- reduce or avoid emitting low frequency harmonics (e.g. less than 2 kHz) from the power supply network by synthesizing a sinusoidal line current
- contributes to controlling the reactive power of a power supply network
- exchanging the electrical power (active and reactive) in generative or regenerative modes
- stabilization of the power supply voltage and energy saving in the supply system
- exchanging electrical energy between power supply networks or other power generations applications like fuel cells and electrical energy storage devices
- coupling of decentralized power sources (e.g. from renewable energy) to the power supply network.

3.2

a.c. filter

filter consisting of passive components, such as inductors, capacitors and resistors connected to the a.c. side of a converter, designed to reduce the circulation of harmonic currents in the associated system

3.3

active filter

AIC operating as a filter to control the specific a.c. side harmonic and interharmonics voltages or currents usually without active power flow

3.4**active infeed application**

application using the properties of an active infeed converter

3.5**active infeed converter****AIC**

self-commutated electronic power converters of all technologies, topologies, voltages and sizes which are connected between to the a.c. power supply network (lines) and usually a stiff d.c. side (current source or voltage source) and which can convert electric power in both directions (generative or regenerative) and which can control the reactive power or the power factor

Note 1 to entry: Some of them can additionally control the harmonics to reduce the distortion of an applied voltage or current.

Note 2 to entry: Basic topologies may be realized as a Voltage Source Converter (VSC) or a Current Source Converter (CSC).

Note 3 to entry: In IEC 60050-551 these terms (VSC and CSC) are defined as voltage stiff a.c./d.c. converter (551-12-03) and current stiff a.c./d.c. converter (551-12-04). Most of the AICs are bi-directional converters and have sources on the d.c. side. So, they are known as voltage source converters and current source converters in this TS.

Note 4 to entry: Some kind of AIC might be realized without a stiff d.c. side (a.c. matrix converter). Also a.c. conversion equipment could be included.

3.6**controlled free-wheeling arm**

by-pass arm constructed with controllable valve device(s)

3.7**controllable harmonics or interharmonics**

set of harmonics or interharmonics which can be influenced directly by the control strategy of the AIC

3.8**conventional converter**

converter based on line commutation technology, that cannot control power factor or harmonics

3.9**converter topology**

different possible arrangements of semiconductor valves and their connections

3.10**d.c. filter**

filter on the d.c. side of a converter, designed to reduce the ripple in the associated system

3.11**d.c. side load**

electrical device consuming or generating power connected to the d.c. side

3.12**effective supply-side filter impedance**

effective impedance of the supply-side filter of the AIC for frequencies in the range of the controllable harmonics or interharmonics

3.13**evidential per unit supply side impedance of the AIC** **$u_{scv, equ}$**

per unit short-circuit voltage drop value of the hardware inductance which is connected between the AIC and the power supply network

$$u_{scv, equ} = Z_{choke} / (U_{LN} / I_{equ})$$

3.14**fundamental and harmonic components**

defined in IEC 60050:101, IEC 60050:161 and IEC 60050:551, respectively and are dedicated for the AIC in this document

3.15**F3E-infeed****fundamental frequency front end infeed**

fundamental frequency front end voltage source converter with its commutation capacitor on the a.c. side which uses line-frequency switched semiconductor valve devices and has regenerative capability

Note 1 to entry: The d.c.-link capacitor which is normally an electrolytic capacitor is basically replaced by an a.c. line side filter, designed to limit the voltage distortion caused by the PWM currents of the inverter stage

3.16**generated harmonics or interharmonics**

set of harmonics or interharmonics which result from the pulse frequency and the pulse pattern

3.17**in-plant point of coupling****IPC**

point on a network inside a system or an installation, electrically nearest to the AIC, at which other apparatus are, or could be, connected

Note 1 to entry: The IPC is usually the point for which electromagnetic compatibility is to be considered. In case of connection to the public supply system the IPC is equivalent to the PCC (Point of Common Coupling).

3.18 **k_{zred}**

ratio of the power supply impedance according to 5.2.4 (95 % values) related to the frequency proportional extrapolated reference impedance according IEC 60725

3.19**line impedance of phase x** **$Z_{Lx, h}$**

line impedance of phase x at harmonic order h

Note 1 to entry: The impedance at a harmonic frequency between the star point of the equivalent power supply and one of the phase terminals at a defined point on a network. The point on a network could be defined to be for example the terminals of the AIC or the in-plant point of coupling.

3.20**long-time energy storage device**

device connected to the d.c.-link directly or by a semiconductor valve device, or a converter, providing rated power for typically seconds to minutes

3.21**neutral impedance at harmonic order h** $Z_{N, h}$

impedance between the star point of the equivalent power supply and neutral terminal at a defined point on a network

Note 1 to entry: The point on a network could be defined to be for example the terminals of the AIC or the in-plant point of coupling.

3.22**PWM controlled converter**

converter using a pulse-width modulation technique in order to control the switching of its semiconductor valve devices

3.23**pulse frequency**

frequency, resulting from the switching frequency and the converter topology, which characterizes, together with the selected pulse pattern, the lowest frequency of non-controllable harmonics or interharmonics at the IPC (in-plant point of coupling)

Note 1 to entry: The switching frequency itself may not be present as a harmonic or interharmonics

3.24**pulse pattern**

pattern of the switched voltages or currents, measurable at the terminal of the converter, resulting from pulse frequency and modulation schemes used

3.25**rated apparent power of equipment** S_{equ}

value calculated from the rated r.m.s. line current I_{equ} of the piece of equipment stated by the manufacturer and dependent on the rated interphase voltage U_{LL}

$$S_{\text{equ}} = \sqrt{3} \times U_{\text{LL}} \times I_{\text{equ}} \quad \text{for balanced three phase equipment}$$

$$S_{\text{equ}} = U_{\text{LL}} \times I_{\text{equ}} \quad \text{for interphase equipment}$$

$$S_{\text{equ}} = U_{\text{LN}} \times I_{\text{equ}} \quad \text{for single phase equipment}$$

3.26**reactive power converter**

converter for reactive power compensation that generates or consumes reactive power without the flow of active power except for the power losses in the converter

[SOURCE: IEC 60050-551:1998, 551-12-15]

3.27**short-circuit power** S_{SC}

value of the three-phase short-circuit power calculated from the nominal line to line system voltage U_{LL} and the impedance $Z_{\text{Lx},1}$ of the system at the point of common coupling (PCC)

Note 1 to entry: In this case the U_{LL} is the nominal line to line voltage of the power supply network.

$$S_{\text{SC}} = (U_{\text{LL}})^2 / Z_{\text{Lx},1}$$

where

$Z_{\text{Lx},1}$ is the supply impedance at the fundamental frequency.

3.28**short-circuit ratio** **R_{SCe}**

characteristic value for the application of a single equipment derived from the Ratio of short-circuit power of the supply to the rated apparent power of the AIC of the single equipment (S_{equ})

$R_{SCe} = S_{SC} / S_{equ}$ for balanced three phase equipment

$R_{SCe} = S_{SC} / (2 * S_{equ})$ for interphase equipment

$R_{SCe} = S_{SC} / (3 * S_{equ})$ for single phase equipment

3.29**short-time energy storage device**

one or more inductors or capacitors providing rated power for about 1 ms to 10 ms and directly connected to the d.c. side

Note 1 to entry: Short time energy storage is used to have a stiff voltage or current characteristic or operate the AIC continually in short time a.c. voltage dip, and time could be more than 10 ms.

Note 2 to entry: Long-time energy storage is used to provide energy to a.c. power system.

3.30**switching frequency**

frequency with which the semiconductor valve devices of a PWM converter are operated

Note 1 to entry: In some converters the switching frequency may not be the same for all semiconductor valve devices.

3.31**total impedance**

resulting impedance consisting of the supply impedance and the supply-side filter impedance of the AIC

3.32 **$U_{LL, 1}$**

fundamental frequency line to line voltage rms value of the power supply network

3.33 **$U_{LL, h}$**

harmonic line to line voltage rms value of the power supply network

3.34 **$U_{LN, h} / U_{LN, 1}$**

relative voltage (line to neutral voltage) at order h

Note 1 to entry: ratio of a harmonic line to neutral voltage amplitude to the fundamental frequency line to neutral voltage amplitude

3.35 **$U_{LL, h} / U_{LL, 1}$**

relative harmonic voltage (line to line) at order h

3.36 **$X_{L, h}$**

actual resulting reactance of the power supply network at the IPC

Note 1 to entry: The index "h" means in any case that the dedicated reactance is considered at a certain harmonic order.

3.37 **$Z_{L,h}$**

actual resulting impedance of the power supply network at the IPC

Note 1 to entry: For harmonic calculation for a single phase load: $Z_L = Z_{Lx} + Z_{LN}$ is used. For a three phase load: $Z_L = Z_{Lx}$ is used. The index "h" means in any case that the dedicated impedance is considered at a certain harmonic order.

4 General system characteristics of PWM active infeed converters connected to the power supply network

4.1 General

In this clause, the voltage source AIC, which is used in large numbers, is chosen as the example.

4.2 Basic topologies and operating principles

4.2.1 General

Active Infeed Applications are mainly available with capacitive (VSC) or inductive (CSC) smoothing on the d.c. side. Some converter concepts use no or nearly no d.c.-side smoothing. The majority of installed units utilize capacitive smoothing.

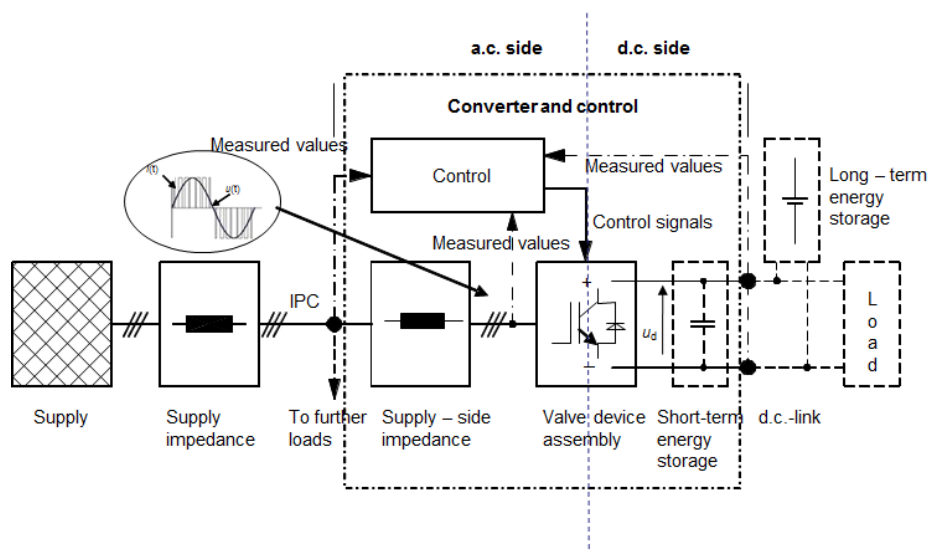
Depending on the rated power and the power supply network availability the connection to the power supply network may be single-phase or three-phase. The three-phase version is selected for the examples.

4.2.2 Operating principles

The main operating principle is to switch the d.c.-side potentials or the d.c.-side currents to the a.c. side conductors with a pulse frequency of normally between 300 Hz and 20 kHz. In this way the desired voltages or currents on the a.c. side are realised as mean values. The pulse frequency is normally high compared to the line frequency and allows quick and accurate control of the voltages and currents on the a.c. side. However, switching between fixed potentials or currents generates undesirable distortions in the high frequency range. Passive a.c.-side filters might be required to mitigate those.

A control system allows a precise control of the fundamental and additional harmonic components. The frequency up to which harmonics can be controlled is determined by the pulse frequency of the converter.

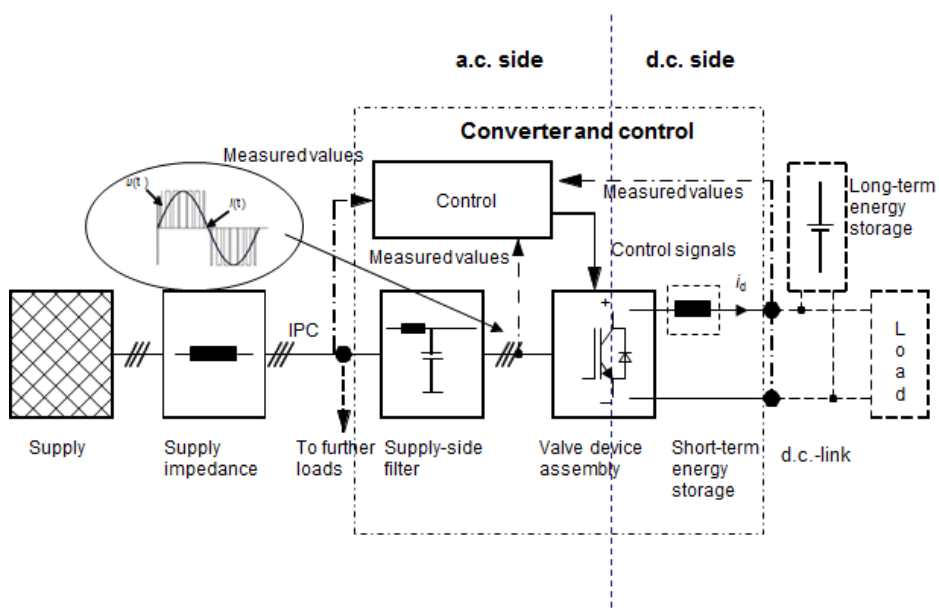
The usual structure of VSC and CSC systems is shown in Figure 1 and Figure 2, respectively:



IEC

NOTE The valve device symbols are used merely for illustration.

Figure 1 – AIC in VSC topology, basic structure



IEC

NOTE The valve device symbols are used merely for illustration.

Figure 2 – AIC in CSC topology, basic structure

Figure 1 and Figure 2 show that the structure of voltage and current source converter systems is very similar. The main differences can be found on the d.c. side, the a.c. side filters and in the type of semiconductors used for the valve device part of the converter. Details can be found in the sections covering the different topologies.

The structure can be separated into three parts.

- Supply impedance at the internal point of coupling (IPC) (see Figure 2) which is mainly inductive.
- Converter and control up to the d.c. side. This part usually contains an a.c. side filter, typically realized as supply side inductance or an LCL-filter with a T-structure.

transformer, if used, is part of (or designed to be used as) the supply-side filter choke. Next in the chain is the valve device part, which may vary in structure – see the following subclause on different topologies as well as on the d.c.-side load characteristic (capacitive smoothing or inductive smoothing). The control typically uses pulse width modulation principles like space vector modulation, optimised synchronous pulse patterns or hysteresis or sliding mode control for pulse pattern generation. In case of space vector modulation the pulse frequency is fixed. In case of optimised synchronous pulse patterns the pulse pattern normally has a fixed shape and is synchronous with respect to the line frequency.

- Load side. The majority of equipment connected are various energy sources or PWM-converter-fed machines. Another typical application are converters to feed passive or mixed loads, as for example in uninterruptible power systems (UPS). If the AIC is used for power factor compensation or harmonic control the load is not required, but can be included. In case of voltage source converters long-term energy storage units may easily be connected in parallel with the d.c.-side smoothing capacitor. In typical applications the d.c.-side smoothing capacitor supplies the rated power for about 1 ms to 10 ms without tripping of the converter. The long-term storage may typically provide rated power for seconds to minutes.

4.2.3 Equivalent circuit of an AIC

The stationary behaviour of AICs is best described using the equivalent circuit consisting of equivalent sources and impedances given in Figure 3.

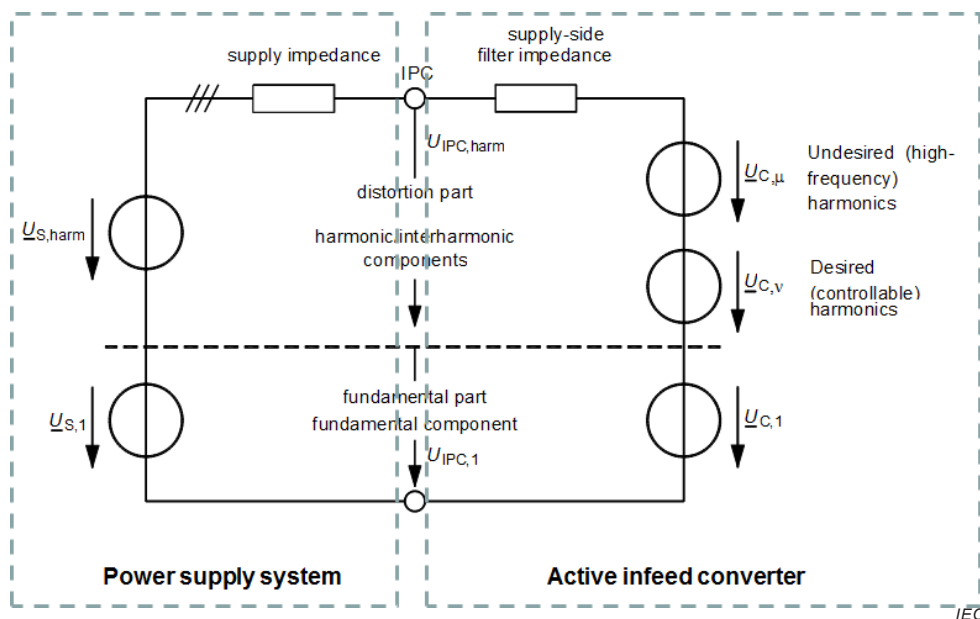


Figure 3 – Equivalent circuit for the interaction of the power supply network with an AIC

For better understanding it is advantageous to separate the power supply network voltages and the converter voltages into their fundamentals and the remaining harmonics. For the converter voltages, two sets of harmonic voltages may be distinguished.

- One set of harmonics which can be controlled directly. This set is defined as controllable or desired harmonics and characterised by the index ν .
- One set of harmonics results from the pulse frequency and the pulse pattern. This set is defined as undesired (generated) harmonics and characterised by the index μ .

The voltage $U_{s,h}$ is the superposition of all (desired and undesired) harmonics caused by all loads.

NOTE Similar conclusions can be drawn concerning current source AICs. In this case the set of voltages in Figure 3 has to be replaced by a set of currents.

4.2.4 Filters

The supply side filter is usually designed to let the desired harmonics pass through the filter and to mitigate the undesired harmonics to a value prescribed by the EMC specifications of the environment. If necessary, additional filter measures may be applied.

Additional design criteria may result from the power-supply system conditions at the IPC as well as from economic constraints.

It should be noted that the frequency of the undesired harmonics is mainly from pulse frequency on upward. The specification of the converter-side filter inductor has to take these high frequencies into account, otherwise the inductor will overheat.

The d.c.-side filter, if used, has to attenuate the ripple of the d.c. voltage or current so that the converter and the possibly connected devices function properly. The specification of the d.c.-link filter has to take the amount of harmonics into account, otherwise it may overheat

In some cases the energy-storage capability of the d.c.-side filter is adapted to the dynamic requirements of the application. One application is the ride-through (continue operation during and after a short interruption of the power supply network). Rapid changes of the energy flow in the power supply network or the load during power transients also need larger d.c. side energy storage elements otherwise the characterising d.c.-link quantity (voltage or current) may leave the tolerance band in which proper operation of the PWM converter is guaranteed. An overshoot of voltage or current, even for a very short time, may destroy the semiconductor valve devices of the converter.

For the fundamental frequency and the controllable harmonics, the supply-side filter may be regarded as purely inductive. Depending on the topology and the chosen control principle, the voltage drop across the total impedance drives the supply-side current.

The total impedance should be limited to allow proper dynamic control of the supply side current.

4.2.5 Pulse patterns

The selected pulse pattern generation scheme greatly influences the characteristics of the converter. The three main basic pattern generation schemes are space vector modulation, optimized synchronous pulse-width modulation and line flux guidance.

NOTE Space vector modulation and symmetric pulse width modulation lead to identical pulse patterns.

In case of space-vector modulation a sequence of zero states and non-zero voltage space vectors is selected in such a way that the voltage space vector requested by the control results as a mean value of the sequence. The zero states selected have to be of equal duration.

In case of symmetric pulse-width modulation, a set-point curve is compared to a triangular reference function. Two ways of treating the set-point curve are known:

- natural sampling directly compares the (analogue) curve to the triangular reference function;
- regular sampling samples values of the set point curve at the extreme values of the triangular function and compares these sampled values to the reference function.

Digital controllers normally use regular sampling. The difference between the two methods is small but leads to slightly different generated harmonics.

A suitable instantaneously defined zero-sequence component added to the reference values assures equal zero-state duration. This is sometimes called “addition of multiple of third order harmonic”. If the half value of the mean of the three phase signal is added to all signals, the result is identical to space vector modulation.

4.2.6 Control methods

A basic introduction into control methods is described in Clause A.1. More detailed description can be found in the references.

4.2.7 Control of current components

The AIC gives the possibility to adjust the fundamental and controllable harmonic components fed into or taken from the line. This feature effectively can be used for mitigation purposes. As a secondary effect, high frequency distortion is generated, which might have to be mitigated by a suitable filter.

The line voltage given by Figure 3 is normally unknown, as is the line impedance that may change without notice, depending on the actual line configuration, including other loads attached. Therefore, control schemes are usually based on the measurable voltage at the IPC (see Figure 1 and Figure 2). In addition, d.c. link quantities are measured.

The flexibility of AICs and associated control schemes offer a large variety of applications and associated control schemes. The main objectives are, however, control of active power and control of reactive power or non-active (vector sum of reactive plus harmonics) power. The desired behaviour can be achieved by controlling the currents caused by the AIC. References for the active, reactive, non-active and purely harmonic currents have to be derived from the line voltages.

One possibility to define the reference for the current is to use resistive load emulation. Energy is then fed to the d.c. link from every available supply voltage component, thus adding damping for undesirable components. If the voltages at the IPC are non-sinusoidal, the line currents will be consequently non-sinusoidal, too.

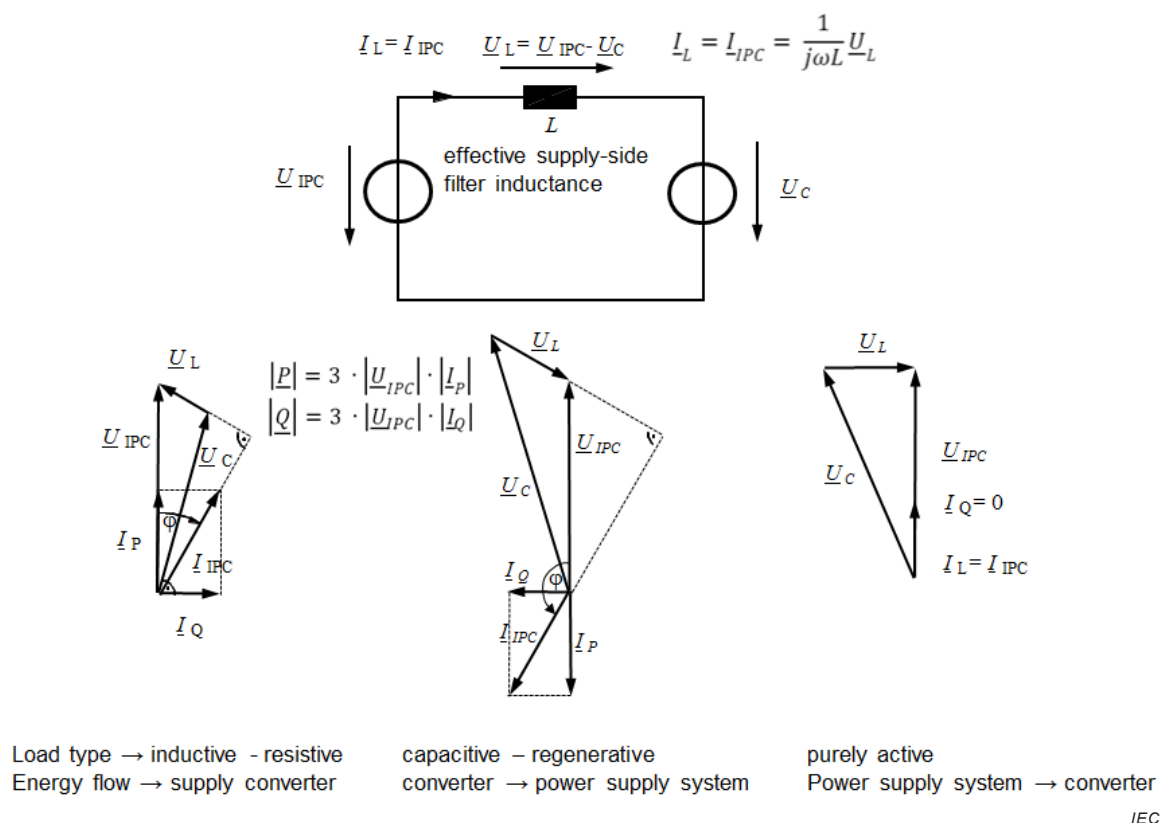
The drawback of resistive load emulation is that it may become unstable and increase harmonics if an attempt is made to feed energy to the supply from the d.c. link. In this case energy should be delivered to the supply only via the fundamental component of the current.

4.2.8 Active power factor correction

This consideration is based on fundamental frequency components described by vectors.

Adequate control of the line-side converter voltage $\underline{U}_C$ allows the voltage $\underline{U}_L$ across the effective supply-side filter impedance to be adjusted to a desired value. This voltage then causes the desired line current $\underline{I}_L$ to flow. In this way the AIC is able to impress any desired amount of reactive current, including zero – and cause any desired amount of reactive power, including zero – inside its specifications. The converter can thus be used as a compensator to maintain a certain voltage level in the a.c. side supply by additionally impressing capacitive or inductive currents.

For an ideal active power factor correction the currents of the filter inductances are orthogonal (they lag or lead by 90°) to the respective supply voltages. Examples of vector diagrams are shown in Figure 4.



NOTE PCC in this case can also be replaced by IPC.

Figure 4 – Voltage and current vectors of line and converter at fundamental frequency for different load conditions

It is obvious that the line-side converter voltage has to be larger than the voltage at the IPC in many cases, depending on the operation point. This has to be taken into account when specifying rated values for the converter. As mentioned above, further reserves are needed for dynamics.

4.3 AIC rating

4.3.1 General

The required AIC ratings are an accumulation of requirements of several origins like sinusoidal conditions, harmonic currents and dynamic conditions.

4.3.2 Converter rating under sinusoidal conditions

The worst-case condition for operation is with rated current, purely capacitive, at the maximum allowed level of the voltage at the IPC. In this case the converter still has to deliver the peak value of line-side converter voltage required instantaneously. Otherwise the amount of capacitive current has to be limited or the line currents will not be as desired.

4.3.3 Converter rating in case of harmonic currents

In addition to the rating discussed for sinusoidal condition in the preceding section, further requirements follow from harmonic currents control. The equivalent circuit diagram (Figure 4) remains valid.

Each desired current harmonic requires an additional voltage at the effective supply-side filter impedance. The superposition principle is applicable. Therefore, all required voltages can be

added. Depending on the phase angle of the harmonic current, the instantaneously required peak value of the converter voltage varies. As a worst-case rating, all peak values of voltage resulting from the fundamental and all desired harmonics have to be added to the peak value of the voltage at the IPC for maximal instantaneous converter voltage. If the rating of the converter does not allow handling this voltage, line currents will not be generated as desired.

In special cases, where the voltage at the IPC contains many harmonics, the peak value of the voltage at the IPC including worst-case superposition of harmonics has to be used for the rating of the converter.

4.3.4 Converter rating under dynamic conditions

The equivalent circuit (Figure 4) still remains valid. However, now the currents in the effective supply-side impedances have to be changed dynamically. This requires a certain amount of voltage across these impedances. This voltage has to be supplied by the converter. Depending on the desired dynamic performance the rating of the converter has to be matched to allow large enough instantaneous values of the AIC voltages.

5 Electromagnetic compatibility (EMC) considerations for the use of AICs

5.1 General

In this clause a selection of EMC aspects is covered. The selection is done in order to choose the appropriate AIC functionality with the provision that there should be no disturbing interference at the power supply network with other equipment.

Moreover the active equalization of the power supply network by using an AIC will be described as well as the typical side effects by using an AIC.

The determination of the power supply impedance in the range between 2 kHz and 20 kHz, the typical withstand capability of power capacitors and other equipment and the displacement of resonance frequencies in the power supply network are considered. This leads to the recommendation of design guidelines for emission values of AICs in the range of 2 kHz up to 150 kHz.

Emission and immunity are given in the relevant product standards e.g. IEC 61800-3 in the case of Power Drive Systems or IEC 62040-2 for Uninterruptible Power Systems.

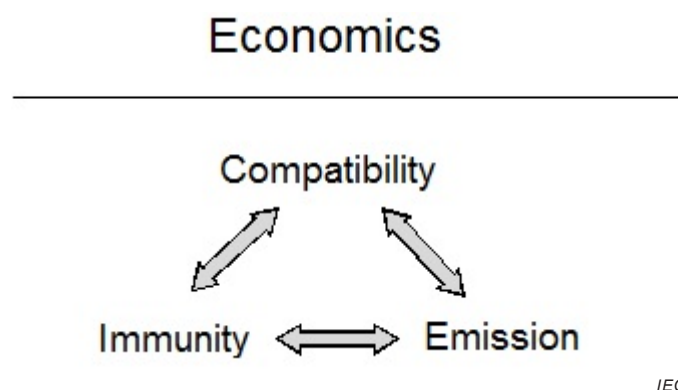


Figure 5 – The basic issues of EMC as tools of economics

The minimum required immunity of electric apparatus, the compatibility levels in the power supply network and the maximum allowed emission of disturbances are directly related to each other. All of them are subject to economic considerations (see Figure 5).

The acceptance of the recommended design guidelines for emission values between 2 kHz and 150 kHz will allow widespread use of AICs in multiple applications for the control of electrical energy in the context of the Smart Grid and Energy Efficiency initiatives.

In the frequency range between 2 kHz to 9 kHz a system of multiple AICs can be designed to meet the emission values at the PCC. This allows the use of cancellation techniques when multiple AICs are used together.

This approach might also be considered above 9 kHz. However, it may be less valid near 150 kHz, due to radiated effects.

5.2 Low-frequency phenomena (<150 kHz)

5.2.1 General

Low-frequency EMC phenomena mainly occur due to conductive, inductive and capacitive coupling of the power supply network to the neighbouring networks and also due to interference between devices connected to the supply network.

Harmonics, voltage fluctuations, voltage dips and commutation notches are part of the low-frequency power supply related phenomena. However, voltage fluctuations and commutation notches are significantly reduced compared to conventional converters.

AICs generate distortion with frequencies originating from the switching of the semiconductor valve devices which have to be sufficiently mitigated by the supply-side filter of the AIC (see Figure B.2).

The power supply network's impedance and short-circuit ratio R_{SCe} have a decisive impact (see 5.2.3.2) on the filter performance. The supply system, its configuration and the load have to be considered together in the evaluation. Thus technical possibilities for the limitation of emissions have to be analysed individually for each application.

If several AICs are connected to the same supply system it has to be noted that the resulting voltage distortion will be lower or equal to the distortion caused by one big equivalent AIC due to the random superposition.

It has to be noted that non-sinusoidal input current is not only generated by distortion of the AIC, but as well by non-sinusoidal supply voltage, causing parasitic currents flowing through applied capacitive input filters.

Measuring quantities at the d.c.-side connections and/or at the supply-side filter is a challenging task. Measuring equipment with a bandwidth of ten to twenty times the pulse frequency is required in case harmonics need to be measured.

See additional information in Annex B.

5.2.2 Emerging converter topologies and their advantages for the power supply network

Figure 7 and Figure 8 show the technological progress and the main milestones of different topologies (see Figure 6) with impact on the power supply network by presenting their typical wave shapes for power supply current distortions and voltages.

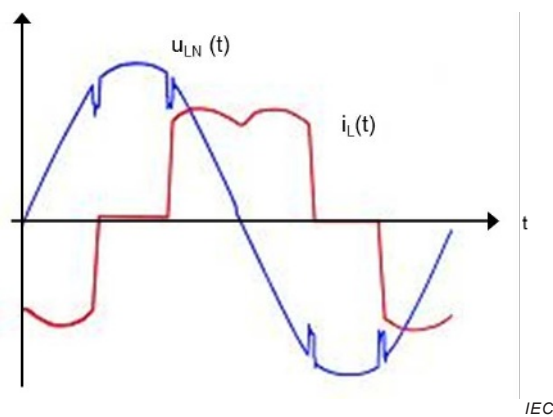


Figure 6 – Typical power supply network current $i_L(t)$ and voltage $u_{LN}(t)$ of a phase controlled converter with d.c. output and inductive smoothing

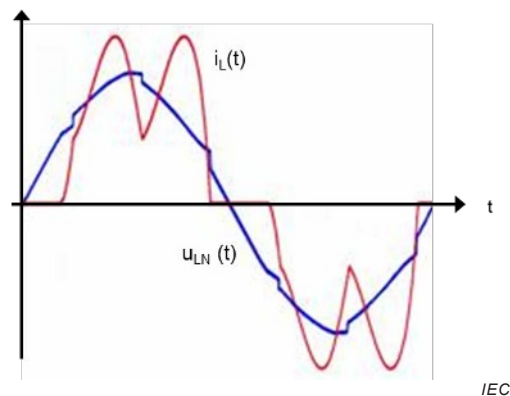


Figure 7 – Typical power supply network current $i_L(t)$ and voltage $u_{LN}(t)$ of an uncontrolled converter with d.c. output and capacitive smoothing

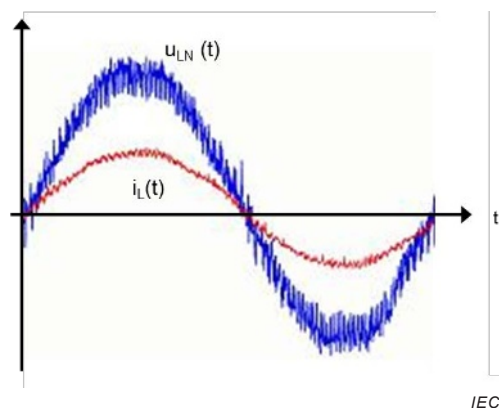


Figure 8 – Typical power supply network current $i_L(t)$ and voltage $u_{LN}(t)$ of an AIC realized by a PWM Converter with capacitive smoothing without additional filters

With the emerging technology development, the approach towards an ideal sinusoidal wave shape of the equipment input current (which had been a goal since long time) has been more closely achieved.

5.2.3 Active equalizing of the power supply network

5.2.3.1 General

An AIC is able to supply active and reactive power (capacitive or inductive) in both directions (4-quadrant operation). Thus if the AIC is correctly rated the user can apply a dynamic reactive power compensation without additional compensator facilities. Figure 9 shows an example of attainable active and reactive power of the AIC at different line voltages.

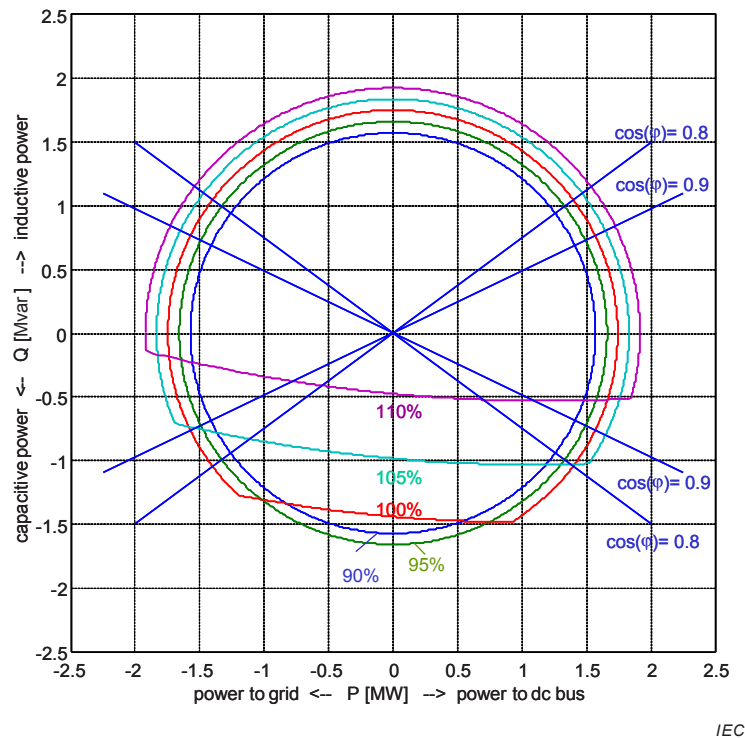


Figure 9 – Example of attainable active and reactive power of the AIC (VSC-type) at different line to line voltages in per unit (with 10 % combined transformer and filter inductor short-circuit voltage, X/R ratio = 10/1, d.c. voltage = 6,5 kV)

For an AIC based on PWM technology, virtually no harmonic current distortion occurs below the pulse frequency unless they are generated intentionally for the purpose of eliminating particular harmonic components (see 4.2.7).

In this case the converter will generally improve the quality of the power supply network (active equalizing of the power supply network) by compensating low frequency harmonics to a desired extent. Further, pre-existing disturbances may be even mitigated by such converters equipped with an appropriate control system and/or higher order filters. A significant portion of harmonic currents at the IPC may be caused by the background distortion of the power supply network voltage.

The different harmonics can be calculated using Fourier analysis and reduced or compensated by separate controllers. An example of a so called active filter is shown in Figure 11 for three phase loads but the method is also applicable to single phase cases.

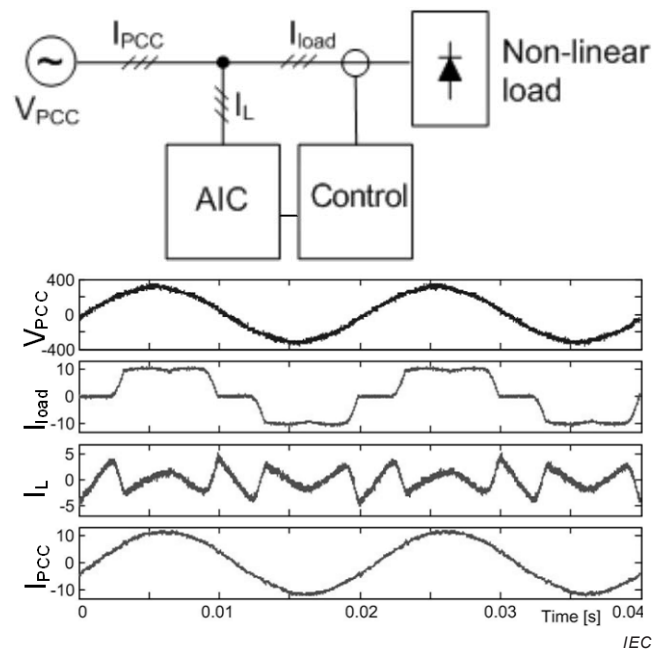


Figure 10 – Principle of compensating given harmonics in the power supply system by using an AIC and suitable control simultaneously

5.2.3.2 Typical side effects

As a typical side effect of the active compensation with the switching action of the semiconductor valves in the AIC, harmonic distortion may occur near the pulse frequency and at integer multiples of it.

NOTE 1 The following text refers to two-level topology according to Clause 6. In case of the application of three-level or multilevel technology, the voltage distortions are substantially lower.

Contrary to a phase controlled bridge with current source characteristic (conventional converters), the voltage waveform of an AIC (VSC) on the supply side of the bridge is determined by the switching action of the semiconductor valves and the voltage of the d.c. link capacitor, see Figure 10. Furthermore, the pulse pattern is fairly independent of the load of the converter.

Due to this characteristic the voltage distortion caused in the power supply network depends on the pulse pattern applied and the voltage sharing between the impedance of the power supply network and the impedance of the supply-side filter of the AIC. When a simple L-filter is used and the capacitances and resistances of the supply system are ignored, this causes the highest distortion. Figure 11 and formulae (1), (2) and (3) show the formation principle of the distortion in the line-to-line and line-to-neutral voltage generated by an AIC with an L-filter and assuming that the supply impedance is inductive.

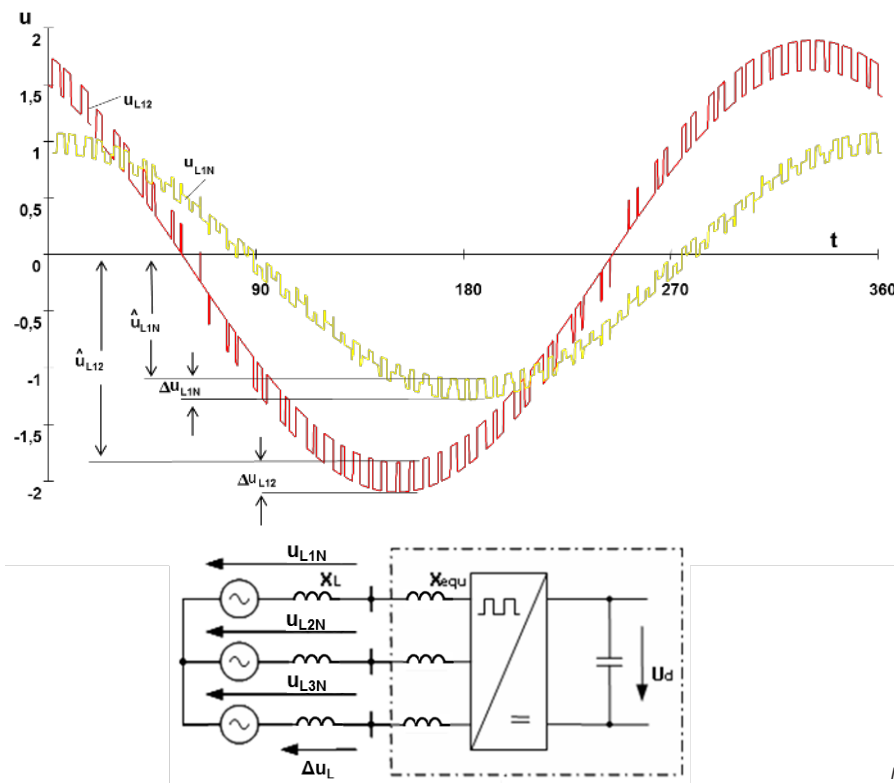


Figure 11 – Typical Voltage Distortion in the Line-to-Line and Line-to-Neutral Voltage generated by an AIC without additional filters (u in % and t in degrees)

$$\frac{\Delta U_{L1N}}{2 \cdot \hat{U}_{L1N}} = \frac{1}{3} \cdot \frac{U_d}{\hat{U}_{L1N}} \cdot \frac{X_L}{X_L + X_{equ}} \quad (1)$$

$$\frac{\Delta U_{L12}}{2 \cdot \hat{U}_{L12}} = \frac{1}{2} \cdot \frac{U_d}{\hat{U}_{L12}} \cdot \frac{X_L}{X_L + X_{equ}} \quad (2)$$

typically:

$$\frac{U_d}{\hat{U}_{L12}} \approx 1,1 \text{ and } \frac{U_d}{\hat{U}_{L1N}} \approx 1,1 \cdot \sqrt{3} \quad (3)$$

Taking into account the frequency dependency of the network impedance according to Figure 27, Formula (2) changes to Formula (4). In order to evaluate the expected distortion in the supply system, it is advisable to use the short-circuit power ratio R_{Sce} for calculation.

$$\frac{\Delta U_{(L1-L2)}}{2 \cdot \hat{U}_{(L1-L2)}} \approx \frac{1}{2} \cdot 1,1 \cdot \frac{X_h}{X_h + u_{scv, equ} \cdot R_{Sce} \cdot h \cdot X_{L1}} \quad (4)$$

Using the formula for k_{Zred} according to 3.18:

$$k_{Zred} = \frac{X_h}{h \cdot X_{L1}} \quad (5)$$

The formula changes to:

$$\frac{\Delta U_{(L1-L2)}}{2 \cdot \hat{U}_{(L1-L2)}} \approx \frac{1}{2} \cdot 1,1 \cdot \frac{X_h}{X_h + u_{scv, equ} \cdot R_{Sce} \cdot \frac{X_h}{k_{Zred}}} \quad (6)$$

Dividing by X_h leads to:

$$\frac{\Delta U_{(L1-L2)}}{2 \cdot \hat{U}_{(L1-L2)}} \approx \frac{k}{1 + u_{scv, equ} \cdot R_{Sce} \frac{1}{k_{Zred}}} = f(k; u_{scv, equ}; R_{Sce}; k_{Zred}) \quad (7)$$

In the example given in Figure 11 the pulse frequency is 3 kHz, short-circuit power ratio of $R_{Sce} = 100$ and the supply-side L-filter inductor $u_{SCV, equ} = 6\%$ (referenced to the base impedance of AIC $Z_B = U_{nominal}^2 / S_{equ}$, thus $X_{equ} = 0,06 R_{Sce} X_L$).

With these values the amplitude of the 3 kHz-ripple in the line-to-line voltage is approximately 1,3 %. Figure 12 shows the typical pulse frequency voltage distortion in the power supply network depending on R_{Sce} and $u_{SCV, equ}$ for an AIC (PWM type; 2-Level) with a pulse frequency of 3 kHz and passive mitigation provided by an L-filter.

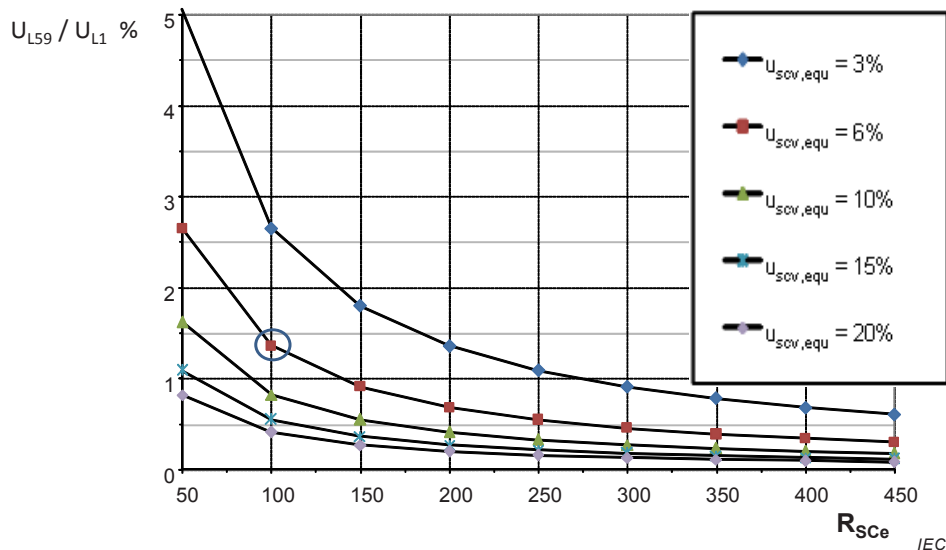


Figure 12 – Basic characteristic of the relative voltage distortion (59th harmonic) of one AIC operated at a pulse frequency of 3 kHz versus R_{Sce} with the line impedance according to 5.2.4

Regarding the side effects on the power supply network it is furthermore remarkable for AICs that the supply impedance plays a more important role in the harmonic current distortion than it does with the conventional converters. The impact is greater with smaller filter reactances. An example of this is shown in Figure 13 for the L-filter case.

The consequence of this characteristic is that harmonic current distortion of the equipment is lower with a weak power supply network than with a stronger one. Therefore calculations based on the current distortion of the equipment measured in a strong power supply network may exaggerate the estimated voltage distortion in a weak power supply network.

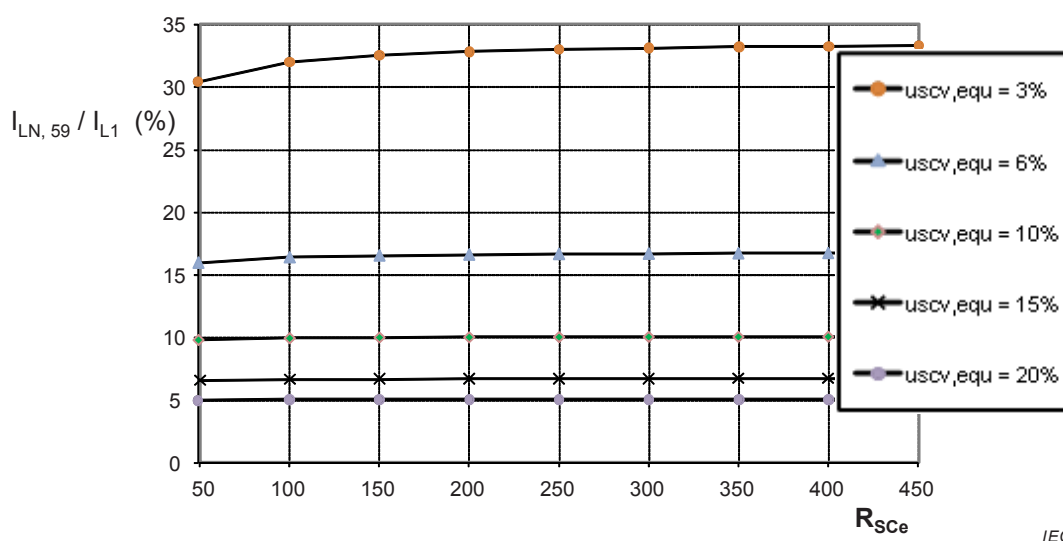


Figure 13 – Basic characteristic of the relative current emission (59th harmonic) of one AIC at a pulse frequency of 3 kHz versus R_{ScE} with the line impedance according to 5.2.4

However, in spite of the fact that the harmonic current distortion decreases with higher supply impedance the impact of the more unfavourable voltage sharing ratio predominates and may result in an excessive voltage distortion level. Therefore additional filter measures might be needed when AICs are connected in particular to the public power supply network.

Several different filter configurations can be applied, all with the aim to reduce the voltage distortion at the pulse frequency and its side bands. Figure 14 shows the three most used state of the art differential mode line filter solutions for VSC. The simplest filter is the L-filter, as described before. An alternative with better filter efficiency and less line frequency voltage drop is the LCL filter. As a power supply network side inductor L_2 , the stray inductance of a transformer may be used. If no active damping in the control is implemented, a passive damping as shown in the damped trapped LCL-filter topology of Figure 14 might be necessary. To increase the damping of a constant pulse frequency ripple further, a trapped LCL filter may be used. With a third inductor a series resonant circuit for the pulse frequency is built. A decrease of the filter performance for pulse frequency multiples should be considered.

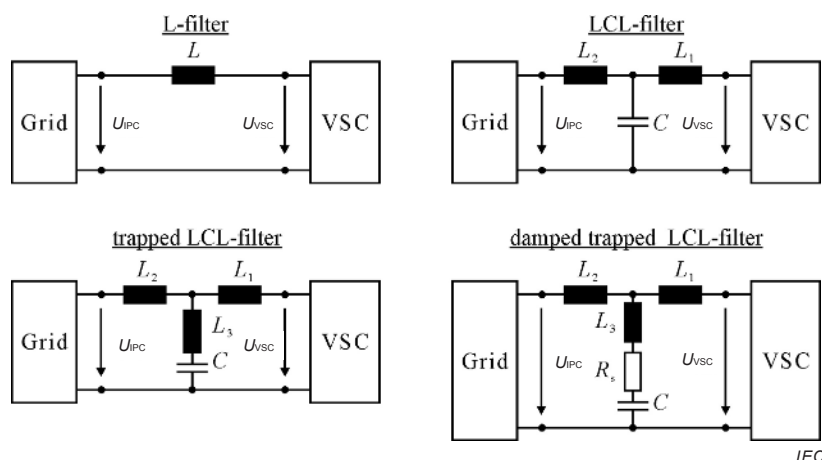


Figure 14 – Single phase electric circuit of the three commonly used differential mode passive line filter topologies for VSC and one example for passive damping

As an example, Figure 15 shows the attenuation of the VSC line to line voltage to the line to line voltage at the IPC. The power supply network is hereby assumed to be resistive-inductive with $R_{line}=40\text{ m}\Omega$ and $L_{line}=100\text{ }\mu\text{H}$. The filter characteristics are

- L-Filter: $L = 4\text{ mH}$
- LCL-Filter: $L_1=1\text{ mH}; L_2=1\text{ mH}; C=4,7\text{ }\mu\text{F}$
- LCL-Filter (trapped): $L_1=1\text{ mH}; L_2=1\text{ mH}; L_3=54\text{ }\mu\text{H}; C=4,7\text{ }\mu\text{F}$
- LCL-Filter (damped and trapped): $L_1=1\text{ mH}; L_2=1\text{ mH}; L_3=54\text{ }\mu\text{H}; C=4,7\text{ }\mu\text{F}; R_S=10\text{ }\Omega$

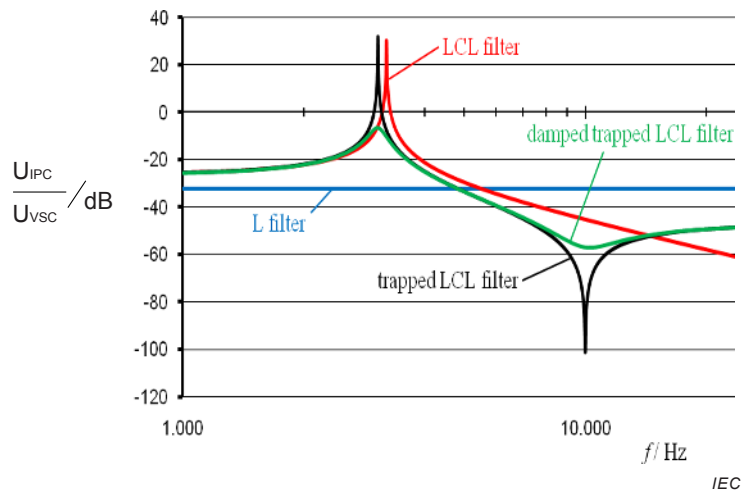


Figure 15 – Example of the attenuation of the VSC line to line voltage to the line to line voltage at the IPC with state of the art differential mode passive line filter topologies

NOTE 2 Especially for L-filters the across the lines (X-) capacitors of any additional EMI filters might be taken into account in the filter design, because they may have a considerable effect on the filter performance.

The design of filter circuits for an AIC has to take into consideration that an undesirable resonance with the power supply network's impedance may appear below the tuned resonance frequency of the filter arrangement which may lead to an unintentional increase of the supply impedance in the lower frequency range. An example of this can be seen in Figure 15 around 2 kHz. As a result of this effect, resonances may arise if conventional converters with significant harmonic distortion at lower frequency are connected on the same power supply network with an AIC.

A practical example is shown in Clause A.7.

In such cases it may be necessary to add damping circuits to the additional filter arrangements. In this way the effect of this resonance is reduced, see Figure 15, green curve. Instead of passive damping circuits, that increase losses and decrease the filter effect, a damping function may be included in the AIC control. However, this kind of active damping requires that the filter resonance frequencies are less than half of the pulse frequency.

5.2.4 Measured power supply network impedances in the range between 2 kHz to 20 kHz

The values of the power supply network impedances in the range of the pulse frequency of an AIC and its harmonics might have significant influence on the conducted emissions of an electric or electronic device.

In a dedicated research project, the power supply network impedances at the IPC in various industrial and public supply systems in Central Europe have been examined. The aim was to determine the statistical distribution of the power supply network impedances up to 20 kHz.

On the one hand this will help to design robust and affordable supply side filters for the AIC and on the other hand the results are useful for the definition of emission levels of AICs.

The studies were performed at several sites in North, Central and South Germany and Northern France over three years. At each measurement location, the power supply network impedances were determined in intervals of one hour. In general, each determination required a whole day measurement (see [1]¹). For explanations of different possible methods see A.8.

All examined networks had a rated voltage of 400 V and all were cable networks. The following results are not valid for overhead lines.

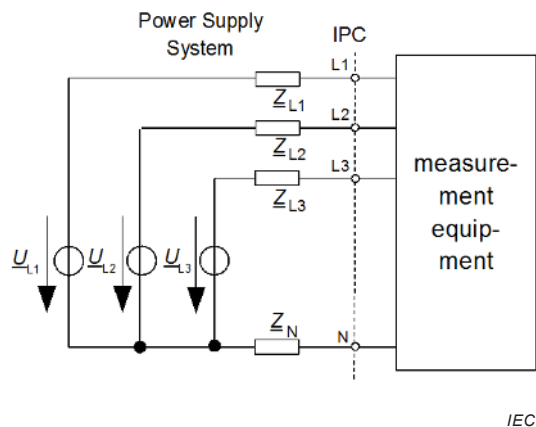


Figure 16 – Connection of the power supply network impedance measurement equipment

Figure 16 shows the connection of the measurement equipment to the power supply network. The measurement equipment provides measurements of up to 20 kHz of:

- the complex line to neutral impedance Z_{L1N} to Z_{L3N} and their mean value
- the complex line to line impedances Z_{L12} to Z_{L31}
- the complex positive-sequence impedances Z_{pos}

Figure 17 shows the impedance characteristic of a low-voltage transformer under no load condition. This basically corresponds to the leakage reactance.

¹ Numbers in square brackets refer to the bibliography.