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Power electronics systems and equipment – Operation conditions and characteristics of active infeed converter applications

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER ELECTRONICS SYSTEMS AND EQUIPMENT –

Operation conditions and characteristics of active infeed converter applications

FOREWORD

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- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

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

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

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

Enquiry draft	Report on voting
22/145/DTS	22/160/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.

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

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

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- withdrawn,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

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INTRODUCTION

This technical specification is necessary because Active Infeed Converters (AIC) are a state of the art technology in power electronic products but which have not been described very well by standardization up to now.

AICs are necessary to feed back some inertia or braking power from a load back to the power supply system

Dispersed power generating equipment is using such AICs to synchronise their voltages and currents to the power supply system.

Therefore the advantage of using AICs in industrial as well as in domestic premises becomes more and more interesting under light of the energy efficiency discussion.

Different possible topologies of AICs are described in this technical specificaton with their specific advantages in order to introduce them and to give an overview for users.

Also utilities are interested in information how the correct application of AICs can additionally help to mitigate harmonics in the power supply system.

POWER ELECTRONICS SYSTEMS AND EQUIPMENT –

Operation conditions and characteristics of active infeed converter applications

1 Scope

This technical specification 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 system (lines) and a current or voltage stiff d.c.-side and which can convert electrical power (active and reactive) in both directions (generative or regenerative).

Applications with AIC are realized together for example with d.c.-sides of adjustable speed Power Drive Systems (PDS), Uninterruptible Power Systems (UPS), active filters, photovoltaic systems, wind turbine systems, etc., of all voltages and power sizes.

Active Infeed Converters are generally connected between the electrical power supply system (lines) and a current or voltage d.c.-side, with the objective to disburden the system from low frequency harmonics (e.g. less than 1 kHz) by a sinusoidal approach of the lines current. Some of them can additionally control the harmonic distortion of an applied voltage or current.

AIC are able to control the power factor of a power supply system section by moving the electrical power (active and reactive) in both directions (generative or regenerative), which enables energy saving in the system and stabilization of the power supply voltage.

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 as well as their mitigation.

2 Normative references

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

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC product standard including 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 62040-2, *Uninterruptible power systems (UPS) – Part 2: Electromagnetic compatibility (EMC) requirements*

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
Active Infeed Converter
AIC
self-commutated electronic power converters of all technologies, topologies, voltages and sizes which are connected between the a.c. power supply system (lines) and 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

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

Basic topologies may be realized as a Voltage Source Converter (VSC) or a Current Source Converter (CSC).

NOTE In the IEV, 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 technical specification.

3.2
active infeed application
application using the advantages of an Active Infeed Converter

3.3
active filter
AIC operating as a filter to control the specific a.c.-side harmonic and interharmonic voltages or currents usually without a d.c.-side load

3.4
PWM converter
converter generally using a pulse-width modulation technique in order to control the switching of its semiconductor valve devices

3.5
switching frequency
mean value of the frequency with which the semiconductor valve devices of a PWM converter are operated

NOTE In some converters the switching frequency may not be the same for all semiconductor valve devices.

3.6
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 In-plant Point of Coupling (IPC)

NOTE The switching frequency itself may not be present as a harmonic or interharmonic.

3.7
pulse pattern
pattern of the switched voltages or currents, measurable at the terminal of the converter, resulting from pulse frequency and modulation schemes used

3.8
In-plant Point of Coupling
IPC
point on a network inside a system or an installation, electrically nearest to a particular load, at which other loads are, or could be, connected

NOTE 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 Point of Common Coupling (PCC).

3.9
d.c.-side load
electrical device optionally connected to the d.c.-Side

NOTE The load may either consume or feed electrical energy.

3.10
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

3.11
long-time energy storage device
device connected to the d.c.-link directly or by a semiconductor valve device, providing rated power for typically seconds to minutes

3.12
DC filter
a filter on the DC side of a converter, designed to reduce the ripple in the associated system

[IEV 551-14-18]

3.13
AC filter
a filter on the AC side of a converter, designed to reduce the circulation of harmonic currents in the associated system

[IEV 551-14-19]

3.14
supply impedance
the actual resulting impedance of the power supply system at the IPC

3.15
total impedance
resulting impedance consisting of the supply impedance and the supply-side filter impedance of the AIC

NOTE In the range of controllable harmonics the total impedance can normally be approximated as purely inductive.

3.16
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

NOTE If no value for this range of frequencies can be given, the value for the fundamental frequency should explicitly be given

3.17
control
purposeful action on or in a process to meet specified objectives

[IEV 351-21-29]

3.18
fundamental component (of a Fourier series)
sinusoidal component of the Fourier series of a periodic quantity having the frequency of the quantity itself

NOTE For practical analysis, an approximation of the periodicity may be necessary.

[IEV 551-20-01]

3.19
harmonic frequency
frequency which is an integer multiple greater than one of the fundamental frequency or of the reference fundamental frequency

[IEV 551-20-05]

3.20
harmonic component
sinusoidal component of a periodic quantity having a harmonic frequency

NOTE For practical analysis, an approximation of the periodicity may be necessary.

[IEV 551-20-07]

3.21
controllable harmonics or interharmonics
set of harmonic or interharmonic components which can be influenced directly by the control strategy of the AIC

3.22
generated harmonics or interharmonics
set of harmonic or interharmonic components which result from the pulse frequency and the pulse pattern

3.23
electric power supply flux (supply flux)
arithmetical flux quantity resulting from integrating the supply voltage

3.24
converter flux
arithmetical flux quantity resulting from integrating the supply-side converter voltage

3.25
controlled freewheeling circuit
a secondary circuit with a controllable valve device, not with a freewheeling diode

3.26
short circuit power
S_{SC}
value of the three-phase short-circuit power calculated from the nominal phase-to-phase system voltage $U_{nominal}$ and the impedance Z of the system at the Point of Common Coupling (PCC)

$$S_{SC} = U^2_{nominal} / Z$$

Where Z is the supply impedance at the power frequency

3.27
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 the rated interphase voltage U_i. [1)]

$$S_{equ} = \sqrt{3} \times U_i \times I_{equ} \quad ^{1)}$$

3.28
short circuit ratio
R_{SCe} [1)]
characteristic value of a piece of equipment derived from the short circuit power S_{SC} divided by the rated apparent power of the equipment (S_{equ})

$$R_{SCe} = S_{SC} / S_{equ} \quad ^{1)}$$

3.29
F3E-infeed (F3E = 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 a regenerative capability.

NOTE The d.c.-link capacitor which is normally a 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.

3.30
converter topology
converter topology is the family term for different possible arrangements and their connections

3.31
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

[IEV 551-12-15]

4 General system characteristics of PWM AIC Connected to the power supply system

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

4.1 Basic topologies and operating principles

4.1.1 General

Active infeed applications are mainly available with capacitive (VSC) and 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 system availability the connection to the power supply system may be single-phase or three-phase. The three-phase version is selected for the examples.

1) for balanced three-phase equipment.

The main operation principle is to switch the d.c.-side potentials or the d.c.-side currents between 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 disturbances in the high-frequency range. Passive a.c.-side filters are normally required to mitigate these disturbances.

A control system allows the precise control of 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.

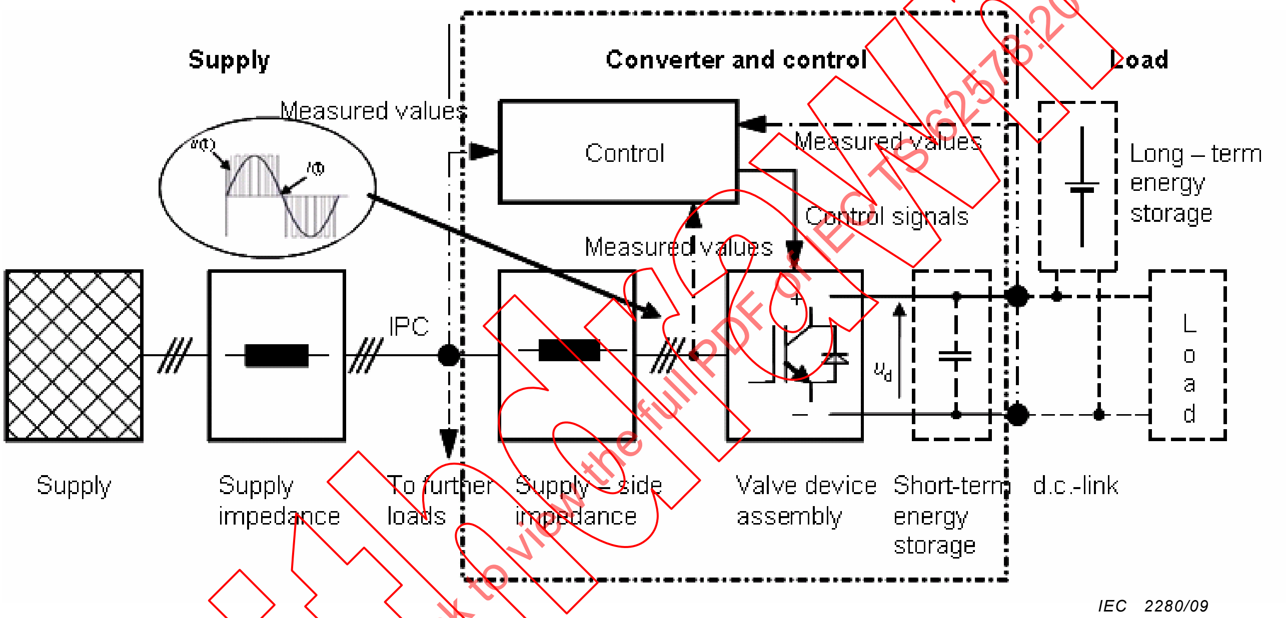


Figure 1 – AIC in VSC topology, basic structure

(Note that the valve device symbols are just used for illustration)

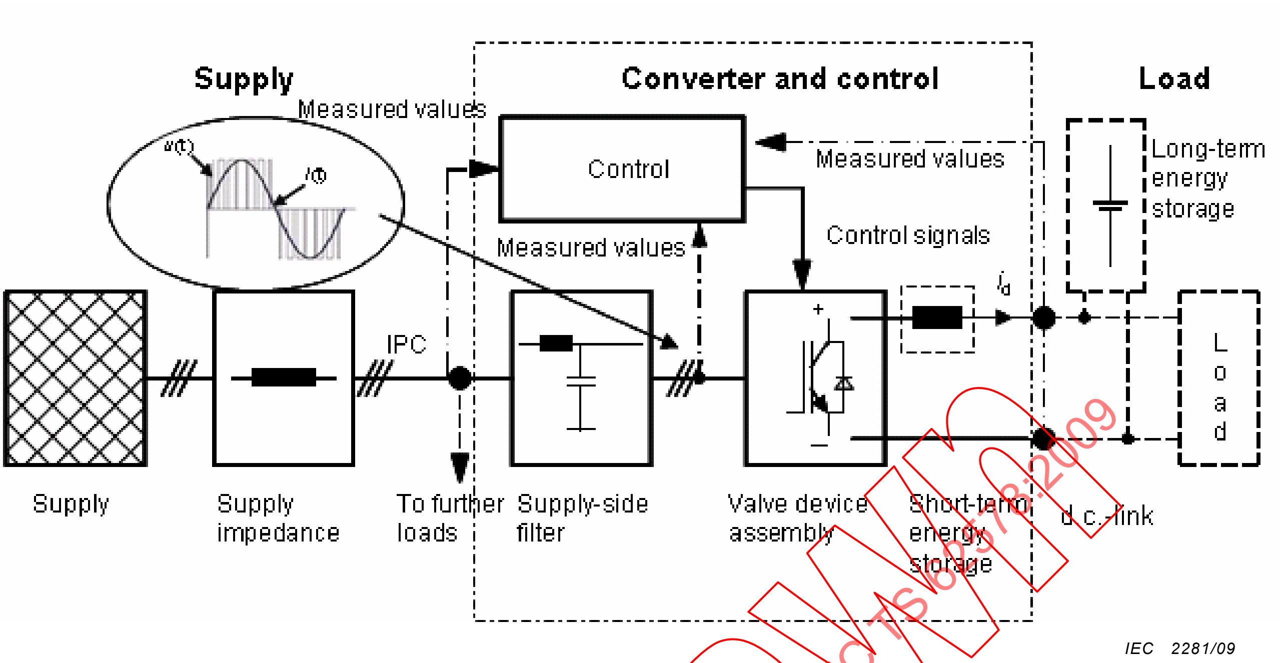


Figure 2 – AIC in CSC topology, basic structure

(Note that the valve device symbols are just used for illustration)

Figures 1 and 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 and 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) which is mainly inductive.
- Converter and control up to d.c.-side. This part usually contains an a.c.-side filter, typically as supply side inductance or LCL-filter with T-structure. A converter transformer, if used, is part of (or designed to be used as) supply-side filter choke. Next in chain is the valve device part, which may vary in structure see following subclauses of different topologies as well as the d.c. side load character (capacitive smoothing or inductive smoothing). The control typically uses space vector modulation, pulse width modulation, optimised synchronous pulse patterns or hysteresis or sliding mode control for pulse pattern generation. In case of pulse width modulation the pulse frequency is fixed. In case of optimised synchronous pulse patterns the pulse pattern is fixed and synchronous with respect to the line frequency. In case of line flux guidance the pulse pattern is asynchronous to the line frequency and varies from period to period.
- Load part. The majority of loads connected are renewable energy equipment and PWM-converter-fed machines. Another typical application are converters to feed passive or mixed loads, as for example in uninterruptible power systems (UPS). This part is not necessary in case of AICs for compensation. In case of voltage source converters long-term energy storage units may be easily connected in parallel to 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 typically may provide rated power for seconds to minutes.

4.1.2 Equivalent circuit of an AIC

The stationary behaviour of AICs is best described by equivalent sources and impedances. These are shown in Figure 3.

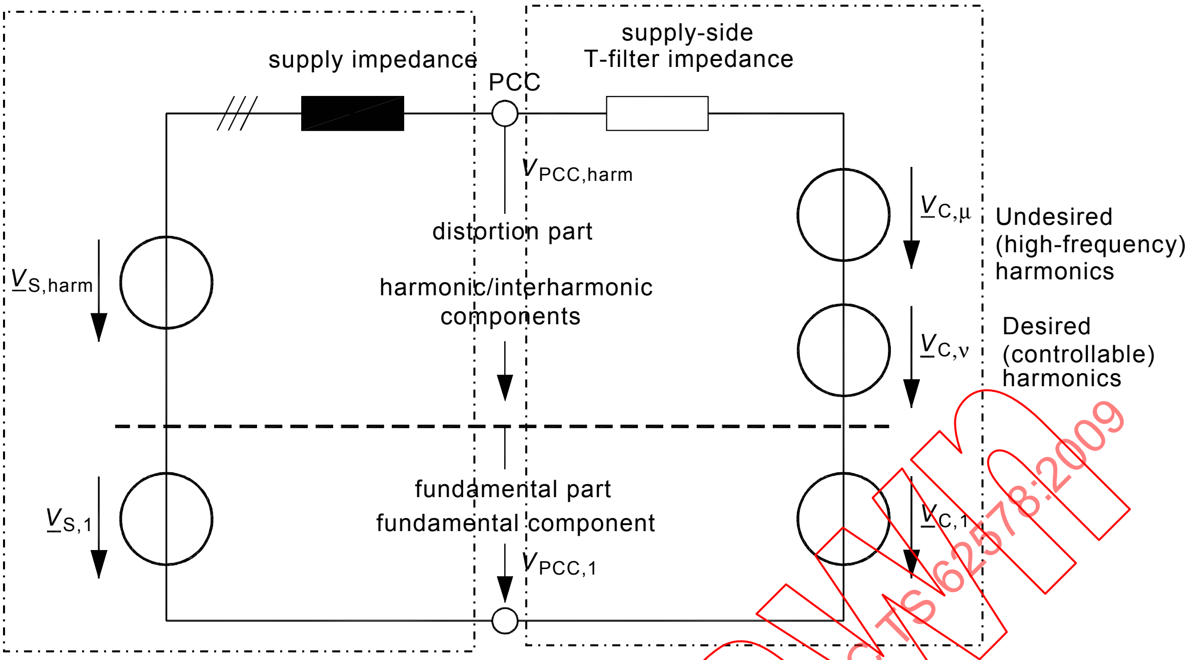


Figure 3 – Equivalent circuit for the interaction of the mains with an AIC

For better understanding it might be advantageous to separate the line 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 V_{sharm} is the superposition of all (desired and undesired) harmonics caused by the AIC and other loads together.

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.

4.1.3 Filters

In the light of economical constraints the supply-side filter might be dimensioned in a way, that the desired harmonics pass through the filter and the undesired harmonics are attenuated to a degree prescribed by EMC specifications of the line. Additional design perspectives may result from the power-supply system conditions at the IPC.

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 such, that the converter and the eventually connected load function properly. The specification of a d.c.-link capacitor has to take the amount of harmonic current into account, otherwise the capacitor may overheat.

In some cases the energy-storage capability of the d.c.-side filter is adapted to dynamic requirements. One application is the ride-through (continue operation during and after a short interruption of the power supply system). Dynamic changes of energy flow of converter or load also need larger d.c.-side energy storage. Otherwise the characterising d.c.-link quantity (voltage or current) may leave a tolerance band in which proper function 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. The voltage drop across the total impedance drives the supply-side current. Quick changes of this supply-side current obviously require high values of the voltage across the total impedance and therefore a higher rated supply-side and thus d.c.-side voltage of the converter. Such quick changes of the line current are required for the control of higher-frequency current components and during dynamic changes.

4.1.4 Pulse patterns

The selected pulse pattern generation influences the characteristics of the converter very much. Three main basic pattern generation schemes are space vector modulation, optimised synchronous pulse patterns and line flux guidance.

It should be noted that 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 a third order harmonic". The result is identical to space vector modulation.

4.1.5 Control methods

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

4.1.6 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 can effectively be used for control purposes. As a secondary effect, high frequency components are generated which might have to be mitigated by a suitable filter.

The line voltage seen in Figure 3 is normally unknown, as well as the line impedance that may change without notice, depending on the actual line configuration, including other loads attached. Therefore, control schemes usually base 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 offers 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 (vectorial sum of reactive plus harmonics) power. The desired load behaviour can be reached 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 voltages.

One possibility to define the reference for 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. Naturally if the voltages at the IPC are distorted, the line currents will be distorted, too.

The drawback of resistive load emulation is that it may become unstable and increase harmonics if the energy is attempted to be fed 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.

4.1.7 Active power factor correction

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

Adequate control of the line-side converter voltage $\underline{V}_C$ allows adjusting the voltage $\underline{V}_L$ across the effective supply-side filter impedance 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. In this way the converter can be used as a compensator to maintain a certain voltage level 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 phasor diagrams are shown in Figure 4.

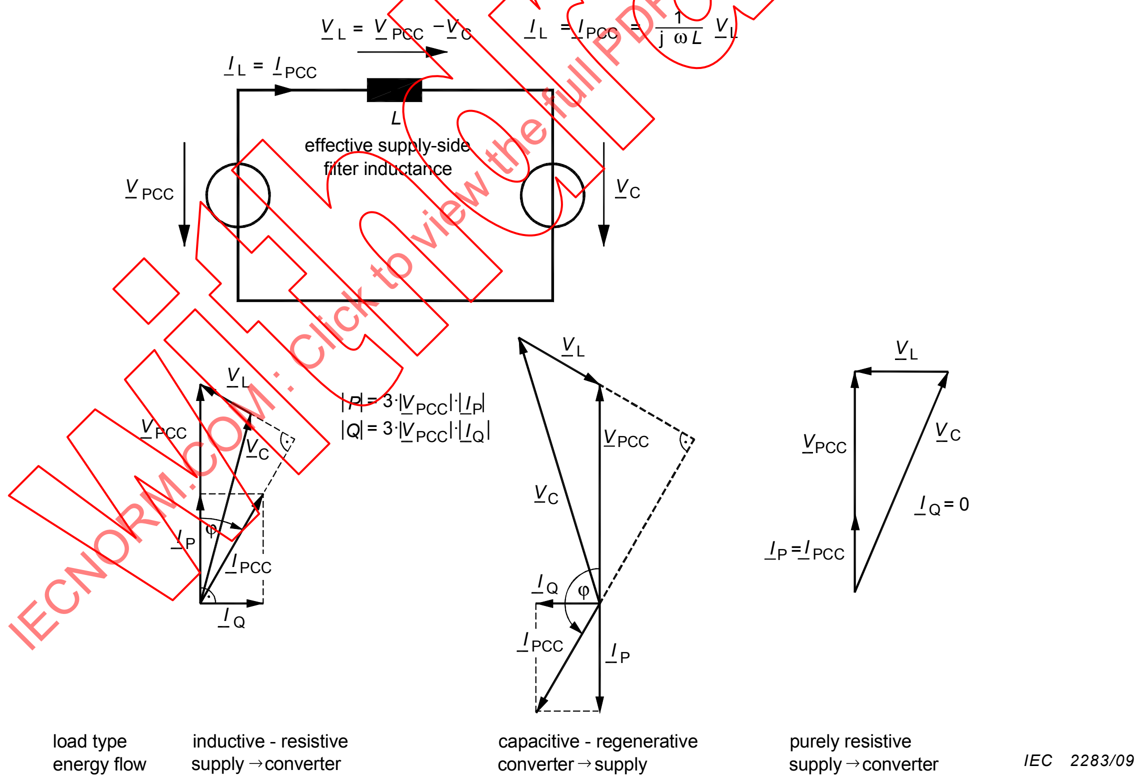


Figure 4 – Voltage and current phasors of line and converter at fundamental frequency for different load conditions

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.

4.2 AIC rating (details to be found in special sections)

4.2.1 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 instantaneously required. Otherwise the amount of capacitive current has to be limited or the line currents will not be as desired.

4.2.2 Converter rating in case of harmonic currents

In addition to the rating discussed for sinusoidal condition in the preceding section, further demands follow from harmonic currents. 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 current harmonics, 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 (distortion) 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 to handle this voltage, line currents will not be generated as desired.

In special cases, where the voltage at the IPC is much distorted, the peak value of the voltage at the IPC including worst-case distortions has to be used for the rating of the converter.

4.2.3 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, which have 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.

4.3 Electromagnetic compatibility (EMC) aspects

4.3.1 General

An electric or electronic device can be called electromagnetically compatible, if the emissions due to the device can be tolerated and if it proves to have an appropriate immunity against external disturbances. Emission and immunity limit lines are given in the relevant product standards (for example IEC 61800-3 in the case of power drive systems (see Figure 5) or IEC 62040-2 for UPS) and in the absence of a product standard the relevant generic standards apply.

AICs generate harmonics having frequencies from the pulse frequency upward. These are mitigated by the supply-side filter, if any. Nevertheless, these harmonics can be found in the voltages and currents at the IPC. Usual measuring equipment for line quantities may not be capable of correctly measuring quantities which contain such high-frequency harmonics. If unusual or unexpected results are displayed, the specification of the measuring equipment should be checked.

Measuring quantities inside an AIC, which is at the line-side or d.c.-side valve device part connections or at the elements of the supply-side filter, is even more demanding. Appropriate measuring equipment with a bandwidth of ten to twenty times the pulse frequency is required.

4.3.2 Low-frequency phenomena (≤150 kHz)

4.3.2.1 Emission

Low-frequency phenomena mainly occur in the mains supply voltage and have to be evaluated there concerning the adherence to the allowed limit values.

System disturbances such as harmonics, voltage fluctuations, voltage dips and commutation notches are part of the low-frequency power supply related phenomena.

Voltage fluctuations and commutation notches are not caused by AICs but may be mitigated by such converters.

Mains impedance and short-circuit ratio RSCe have a decisive impact (see 4.5.1.2) for the reduction of harmonics. The power supply system, its configuration and the load have to be considered together in the evaluation. The technical possibilities for the limitation of emissions have to be analyzed individually.

A considerable reduction of voltage harmonics in the range of up to 2 kHz is achieved by using chokes and in the range up to 20 kHz by using notch filters. The power supply system impedance has to be considered for the filter performance.

In case of installation of several AICs at the same supply system it has to be noted that the distortion will be lower or equal to the distortion caused by one equivalent power AIC due to the very low simultaneity factor of the higher order harmonics

4.3.2.2 Immunity

Lack of supply voltage quality may impact AIC through

- deviation of the wave shape from ideal e.g. through harmonics or flicker;
- complete loss of the mains voltage for seconds or hours;
- under or over voltage exceeding the 10 % tolerance limit for longer periods;
- short voltage dips and swells, both symmetrical and asymmetrical, due to faults or switching operations in the supply;
- transients with high stress peaks in the kV and µs-range.

AICs have to withstand such effects in the supply within responses specified in the respective EMC product standards.

4.3.3 High-frequency phenomena (> 150 kHz)

4.3.3.1 Emission

To reduce interference (differential/symmetrical mode and common mode/asymmetrical mode), the choice of adequate components and methods should be used in order to find an economical solution. The reduction of the common mode interference is similar to the interference suppression of switch mode power supplies. However, due to the bigger size of the AICs the capacitive currents are higher and thus adequately sized mitigation components are required. Further, correct earthing and shielding of the supply cables is important.

The mitigation of the differential mode high frequency interferences may be incorporated with the harmonic filter components. However, care has to be taken in the design of the filter components in order to preserve their low frequency properties in the high frequency range.

4.3.3.2 Immunity

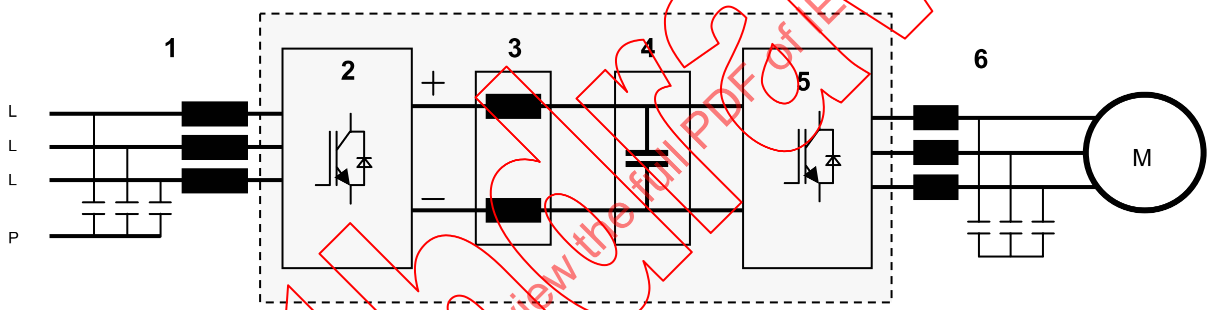
The radio frequency shielding has to be constructively provided at the input of the device, in the device itself and at the output towards the load. Usually the internal interference of the AIC is much higher than the interference from external sources. Thus the cross-coupling from internal power cabling to signal cabling has to be avoided. Signal inputs and outputs have to be protected by galvanic separation or separated power supplies.

4.3.3.3 EMI filters

In the absence of EMI filters the high frequency interference levels can reach values that exceed 120 dBµV. EMI filtering is necessary in most applications in order to comply with the required limits.

NOTE The use of EMI filters may have an incompatibility effect with residual current device (RCD) protection devices because of increased leakage currents.

In order to achieve an EMC-reasonable solution, the combination of following mitigation techniques are needed: filtering, grounding and shielding.



IEC 2284/09

1 EMI-filter or choke
2 Supply-side converter (AIC)
3 common mode chokes
4 d.c.-link capacitors smooth the d.c.-voltage
5 Motor-side converter
6 Output chokes or filter

Figure 5 – Block diagram of a typical PDS with high frequency EMC filter system

4.4 Different converter topologies and their influences on the power supply system

Different topologies on the supply-side of the converters have been applied in the past with quite different influences on the power supply system. Figures 6 to 8 show the technological progress and the main milestones of those topologies by presenting their typical wave shapes for power supply current distortions and voltages.

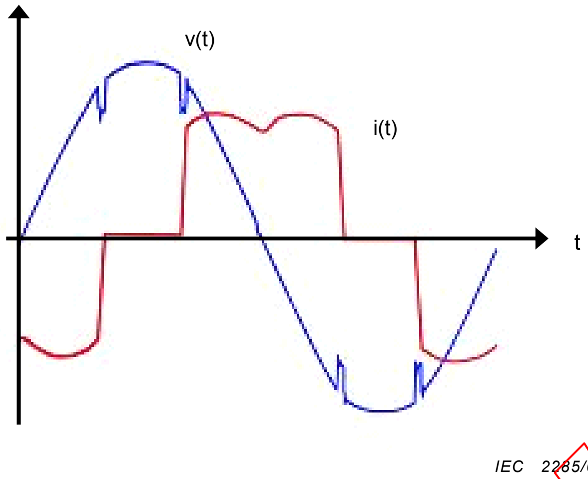


Figure 6 – Typical mains current and voltage of a phase controlled converter with d.c.-output and inductive smoothing

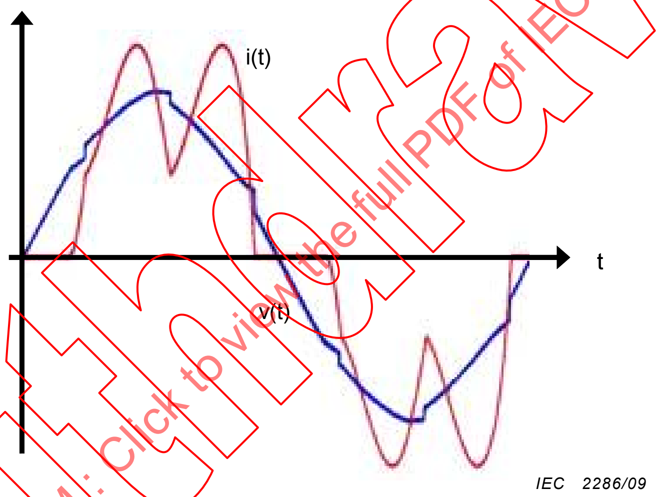


Figure 7 – Typical mains current and voltage of an uncontrolled converter with d.c.-output and capacitive smoothing

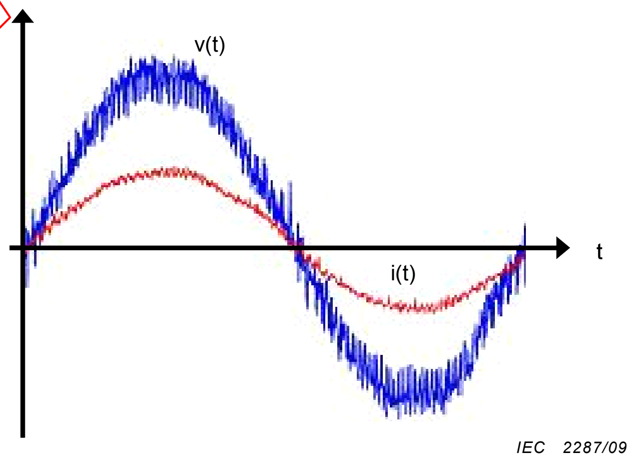


Figure 8 – Typical mains current and voltage of an AIC realized by a PWM Converter with capacitive smoothing without additional filters

With emerging technology development the required approach towards the ideal sinusoidal wave shape of the mains current was more closely achieved.

4.5 Active power / reactive power

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 so-called Active Energy Management (AEM) which includes dynamic reactive power compensation without additional compensator facilities.

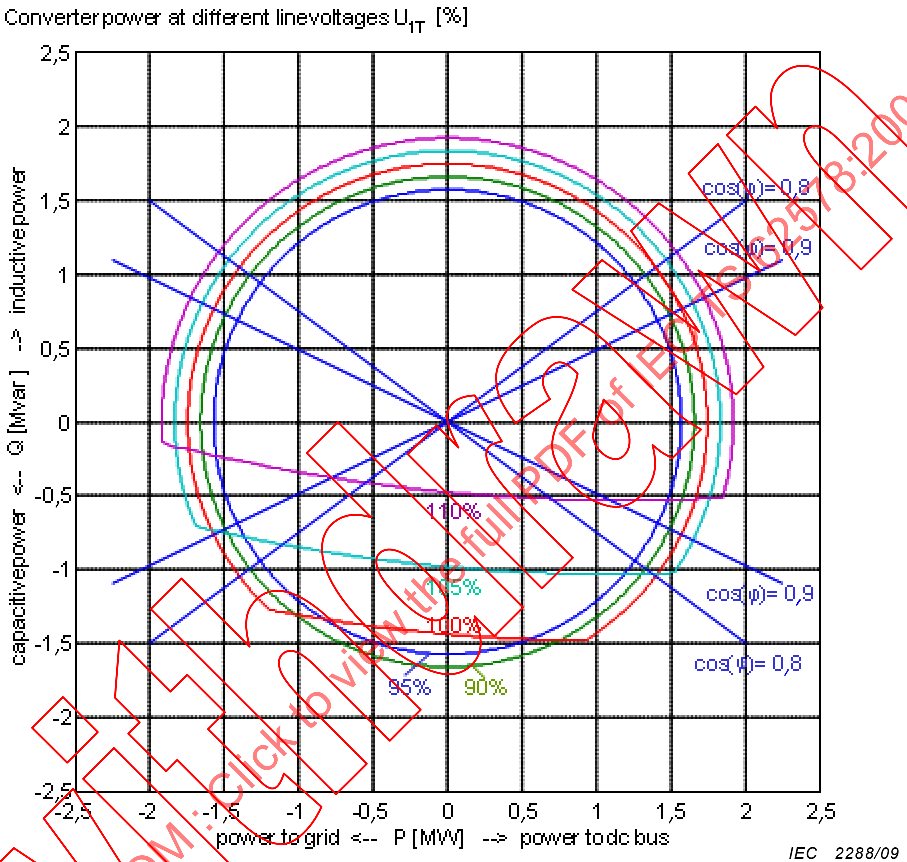


Figure 9 – Example of attainable active and reactive power of the AIC at different line voltages in per unit (with 10 % combined transformer and filter inductor short circuit voltage, X/R ratio = 10/1, d.c. voltage = 6,5 kV)

4.5.1 Harmonics

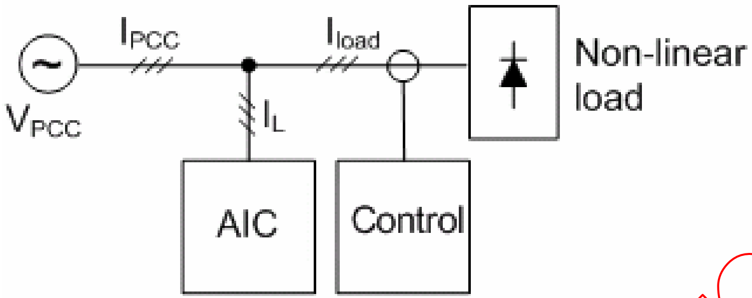
4.5.1.1 Desired effects

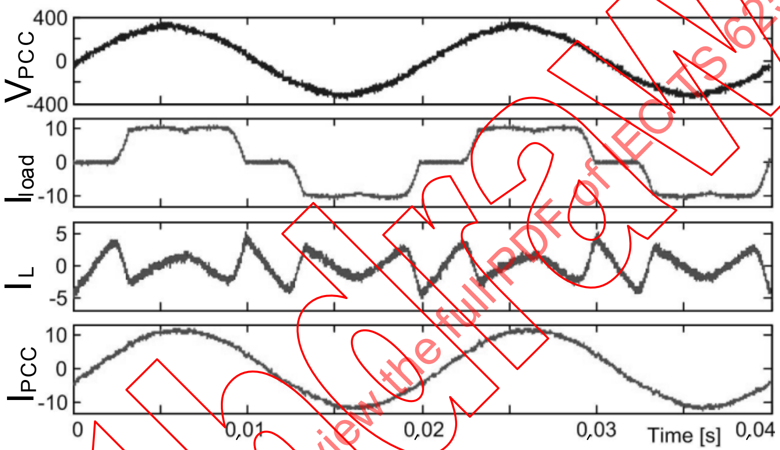
For an AIC based on PWM technology, virtually no harmonic current emissions occur below the pulse frequency unless they are generated intentionally for the purpose of controlling particular harmonic components (see 4.1.5).

In this case the converter may improve the power supply situation by compensating given low frequency harmonics to a certain extent.

To obtain this result suitable pulse patterns have to be generated by the converter in order to control the harmonics.

For this purpose the respective harmonics can be calculated using Fourier analysis and reduced or compensated by separate controllers. An example is shown in Figure 10 for three phase loads but is also applicable to single phase cases.





IEC 2289/09

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

4.5.1.2 Undesirable effects

As an undesirable effect for such kind of converters harmonic distortions may occur near the pulse frequency and integer multiples of it.

NOTE The following clauses refer to two-level topology according to Clause 5. 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 connected to the power supply system (conventional converters), the basic characteristic of the voltage waveform of an AIC (VSC) on the mains-side of the bridge is determined by the switching action and the voltage of the d.c. link capacitor, see Fgure 16.

Due to this characteristic the voltage distortion caused in the power supply system depends just on the pulse pattern applied and the voltage sharing which is given from the line impedance on one hand and the line-side converter impedance on the other hand.

When a simple L-filter is applied and the capacitances of the supply network are ignored, the voltage sharing ratio is valid for all frequencies generated by the pulse pattern. In addition to that, the distortion is fairly independent from the load of the converter.

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 a pulse frequency of 3 kHz and without additional filters, a supply-side inductor X_{equ} = 6 % (represented by equivalent short circuit voltage S_{CVequ}), a short-circuit power ratio of R_{SCe} = 100 and assuming the supply impedance to be inductive.

The 3 kHz-ripple in the line-to-line Voltage of this example may reach approximately 7,5 %.

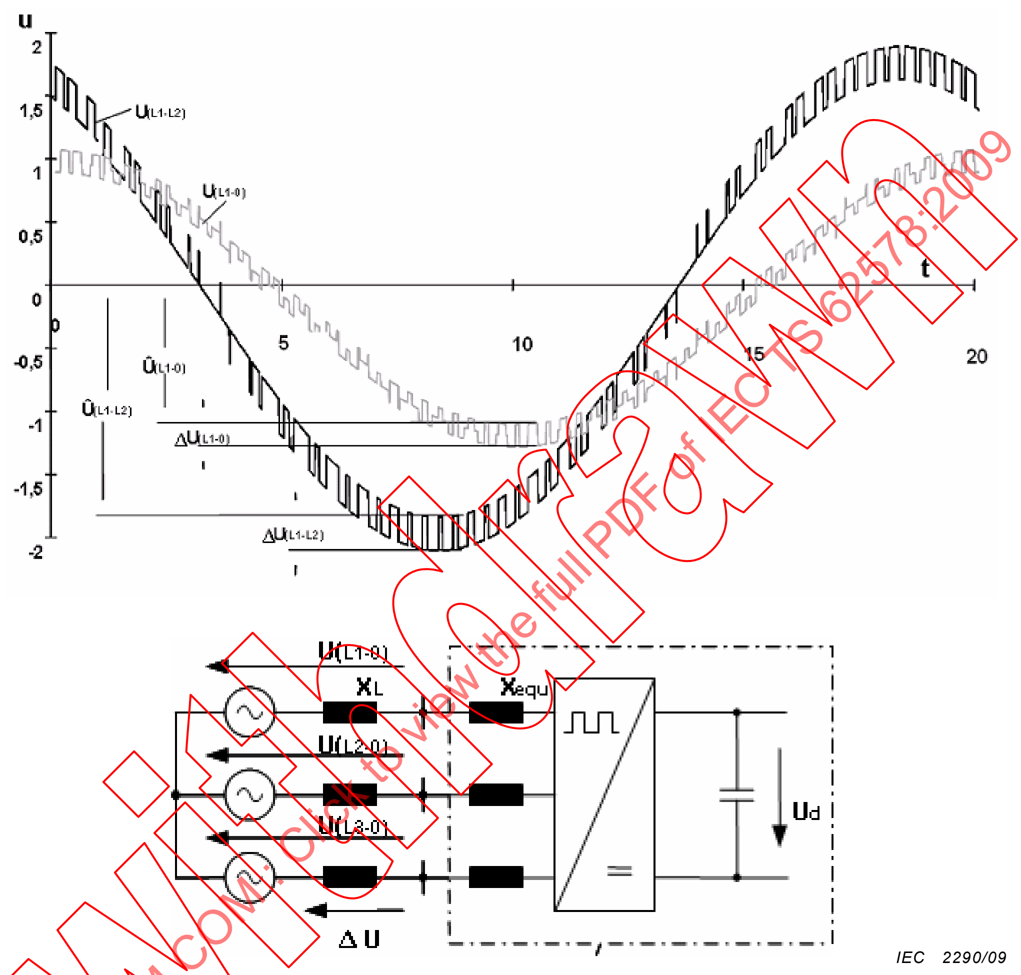


Figure 11 – Typical voltage distortion in the line-to-line and line-to-neutral voltage generated by an AIC without additional filters

$$\frac{\Delta U_{(L1-0)}}{2 \cdot \hat{U}_{(L1-0)}} = \frac{1}{3} \cdot \frac{U_d}{\hat{U}_{(L1-0)}} \cdot \frac{X_L}{X_L + X_E} \quad (1)$$

$$\frac{\Delta U_{(L1-L2)}}{2 \cdot \hat{U}_{(L1-L2)}} = \frac{1}{2} \cdot \frac{U_d}{\hat{U}_{(L1-L2)}} \cdot \frac{X_L}{X_L + X_E} \quad (2)$$

$$\text{typical: } \frac{U_d}{\hat{U}_{(L1-L2)}} \approx 1{,}1 \text{ resp. } \cdot \frac{U_d}{\hat{U}_{(L1-0)}} \approx 1{,}1 \cdot \sqrt{3} \quad (3)$$

In order to evaluate the expected distortion in the mains it is advisable to use the power ratio R_{SCe} for calculation because the results are independent from the power of the respective equipment considered.

Figure 12 shows the typical voltage distortion in the power supply system depending on R_{SCe} caused by an AIC (PWM type; 2-Level) with a pulse frequency of 3 kHz and passive mitigation provided by chokes (SCV_{equ} as parameter), without additional filters.

As shown here additional passive mitigation methods might be inevitable for such kind of converters

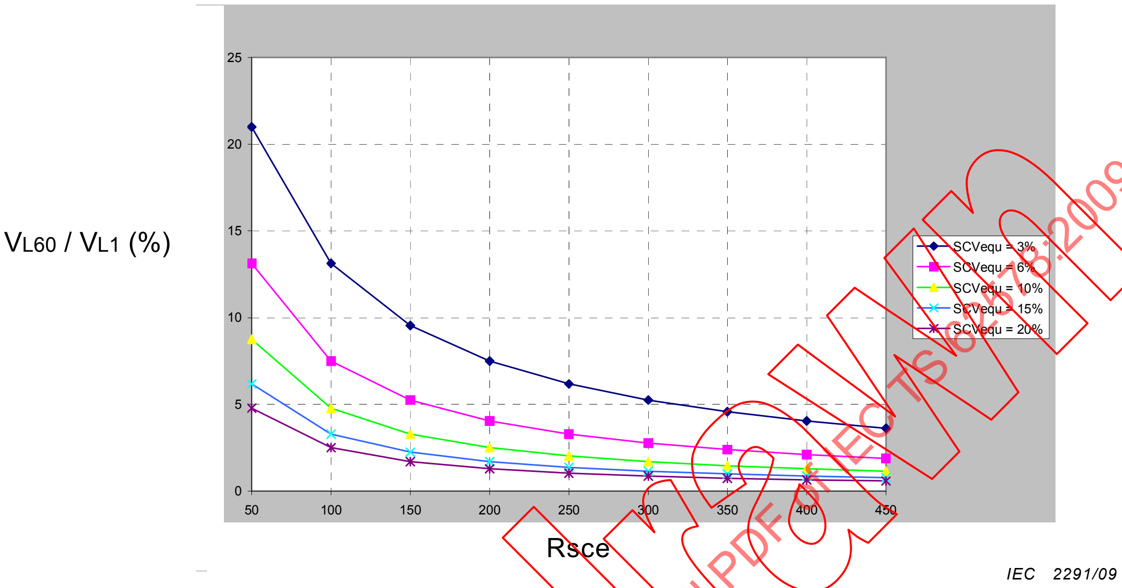
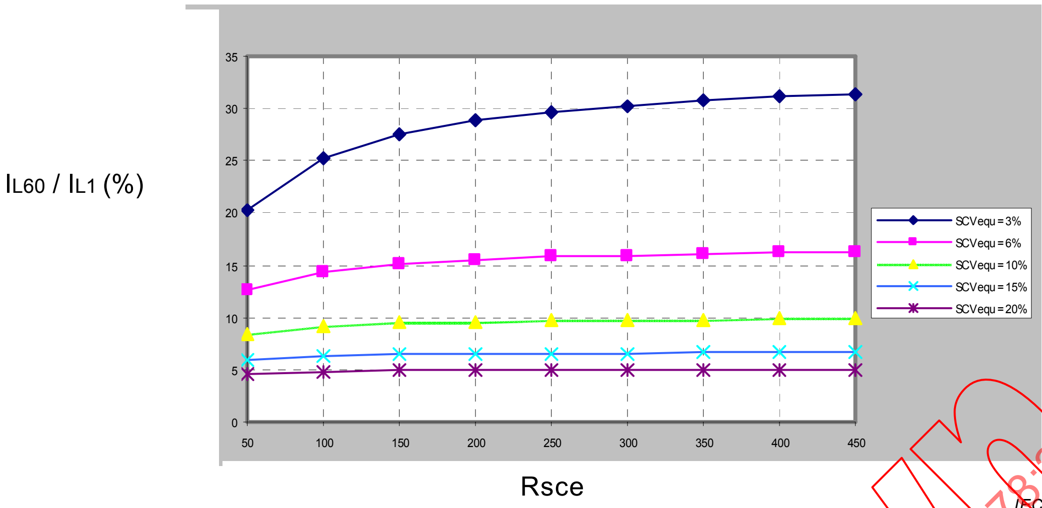


Figure 12 – Typical relative voltage of the 60th harmonic of an AIC depending on R_{SCe}

Regarding the effects on the mains it is furthermore remarkable for this kind of converter that the line impedance plays a more important role in view of the harmonic current emission of the converter than it was the case for the conventional types (see Figure 13). The impact increases with smaller converter reactances.

The consequence of this characteristic is that in case of a weak power supply system with comparatively high mains impedance this may lead to smaller harmonic current emissions of the equipment compared to a stronger power supply system. Therefore the current emission of the equipment may not reflect its effect on the mains sufficiently.

The voltage distortion which is caused by the equipment should also be noted for a comprehensive consideration.



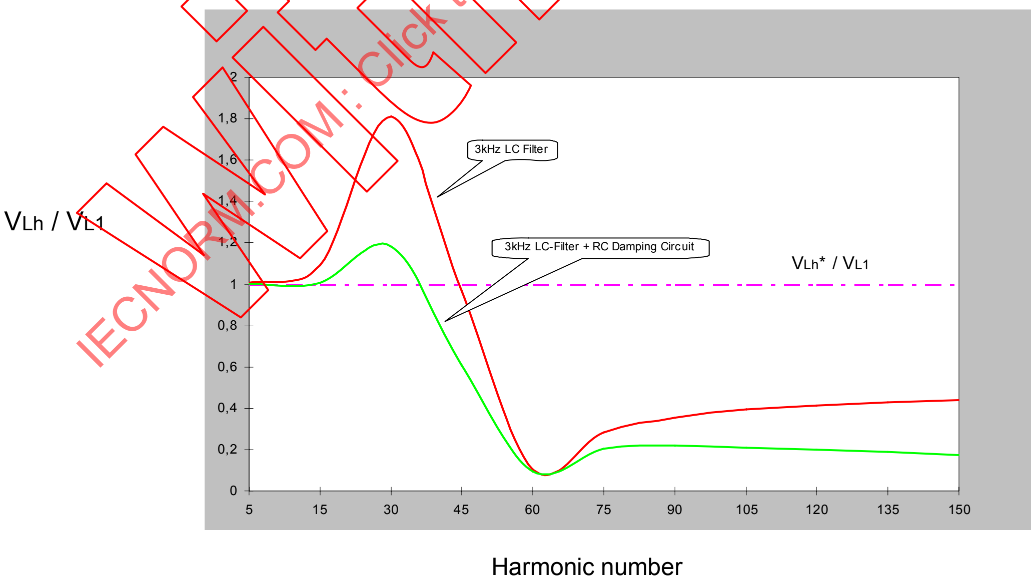
IEC 2292/09

Figure 13 – Typical relative current emission of the 60th harmonic of an AIC depending on R_{Sce}

In spite of the fact that the harmonic current emission decreases with higher line impedances the impact of the more unfavourable voltage sharing ratio may predominate and may result at higher impedances of the power supply system in an increased voltage distortion level.

Therefore additional filter measures might be needed when AICs are connected to the public Power Supply System in particular.

A lot of different filter configurations could be applied, all with the aim to reduce the voltage distortion at the pulse frequency and its side bands. In this way the distortion level at 3 kHz for example might be attenuated considerably.



IEC 2293/09

Figure 14 – Typical impact of additional filter measures to the voltage distortion level of an AIC (V_{Lh}* / V_{L1} is the voltage distortion with only a line side inductive impedance)

Figure 14 shows the typical impact of such an LC-filter-arrangement in parallel connected to an AIC. Attenuation up to 10 % for the amplitudes near by the pulse frequency (ordinal number 60) could be achieved for this example (see top curve shape at ordinal number 60).

Due to this measure an initial distortion level (without additional filter) of approximately 7,5 % (as given according to Figure 12, for example R_{SCe} = 100; SCV_{equ} = 6 %) may be attenuated down to 0,75 % with such an arrangement.

The design of additional filter circuits for an AIC has to take into consideration the fact, that below the tuned resonance frequency of the filter arrangement an undesirable resonance with the line impedance may appear which may lead to an unintentional increase of the line impedance in the lower frequency range (see Figure 14, top curve shape at ordinal number 30). As a result of this effect resonances might arise if conventional converters with significant harmonic components at lower frequency and an AIC are connected on the same power supply system.

In such cases it might be necessary to add damping circuits to the additional filter arrangements. In this way the resonance increase effect might be reduced accordingly (see Figure 14, bottom curve shape at ordinal number 30).

4.6 Audible noise effects

Due to the voltage distortion an increase in audible noise of different electrical equipment (i.e. plug in small power supplies, chokes in fluorescent lamps, incandescent lamps, glass-ceramic cook tops) connected to the same power supply systems may occur.

Together with the implementing of appropriate mitigation for the voltage distortion, the filtering measures would come along with decreasing the audible noise.

4.7 Leakage currents

Because of impedances between energized parts and earth, such as capacitors connected between the power supply system conductors and earth in EMI filters, or stray capacitances between power supply systems conductors and earth in shielded power cables, the leakage currents might be above 3,5 mA. Therefore firm and increased earth connection is required (see IEC 61800-5-1 for PDS). Residual Current Devices (RCD) are usually not compatible with professional equipment.

4.8 Aspects of system integration and dedicated tests

The electrical and thermal safety of converters of this type are tested according to IEC 61800-5-1 in the case of power drive systems, or IEC 62040-1 in case of an UPS.

In view of the requirements for AICs with regard to protection against electric shock it has to be considered that VSCs in particular are usually equipped with large d.c.-link capacitors which store the electric energy even after disconnection from the supply. Therefore appropriate measures have to be provided in order to discharge the capacitors after switching off the AIC. Testing should be performed by recalculation of the energy or measurement of the voltage 5 s or 1 s after switching off of the AIC. Where several capacitors are interconnected throughout the circuit, this should be allowed for in such calculations.

For aspects of system integration the IEC 62103 applies.

The following type tests are to be made for AICs additionally to established tests for uncontrolled rectifiers:

- operational behaviour at asymmetrical line voltages;
- turn-off in case of supply over and under voltage;

- operational behaviour in the case of single-phase and three-phase supply voltage interruptions and short dips;
- short-circuit at the AIC supply-side terminal (equipment to turn-off in case of over-current);
- turn-off with maximum current and highest reference value of the d.c.-link voltage (d.c.-link voltage shall not rise to inadmissible values);
- disconnection from the electrical power supply system during energy recovery.

Further tests may be required but are under consideration.

5 Characteristics of a PWM AIC of voltage source type and two level topology

This clause is about the special properties of two level PWM voltage source AIC.

5.1 General function, basic circuit topologies

Two level PWM voltage source AICs usually use pulse frequencies between 1,5 kHz and 16 kHz. They are capable of four-quadrant operation and can control a sinusoidal line current of any phase angle. Active and reactive power can be controlled independently of each other. In addition active filters can be realized with the same circuit. Because of the generative power ability, the good control possibilities as well as the small line interference they are used with frequency converters for drives, wind-power systems as well as an improved technology alternative to uncontrolled rectifiers.

Figure 15 shows the basic topology of a two level PWM voltage source AIC. It consists of a supply side reactance X_{equ}, the electronic valve devices and the d.c.-link capacitor C_d. The load can be any circuit with d.c.-voltage input, e.g. a chopper or a machine-side converter. Active filters normally do not have load. The electronic valve devices connect the d.c. voltage u_d to the supply phases L1 to L3. Reactances X_{equ} separate the instantaneous values of the supply and the converter input voltages.

A minimum value of the reactance ($X_L + X_{equ}$) between supply voltage and converter input is required for proper function. Additional filter components (see 4.3.2.3 and 4.5.1.2) are necessary to limit the harmonics to permissible values.

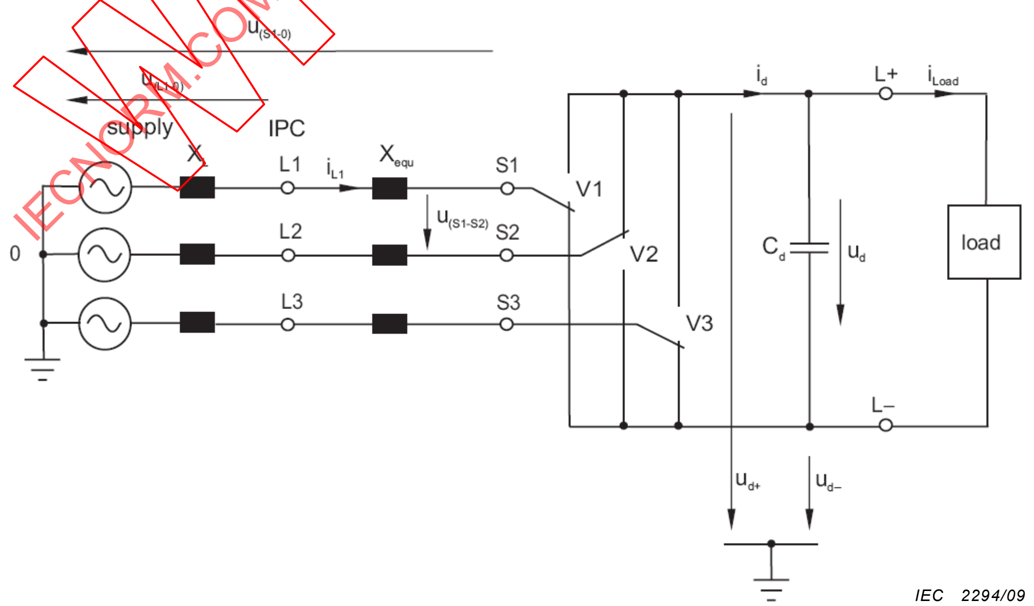


Figure 15 – Basic topology of a two level PWM voltage source AIC

As the d.c.-link of a two level PWM voltage source AICs has no connection to the neutral of the supply, the phase-to-phase voltage at the converter input is +/- u_d or zero and the d.c.-link has a common mode voltage to ground.

$$u_{CM} = \frac{u_{d+} + u_{d-}}{2}$$

Figure 16 show typical waveforms of the phase-to-phase voltage $u_{(S1\text{-}S2)}$ and the phase-to-neutral voltage $u_{(S1\text{-}0)}$ related to U_p (U_p: nominal line to neutral voltage). The common mode voltage u_{CM} of the d.c.-link is shown in Figure 17.

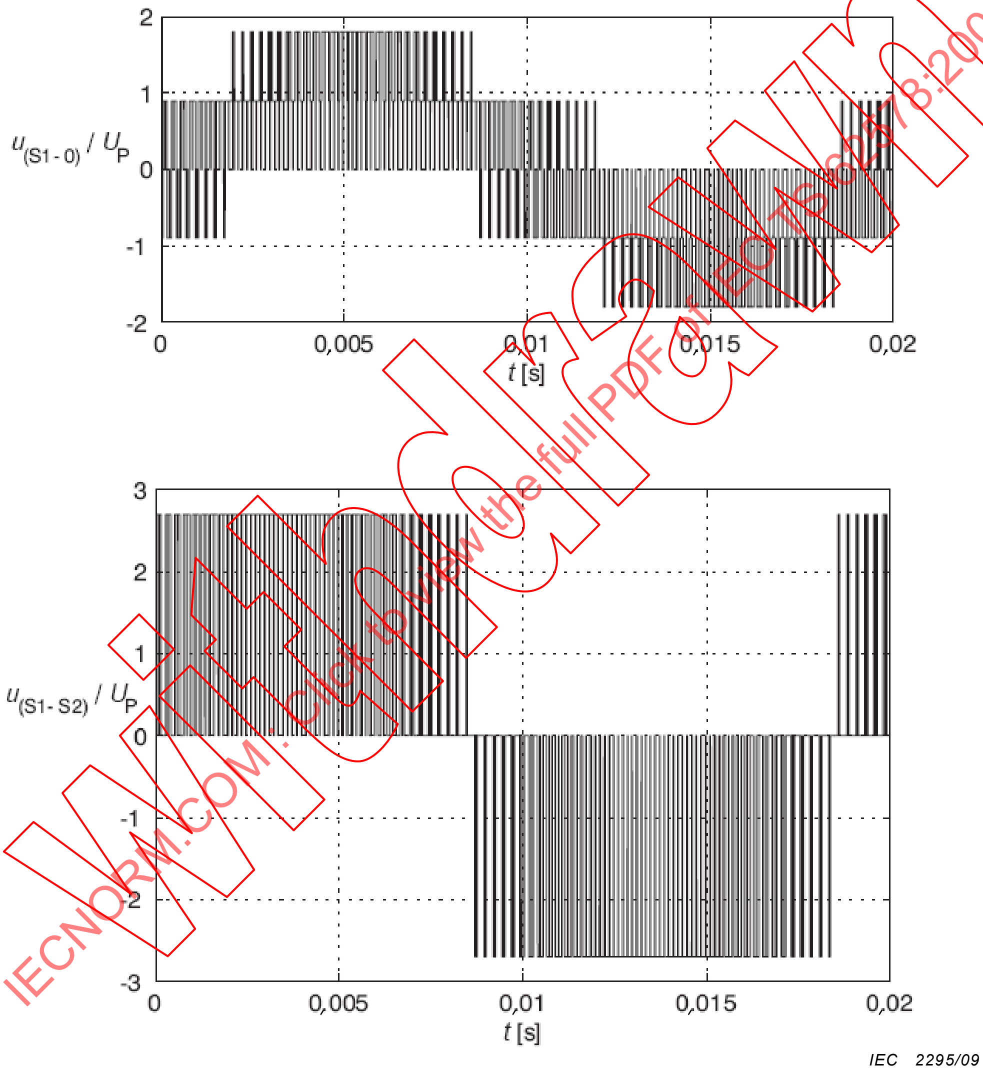


Figure 16 – Typical waveforms of voltages $u_{(S1\text{-}S2)}$ / U_P and voltage $u_{(S1\text{-}0)}$ / U_P, at pulse frequency of 4 kHz – Power supply frequency is 50 Hz

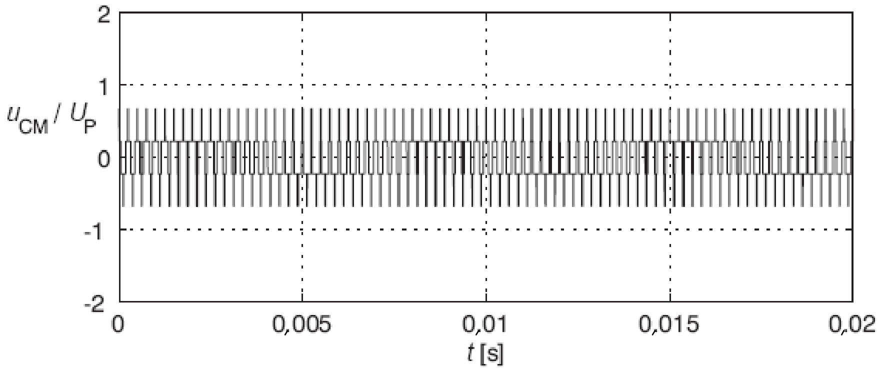


Figure 17 – Typical waveforms of the common mode voltage u_{CM} / U_P, at pulse frequency of 4 kHz – Power supply frequency is 50 Hz

A typical current i_{L1} at a pulse frequency of 4 kHz and a relative impedance SCV_{equ} of 6 % is shown in Figure 18 at nominal load. Increasing the pulse frequency or the reactances of X_{equ} reduces the current ripple. Normalized to the rated line current I_{equ}, the current ripple is nearly independent of supply power and power factor.

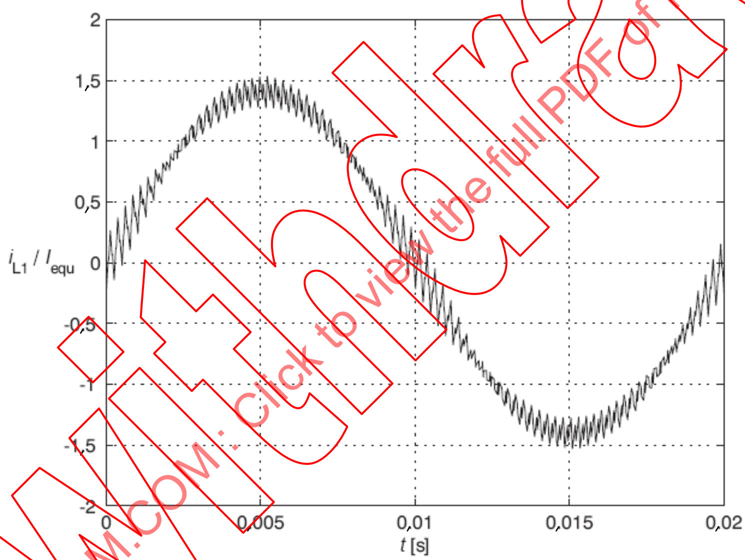


Figure 18 – Waveform of the current i_{L1} / I_{equ} at pulse frequency of 4 kHz, relative impedance of SCV_{equ} = 6 % – Power supply frequency is 50 Hz

5.2 Power control

Line currents or active and reactive power are controlled indirectly via the modulation index of the modulation circuit. All four quadrants of the current-voltage phase (i.e. all phase angles) are accessible (see 4.1.6).

Figure 19 shows as an example the block diagram of a control scheme of a two level PWM AIC with constant d.c.-link voltage.

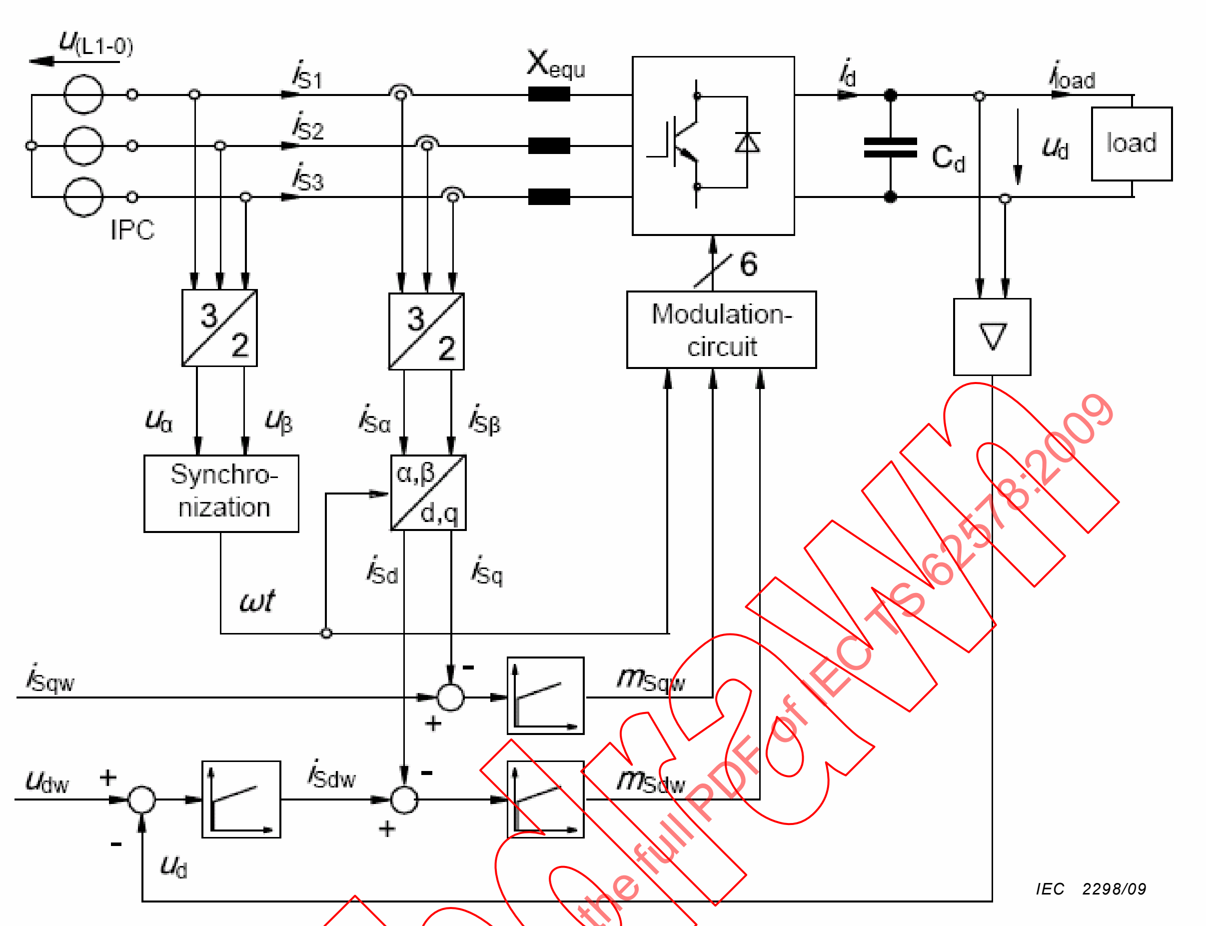


Figure 19 – Block diagram of a two level PWM AIC

Similarly to vector control of rotating-field electrical machines the current components in d-q-coordinates are used, where the d-component represents the active current, the q-component the reactive current. The d.c.- link voltage control defines the reference value of the d-component (active current) whereas the reference value of the q-component (reactive current) is arbitrary (mostly zero).

The reference value of the d.c.-link voltage shall be higher than the amplitude of the phase-to-phase voltage for proper function and lower than the maximum d.c.-link voltage which is limited by the used electrical devices (switches, capacitors).

5.3 Dynamic performance

The dynamic performance is mainly determined by the reactance X_{equ}. For fast current control a low reactance of X_{equ} is needed. Most applications are using a relative reactance of typically SCV_{equ} = 2 % to 10 %.

A higher value of the d.c.-link voltage will improve the dynamic performance, too, but the switching losses and the cost of semiconductor valve devices and capacitors will rise accordingly. Therefore the reference voltage is set with additional safety margins to a value a few percents higher than the amplitude of the phase to phase voltage.

Two aspects specify the d.c.-link capacity (short term energy storage):

- lifetime of (electrolytic) capacitors;
- dynamic behaviour of the d.c. load.

In applications where the d.c. load may change very quickly, the d.c.-link voltage can reach excessive values. Sufficient amount of capacitance is needed in order to reduce the voltage changes in the d.c.-link. When electrolytic capacitors are used, the capacitance is often high enough with typical dimensioning based on capacitor current rating and lifetime. However, film capacitors have higher current ratings than equivalent electrolytic ones. Thus special attention has to be paid to d.c.-link voltage variation when film capacitors are used. Often feed forward of the d.c. load is needed to speed up and stabilize the d.c. voltage control.

Another advantage over controlled converter with thyristors is the stable working in cases of high electrical power supply system impedances, if a current control is implemented.

5.4 Mains interference, desired

It is possible to use voltage source PWM AICs for compensation of specific harmonics.

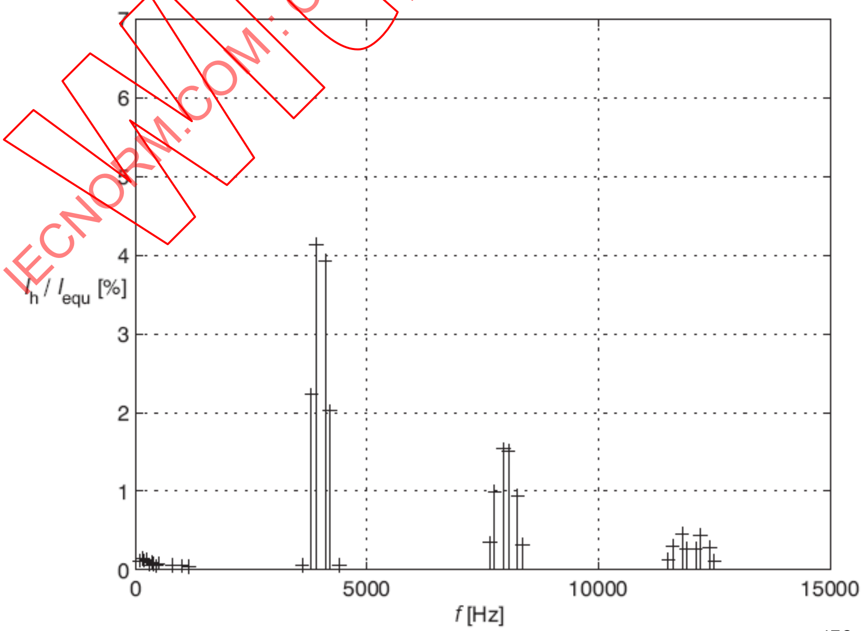
If the pulse frequency is above 2 kHz, these converters fulfil the requirements of the referenced International Standards in the low frequency range without additional filtering.

Harmonics components beneath the half of the pulse frequency of two level converters can be controlled to very low values (see 4.5). Another advantage is that flicker due to changes in the AIC load may not be a problem, since the power factor of the line current is close to 1 or can even be set capacitive. The optimum power factor to suppress voltage changes is dependant on the electrical power supply system impedance which is normally inductive.

5.5 Mains interference, undesirable

Figure 20 shows a simulated result of generated harmonics of the current i_{L1} at a given reactance X_{equ}. Near to the pulse frequency of 4 kHz the highest harmonic components occur ("sidebands" of $f_p \pm g \times f_L$ with $g = 2 \times n - 1$). More components are near each multiple of the pulse frequency and decrease to higher frequencies. These harmonics can only be reduced by a filter of higher order.

In addition harmonics of lower order caused by the supply voltage and controller deviations are measurable in real applications.



IEC 2299/09

Figure 20 – Harmonics of the current i_{L1} of reactance X_{equ}, pulse frequency 4 kHz, relative reactance of SCV_{equ} = 6 %

Figure 21 shows the supply voltages $u_{(L1-L2)}$ and $u_{(L1-0)}$. The voltage distortion of both voltages with only ac side inductive impedance is about 6,6 %. See 4.5.1.2 for detail.

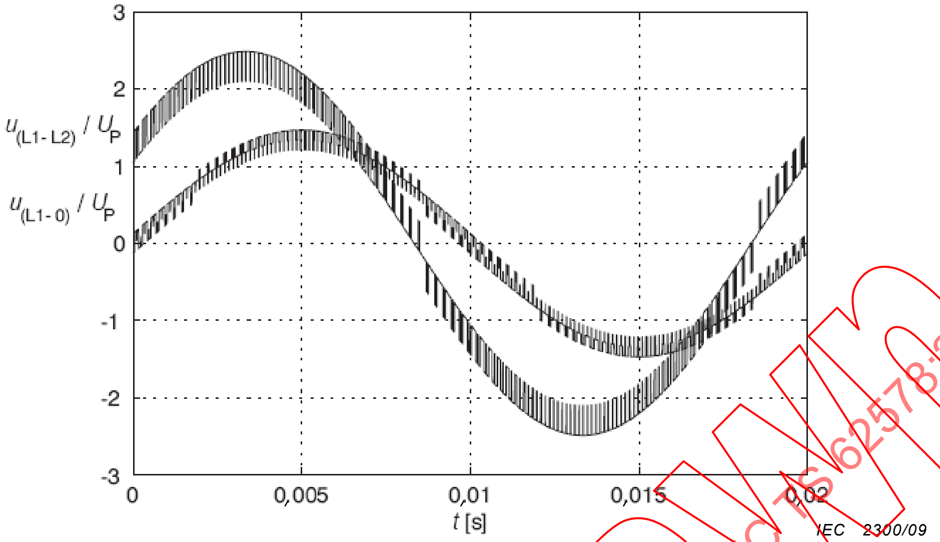


Figure 21 – Typical waveforms of voltages voltage $u_{(L1-0)}$ / U_P and $u_{(L1-L2)}$ / U_P at pulse frequency of 4 kHz, relative reactance of SCV$_{equ}$ = 6 %, R_{SCe} = 100

5.6 Availability and system aspects

Two level PWM voltage source AICs are state of the art in the field of LV applications and are used for UPS, wind-power and solar energy applications and active filters. Electrical power drives systems generally use two level PWM voltage source AICs for regenerative energy supply.

With sinusoidal line currents and a power factor of approximately 1, the losses are two to four times more than in the case of thyristor controlled converters.. On the other hand the RMS value of the line current is about 20 % lower compared to an uncontrolled rectifier.

If IGBTs are used as power semiconductors the switching losses are higher than the losses of a line commutated thyristor converter because of the higher switching frequency.

5.7 Operation in active filter mode

The control is similar to the block diagram in Figure 19. Additional harmonics are added to the reference values of the d- and q-components of the currents. Mains interferences (see 5.5) are not affected.

6 Characteristics of a PWM AIC of voltage source type and three level topology

6.1 General function, basic circuit topologies

A three level PWM converter is equivalent to a combination of two series connected two level systems with a common neutral point. This means that, with the same d.c. voltage level for each d.c. capacitor, a three level converter achieves an output voltage which is twice as high as that of a two level inverter system. In this case, the correct voltage distribution between the respective phase modules is achieved by means of diodes which fix the potentials (Neutral-Point-Clamped (NPC)-Technology). Mainly two basic topologies of three-level converters are used: NPC (which is practically limited to three levels) and the flying-capacitor (which can also be applied to multi-level topologies with more than three levels, see Clause 7). In case of NPC technology, the neutral point is connected to the a.c. input terminals through diodes.

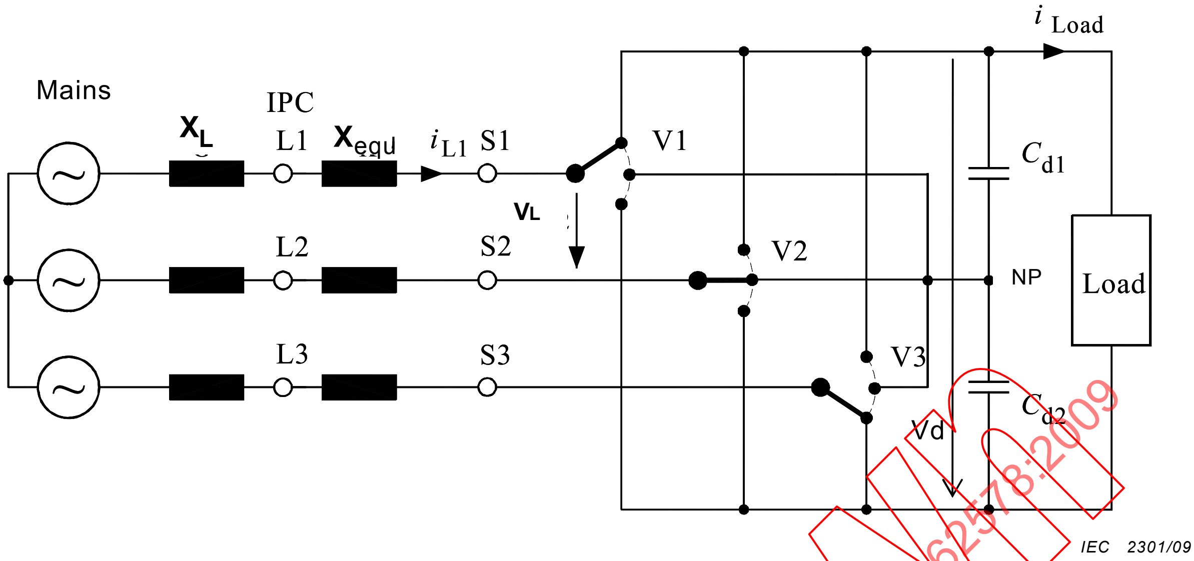


Figure 22 – Basic topology of a three level AIC – For a Power Drive System (PDS), the same topology may be used also on the load side

As the two level arm pairs of the three level phase leg are switched, it can provide three potentials referred to the potential of point "NP" of the d.c.-link, i.e.: 0, ± 0,5 V_d.

The suitably staggered switching of the arms gives phase-to-phase voltages of the three level inverter with five different voltage levels, i.e.: 0, ± 0,5 V_d, ± V_d.

Referred to the potential of point "NP" in Figure 22 the resultant pulse frequency is two times the valves switching frequency (for example 150 Hz switching frequency of each valve device results in a 300 Hz switching frequency at the output). An example is shown in Figure 23.

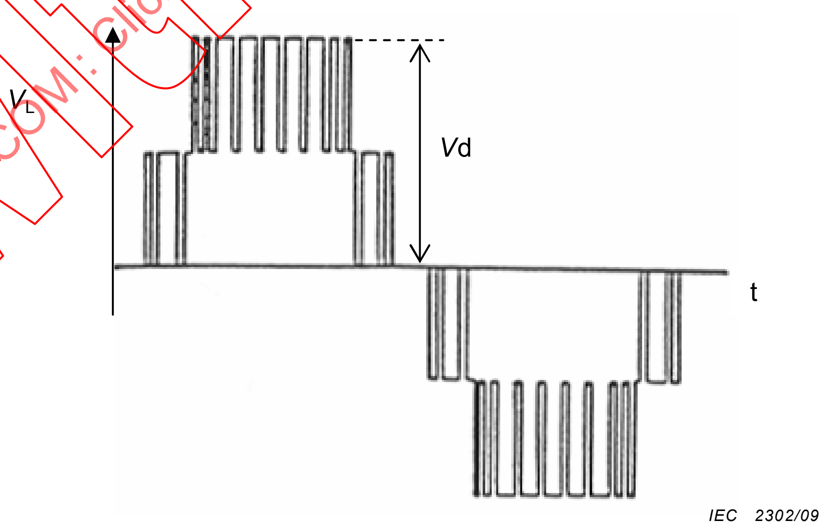


Figure 23 – Typical curve shape of the phase-to-phase voltage of a three level PWM converter

6.2 Power control

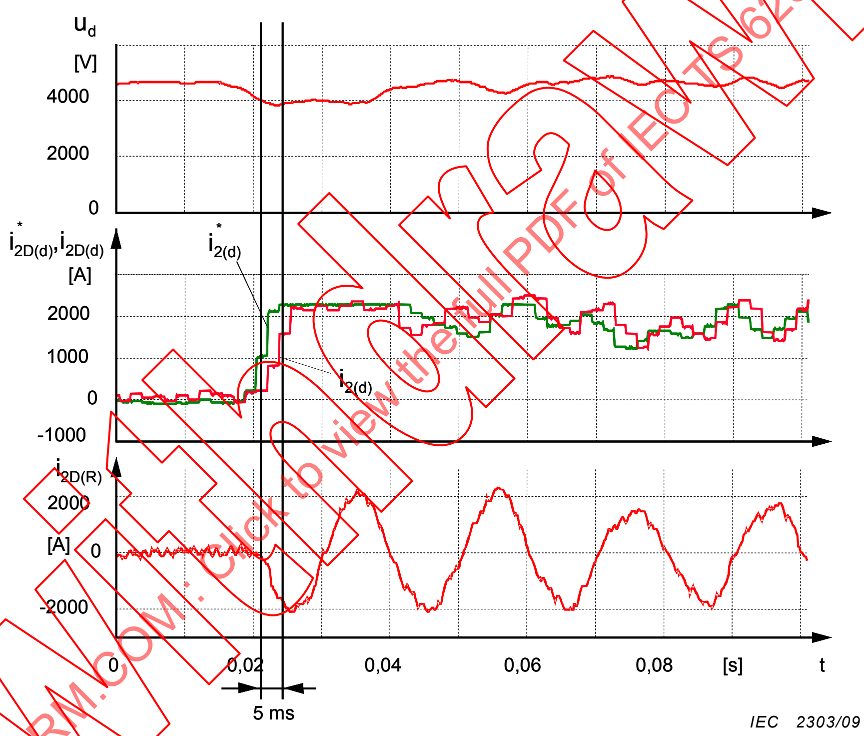
By using suitable semiconductors (IGBTs; GTOs; IGCTs) generally available on the market with a maximum peak forward blocking voltage of about 5 kV the nominal drive converter power ranges up to around 10 MVA with an output voltage of approximately 3,3 kV. With parallel connection it is possible to handle around 20 MVA and higher ratings with this technology.

In view of the increase of switching losses of the semiconductor valve devices for high power and high peak reverse forward voltages the pulse frequency sometimes has to be reduced considerably compared with low power systems.

6.3 Dynamic performance

Digital control tasks of such PDS converters are normally handled by high performance microprocessor units in multi-tasking mode with sampling times shorter than 1 ms.

The controller features a highly dynamic control response with rise times in the order of a few milliseconds and permits flexible adaptation to the different requirements through the use of suitably optimised pulse patterns.



Top: d.c.-link voltage
Middle: reference value i^*_{2D} and actual value i_{2D} of the d.c-load current
Bottom: line current

Figure 24 – Example of a sudden load change of a 13 MW PDS three level converter where the current control achieves a response time within 5 ms

6.4 Mains interference, undesirable

The pulse frequency of a three-level converter determines the frequency band above which the undesirable harmonics cannot be influenced.

In the case of a suitable PWM control, the phase voltage of a three-level converter never contains steps larger than 1/2 V_d. This reduces capacitive current ripples resulting from these voltage steps compared to two-level converters.

As the voltage steps related to d.c.-link voltage are only 50 % of an comparable two-level AIC, the generated current harmonics have a mean amplitude value of roughly 25 % of a two-level AIC with the same valve device switching frequency (see A.3.1).

6.5 Availability and system aspects

Three-level converters in Neutral Point Clamped (NPC) and Flying Capacitors (FC) topologies are state-of-the-art for high-power applications of any kind. Typical applications include process-oriented drives where additionally high dynamic behaviour is required (e.g. rolling mills) and the advantages of the power and harmonic control can be used. The efficiency of such high performance system reaches at least 96 %.

From the harmonics point of view, the three level PWM AICs have the following characteristic: The lowest harmonic frequency is the effective pulse frequency of the converter output voltage. The harmonic distortion factor for this voltage, without additional filter, is approximately 10 %. The harmonics of the integer multiple of the pulse frequency is also generated additionally but with much smaller amplitudes.

The amplitude of the harmonic current for the pulse frequency resulting from this harmonic voltage depends on the impedances between the supply voltage and converter input and the pulse frequency, is fairly independent from the load and virtually negligible (3 %). If necessary the harmonic current can be reduced by using additional filters.

7 Characteristics of a PWM AIC of voltage source type and multi-level topology

7.1 General function, basic circuit topologies

For easier understanding, a multi-level converter can be treated as several two-level converters connected in series (see Figure 25). This means that, with the same semiconductor valve devices, an n-level converter achieves an output voltage which is (n-1)-times as high as that of a two-level system.

Suitable control of the valve devices gives phase-to-phase voltages with many different voltage levels. With increasing number of levels the approximation of the desired voltage and current waveform (often sinusoidal) becomes better and better.

With several two level systems connected in series each of them is phase shifted triggered in such a manner that at the output a terraced voltage curve shape arises which has a good approach to the sinusoidal waveform, even without filter. The correct voltage distribution between the respective valve devices is achieved by means of capacitors with floating potential which requires a switching frequency as high as possible and appropriate switching of the valve devices. The rating of the capacitors depends on the switching frequency (see A.3.2).

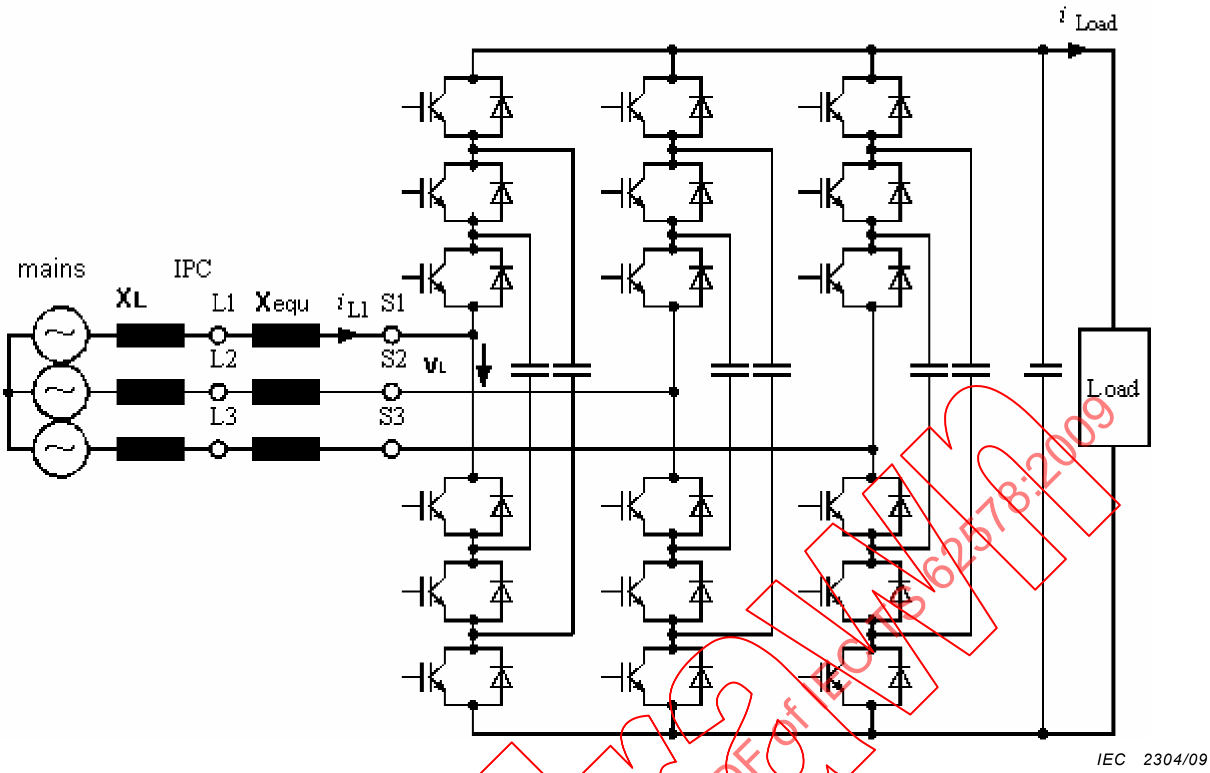


Figure 25 – Typical topology of a flying capacitor (FC) four level AIC

The respective two level systems of a multilevel converter are switched independently of each other, so that the mains side potential for a half wave can assume four potentials, if a four level converter is considered, i.e. : 0; ± 1/3 V_d; ± 2/3 V_d; ± V_d (see Figure 26).

The suitably staggered control of the valve devices gives at a four level converter phase-to-phase voltages with seven different voltage levels for the entire inverter system (see A.3.2).

This FC technology is not limited to 4 levels. Six or more levels are possible but normally not applied because of economical reasons. The more levels that are used the better is the approach to the sinusoidal waveform and the lower is the dv/dt-stress for insulation systems of wound inductive components (e.g. transformers).

As the voltage steps of a four-level AIC related to d.c.-link voltage are only 30 % of an comparable two-level AIC and because the achievable input voltage is three times as much, the generated current harmonics have a mean amplitude value of roughly 10 % of a two-level AIC with the same valve device switching frequency (see A.3.1).

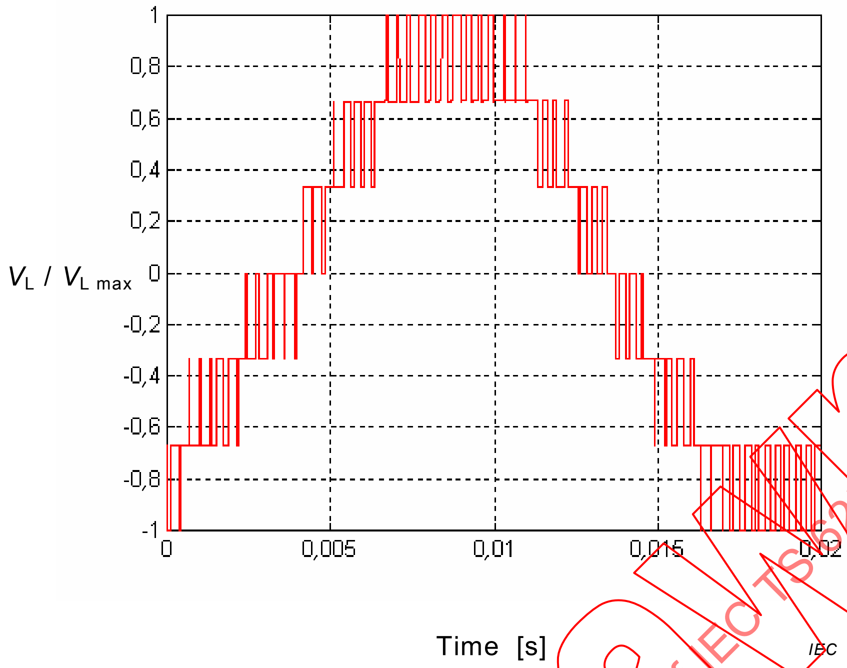


Figure 26 – Typical curve shape of the phase-to-phase voltage of a multi-(four)-level AIC

7.2 Power control

In comparison to two- and three-level converters only the following differences have to be taken into account when referring to Clauses 5 and 6.

- The visible resulting pulse frequency at the output increases with the number n of levels, while the switching frequency of the semiconductor valve devices remains constant. This leads to a better dynamic performance and an increased frequency range for desired (controllable) harmonics. Undesired (uncontrollable) harmonics start at higher frequencies.
- The voltage steps are reduced leading to smaller capacitive currents (reduced stress for any filters, connected cables and capacitors.
- Multilevel converters are normally used only if high power, high voltage and very low undesirable harmonics are required.

By using suitable semiconductors (IGBTs) with a maximum blocking voltage of about 3 kV which are commonly available on the market, the nominal output power ranges between 0.3 and 3 MVA for air-cooled versions and 2 MVA up to 5 MVA for water-cooled versions, with output voltages of approximately 2,4 kV to 4,2 kV.

Due to the increased switching losses of the semiconductor valve devices for high power and high blocking voltages, the pulse frequency for high power AIC has to be reduced considerably compared with low power systems (two levels). Additionally it has to be considered that the effective visible switching frequency of the a.c. voltage of such a system is three times higher than the pulse frequency of each valve device (for example 1 kHz switching frequency of each valve device results in an 3 kHz switching frequency at the output)

7.3 Dynamic performance

Digital control tasks of such AICs are normally handled by high performance microprocessor units in multi-tasking mode with sampling times shorter than 1 ms.

The controller features short response times and permits flexible adaptation to the different requirements through the use of suitably optimised pulse patterns.

7.4 Mains interference

From the point of view of the harmonics the multilevel PWM AIC based on 4 levels has the following characteristics:

- The lowest harmonic frequency which occurs is the effective pulse frequency of the converter output voltage (usually 3 kHz). The distortion factor for the voltage on the IPC, without additional filter, is approximately 5 % (an example is shown in Figure 27).
- Integer multiple of the pulse frequency occur additionally but with much smaller amplitudes. The amplitude of the harmonic current for the pulse frequency resulting from this harmonic voltage depends on the transformer impedance, the network impedance and the pulse frequency, is fairly independent from the load and virtually negligible (2 %). If necessary the distortion can be decreased by using additional filters.

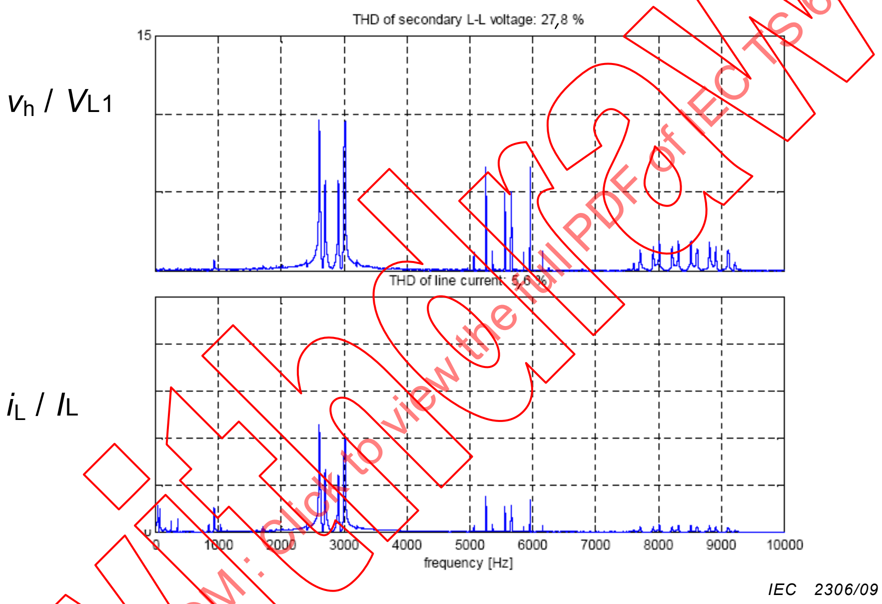


Figure 27 – Harmonic frequencies and amplitudes in the line voltage measured directly at the bridge terminals in Figure 25 and the line current of a multilevel (four) AIC (transformer with 10 % short circuit voltage)

7.5 Availability and system aspects

This type of converter is used for high power applications in all branches of industry where the high dynamic of the AIC is required. Marine applications and network distribution systems (e.g. because of the excellent capability to perform Active Energy Management (AEM) and active harmonic control) are typical examples for that.

The efficiency of such high performance system exceeds 96 %.

8 Characteristics of a F3E AIC of voltage source type

8.1 General function, basic circuit topologies

The F3E AIC consists of a standard diode bridge with antiparallel connected IGBTs. If the current flows in the direction of the load (e.g. a PWM motor inverter), it goes through the diodes. If the current flow is in the direction of the mains, it goes through the IGBTs.

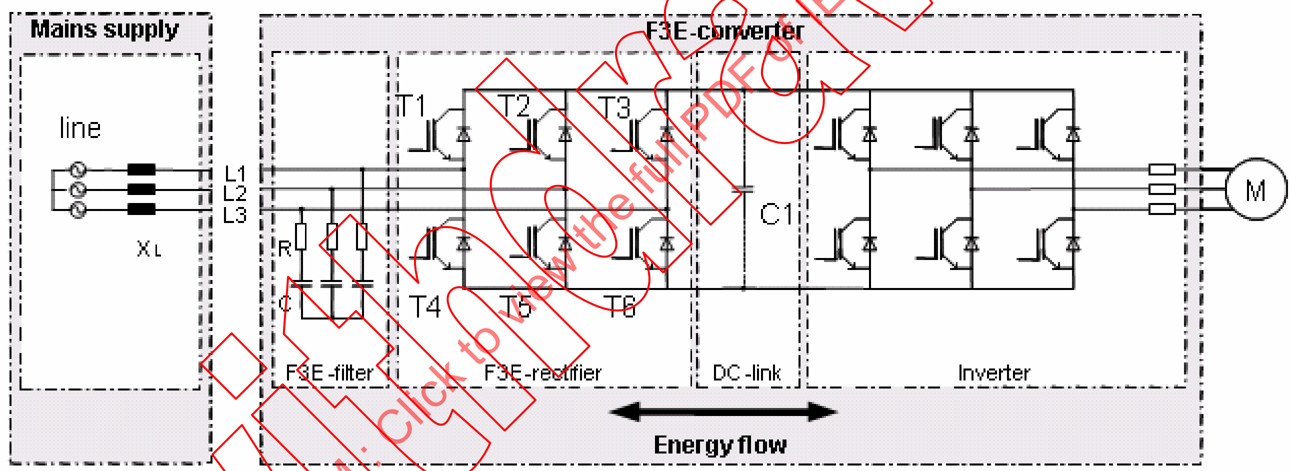
The switching of the IGBTs is synchronous to the current flow in the respective antiparallel connected diodes and therefore very simple. Rectangular current pulses with duration of half the mains frequency period are achieved with low switching losses.

The topology of a F3E AIC consists of a “Fundamental Frequency Front End” or so called “F3E-AIC” connected to a load (see Figure 28).

The d.c.-link 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 as shown in Figure 28.

Compared to the standard PWM inverter topology with diode rectifier, braking chopper and electrolytic d.c.-link capacitors three major advantages, energy regeneration to mains, lower harmonics – nearly no inductors necessary, extended lifetime compared to a converter with electrolytic d.c.-link capacitors shall be noted. However the output voltage of the inverter might be slightly reduced and needs higher pulse frequencies and control effort for the connected PWM inverter and there may be some power losses in the F3E-Filter resistors.

From practical experience it has been shown that in many cases only small additional mains side inductor is necessary to protect other equipment, fed by the same supply system, against voltage distortion caused by the F3E AIC.



IEC 2307/09

Figure 28 – Topology of a F3E AIC

Compared to a standard PWM converter with diode rectifier two major differences are obvious. In case of power drive systems Rectifier braking chopper/resistor are replaced by an “F3E-AIC”. The capacitors sourcing the PWM current of the inverter stage, moved from d.c.-link to a.c. mains are of much smaller ratings and can therefore be changed from electrolytic to a.c. metallised foil type capacitors.

8.2 Power control and line side filter

The line side filter is necessary to serve low-inductive source for the PWM currents of the output inverter stage and to limit the voltage ripple caused by these currents.

To avoid resonance problems the filter has to be damped by series resistors (see Figure 29). The effect of the filter can be demonstrated with a simple equivalent circuit representing the mains reactance X_L, the filter capacitance C, the damping resistors R and the exciting a.c. current source i(t).

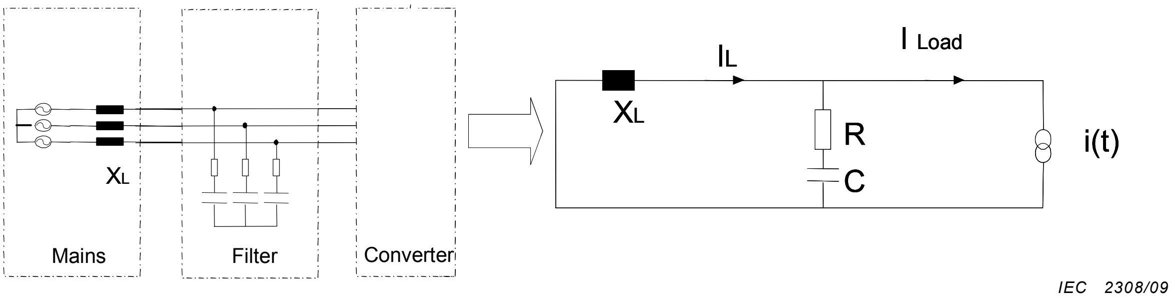


Figure 29 – Line side filter and equivalent circuit for the F3E-converter behaviour for the power supply system

The current transfer function G(f) depends upon the mains impedance. Here the mains impedance was supposed to be purely inductive. To normalise the reactance to the rated power of the converter the term R_{SCe} has been introduced in literature and standards (see definitions 3.24 to 3.26).

$$G(f) = i_{L1} / i_{conv} \tag{4}$$

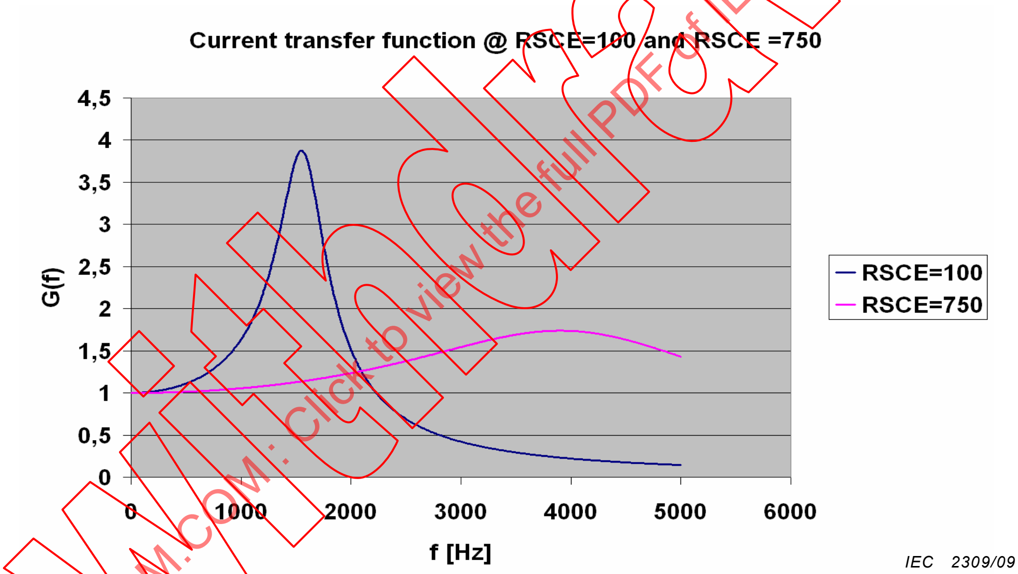


Figure 30 – Current transfer function together with R_{SCe} = 100 and R_{SCe} = 750 and a line side filter : $G(f) = i_{L1} / i_{conv}$

The higher the value of R_{SCe}, the lower the value of the mains impedance. In Figure 30 the current transfer function G(f) for two different R_{SCe} values has been calculated.

At a switching frequency of for example 4 kHz the PWM current ripple will be attenuated by a factor of 5 in case of R_{Sce} =100, where in case of R_{Sce} = 750 it will be increased. This has to be considered and may affect other equipment. Therefore not the current itself should be in focus, but voltage distortion caused by this current. To calculate this voltage distortion, one has to consider the current amplitude as well as the mains impedance.

$$U_h = X_L * i_{Lh} \tag{5}$$

The following diagram shows, how the mains voltage ripple changes with mains impedance, normalized to filter impedance.

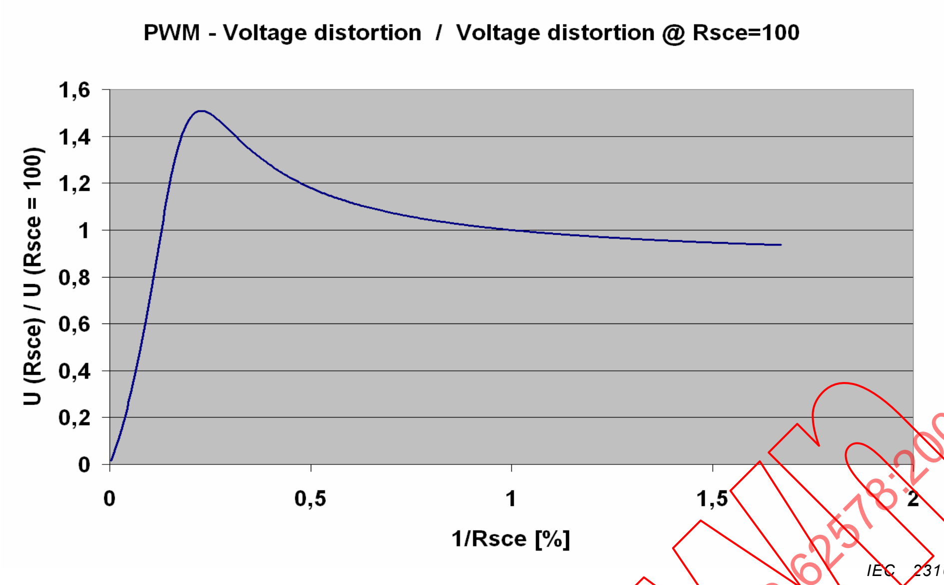


Figure 31 – PWM – voltage distortion over mains impedance for F3E-infeed including mains side filter

As expected from an ideal voltage source with no impedance, there is no voltage distortion – the result will be a clean, ideal sinusoidal waveform. No other equipment connected to these mains might be influenced.

In the resonance point the highest voltage distortion occurs. The filter should be designed so that this value is comparable to the PWM voltage distortion values of a general AIC.

Figure 32 shows the power spectrum of a 75 kW F3E-converter with the fundamental current being 116A (r.m.s. value) and a PWM-frequency of 4 kHz. The scaling is 2 kHz/div and 1,25 A/div.

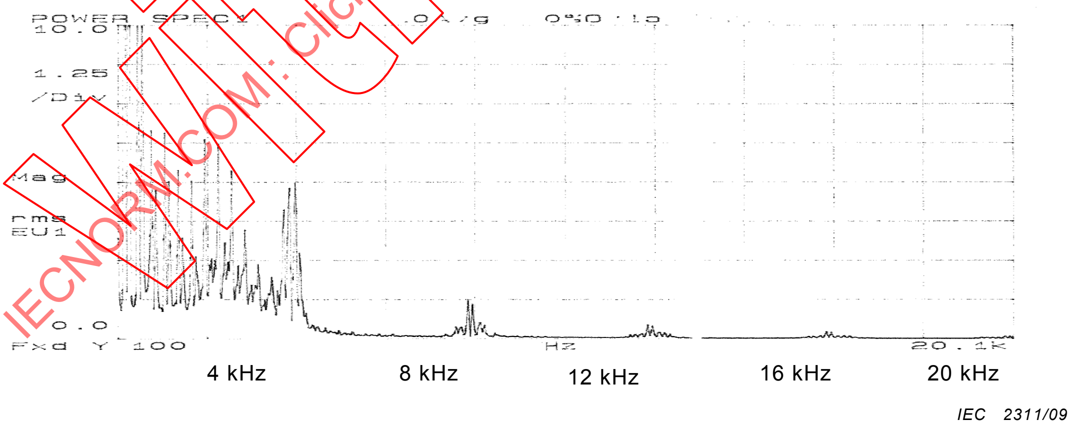


Figure 32 – Input current spectrum of a 75kW-F3E-converter

8.3 Dynamic performance

In case that it is used as the infeed of a PDS, the dynamic behaviour of the PDS is not influenced at all by the F3E-AIC.

8.4 Mains interference, low frequency components

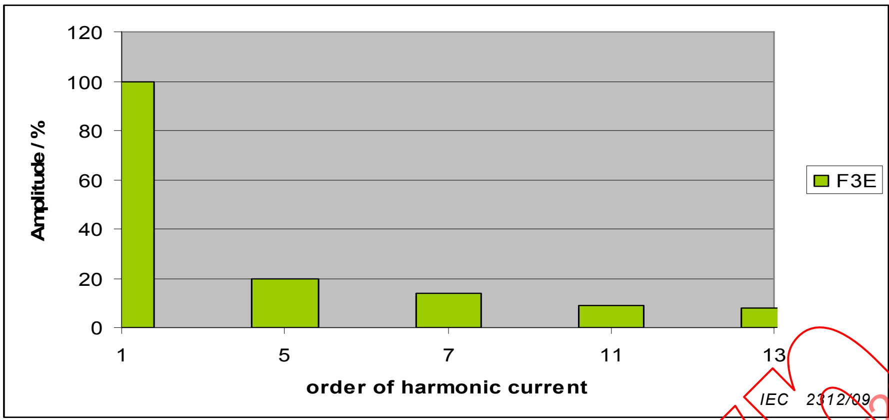


Figure 33 – Harmonic spectrum of the input current of a F3E-converter with R_{SCe} = 100

Figure 33 shows the typical harmonic spectrum of the input current under condition R_{SCe} = 100. With a F3E-Infeed the harmonic content represented by most significant harmonics influences can be reduced considerably (in case on the fifth harmonic down to less than 25 %).

9 Characteristics of an AIC of voltage source type in pulse chopper topology

9.1 General function, basic circuit topologies

Caused by a high population of single phase bridge fed electronically loads (TV-sets, power supplies of generic household and office equipment), with capacitive smoothing at the d.c.-side, the voltage distortion of the power supply system is stressed towards the 3rd and 5th voltage distortion.

This results from an arithmetic superposition phenomenon of all capacitive loading currents of all single phase equipment simultaneously (see Figure 34), which happens when the phase voltage reaches its periodical maximum.

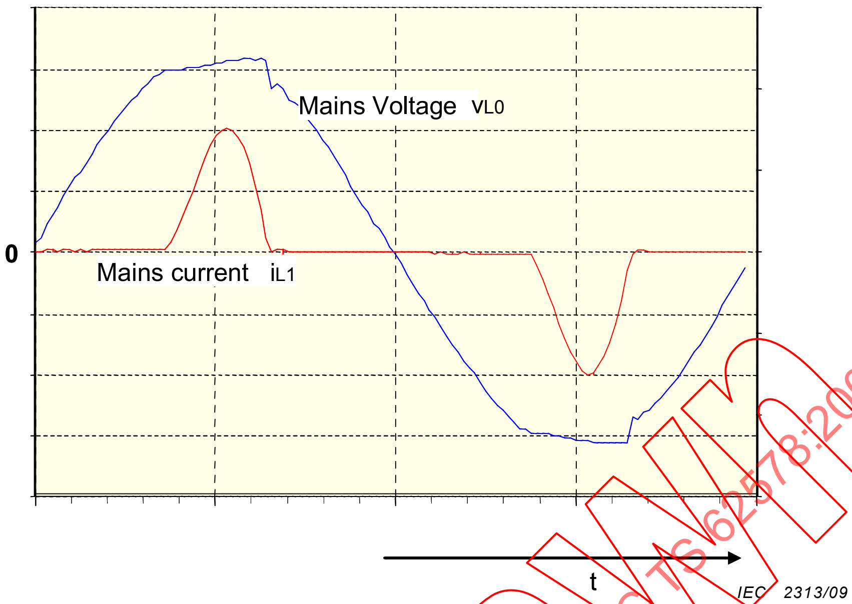


Figure 34 – An example of distortion effect by a single phase converter with capacitive load – The current waveforms of many units are similar and the effect on the power supply system is multiplied

In order to improve this situation economically, mitigation methods are contemplated by the manufacturers of such products.

One commonly applied solution is based on the topology of so-called AIC pulse choppers. AIC pulse choppers are PWM converters with a.c. supply mains input and d.c. or a.c. output. There are different variants of the pulse chopper according to the application. The AIC topology for a.c. to a.c. conversion is shown in Figure 35. These are normally used for power supplies and also known sometimes as "power factor controllers".

The AIC pulse chopper controls the amplitude of the output voltage by means of pulse width modulation. Bidirectional and reverse blocking power semiconductors in the forward and freewheeling path are necessary. Because of the lack of these elements they are actually composed of a combination of power transistors and power diodes.

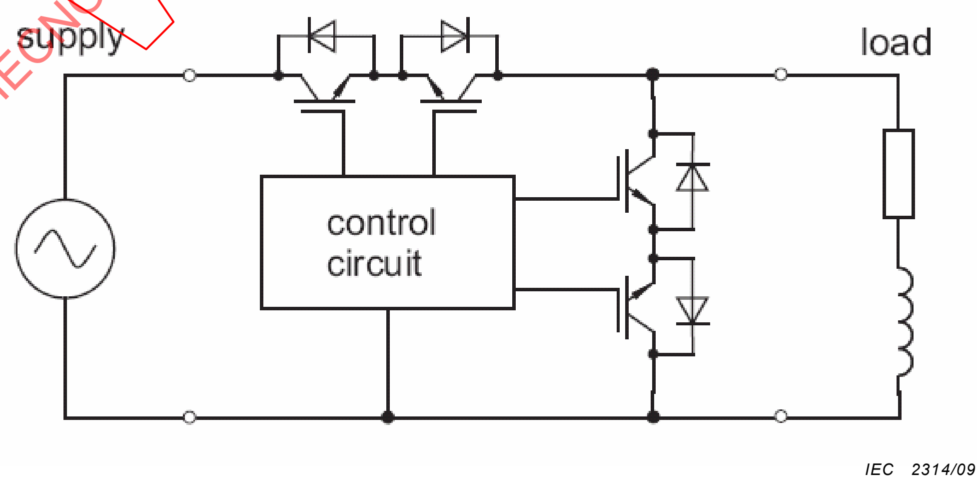


Figure 35 – a.c. to a.c. AIC pulse chopper, basic circuit

In operation the a.c. to a.c. converter circuit switches the sinusoidal a.c. supply mains voltage to the output a.c. side for a controlled part of the PWM period in every pulse period.

Thus, for each PWM period the output voltage can be controlled between zero and the actual, sinusoidal time dependent supply mains voltage. As the load usually has an inductive component, the output or load current is moderately smoothed. The current shape depends on the PWM method. For steady state conditions a constant modulation index can be assumed which leads to a sinusoidal voltage (sliding mean value) and sinusoidal current, both at supply mains frequency, with superimposed harmonics at switching frequency.

Nevertheless, in dynamic operation the modulation index varies depending on the control. AIC pulse choppers generally operate with a switching frequency between 2 kHz and 10 kHz.

The use of an AIC pulse chopper instead of a thyristor phase angle controlled circuit is recommended for one phase applications if the mains interference is too large (the maximum emission of the third, fifth and seventh harmonic is already reached).

9.2 Mains interference, desired

As the output voltage can be controlled with the PWM, it is possible to control specified harmonics desired to for example compensate mains existing low order harmonics.

9.3 Mains interference, undesired

AIC pulse choppers generate harmonics on the supply mains side with a frequency of the pulse frequency, its sidebands and multiples. As a result some filtering elements might be included in the topology in order to mitigate the effect on the power supply system.

Not only the switching frequency is important; also the current and voltage slopes of the switching have to be taken into account.

The filter shall be integrated in a part in the AIC pulse chopper. The application and the design of the filter depends on the intended use in public or industrial power supply systems.

9.4 Availability

A high availability is expected, because the AIC pulse choppers are short-circuit-proof.

9.5 Performance

AIC pulse choppers are applicable for elimination of disturbances. Conventional power controllers have not until now been able to replace an auto transformer in boost-circuits. This is only possible with AIC pulse choppers with a controlled free-wheeling arm.

9.6 Availability and system aspects

The forward conduction losses arise in one active switch and the series diode and during free wheeling in the freewheeling diode (d.c. load) and additional active switch (for a.c. loads). So, compared to thyristor controlled rectifiers for d.c. loads higher losses will occur. The losses are dependent on the load (impedance, transformer and boost).

10 Characteristics of a two level PWM AIC of current source type

10.1 General function, basic converter connections

A typical converter connection for a three phase current source PWM AIC is given by Figure 36.

The converter consists of three phase legs containing two switching devices i.e. power semiconductors. This current source AIC is connected to the electrical power supply system via a filter that most commonly consists of an inductor additional to the electrical power supply system impedance and filter capacitors required by this special converter connection.

At the d.c. side, the converter is connected to a d.c. inductor for current smoothing and short time energy storage. At the d.c. terminals an either active or passive load can be connected.

Due to the special properties of this circuit, negative voltages can occur at the semiconductors which therefore should have to be fully reverse blocking or otherwise diodes in series to the switching devices are to be added.

For medium to high power converters being applied in the industry reverse blocking Gate Turn Off Thyristors (GTOs) are commonly used.

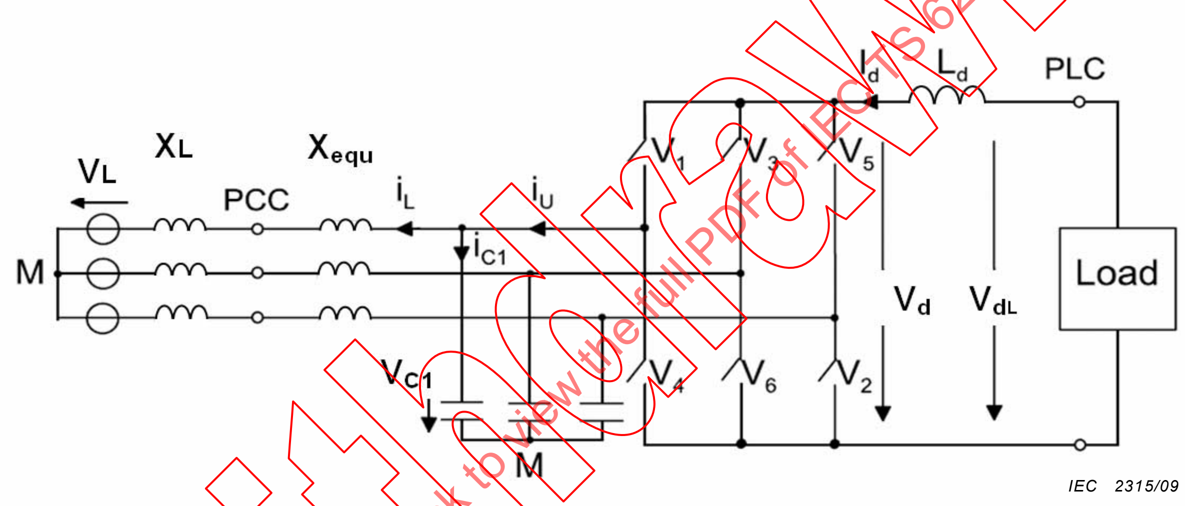


Figure 36 – Converter connection of a current source AIC

Current source type PWM AICs convert d.c. currents to three phase a.c. currents that are fed into the electrical power supply system or vice versa.

Full four quadrant operation of the electrical power supply system side quantities (voltage and current) is possible to fully control all types of apparent power, active and reactive.

The current source converter is characterized by a step up behavior of the voltage in direction to the electrical power supply system. While feeding power into the mains with fixed voltage the mean value of the d.c. voltage Vd may assume values between zero and the amplitude value of VC1 of the mains filter capacitor .

The pulse width modulation of current source type AIC is very similar to that of the VSC, see references [10.1][2] – [10.4]. The a.c. side converter current consists of pulses of the d.c. side current as can be seen in Figure 37 for a high frequency PWM converter.

They show a similar outline as the a.c. side line to line voltages of a VSC. The pulsed a.c. side converter current is smoothed by the LC filter yielding an almost sinusoidal electrical power supply system current waveform that is only superimposed by a small ripple.

2 Figures in square brackets refer to bibliography.

The d.c. voltage Vd is composed out of periodic pulses of all line to line capacitor voltages, being sectional switched to the d.c. side.

High power applications commonly use low switching frequencies of the semiconductors (typically from 300 Hz up to 1 000 Hz). Optimized pulse patterns are commonly calculated offline in order to eliminate specific harmonics.

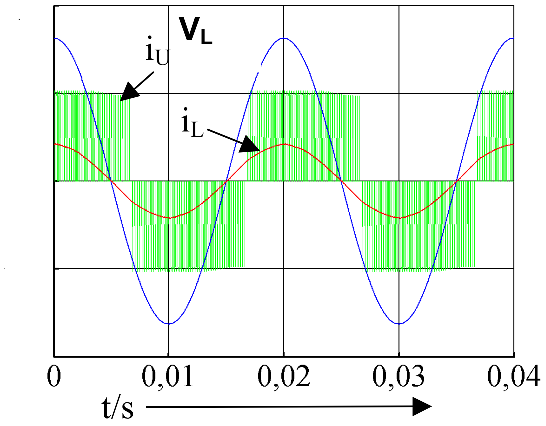


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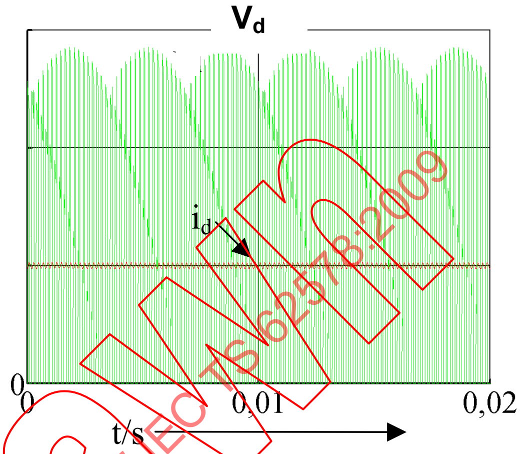
Figure 37a



IEC 2317/09

Figure 37b

37a Electrical power supply system voltage, electrical power supply system current, pulsed a.c. side converter current;

37b current and voltage on the d.c. side

Figure 37 – Typical waveforms of currents and voltages of a current source AIC with high switching frequency

10.2 Power control

The a.c. side control structure usually features a cascaded control structure with the inner control loop controlling the electrical power supply system current and the outer one controlling the power. The control of the current components can be realized similar to field oriented control for three phase a.c. machines.

As the a.c. side LC filter represents an oscillatory system it is recommended to implement damping functions (actively or with a subordinate capacitor control circuit [10.5] – [10.7]).

The control scheme (see Figure 38) is very similar to that of the voltage source system. The superimposed d.c.-link current control replaces the d.c.-link voltage control, and the controlled modulation of the mains side converter currents is used instead of modulation of the voltages

Conduction and switching losses in the power semiconductors devices are about the same as in VSCs and three up to four times of the losses of a three phase diode bridge rectifier, [10.10].

For high power AICs an efficiency of 97,5 % to 98,5 % including the losses of the necessary passive elements can be achieved. If additional series diodes are required for a CSC with non reverse blocking devices, the conduction losses and thus the overall losses may be higher than in the VSC.

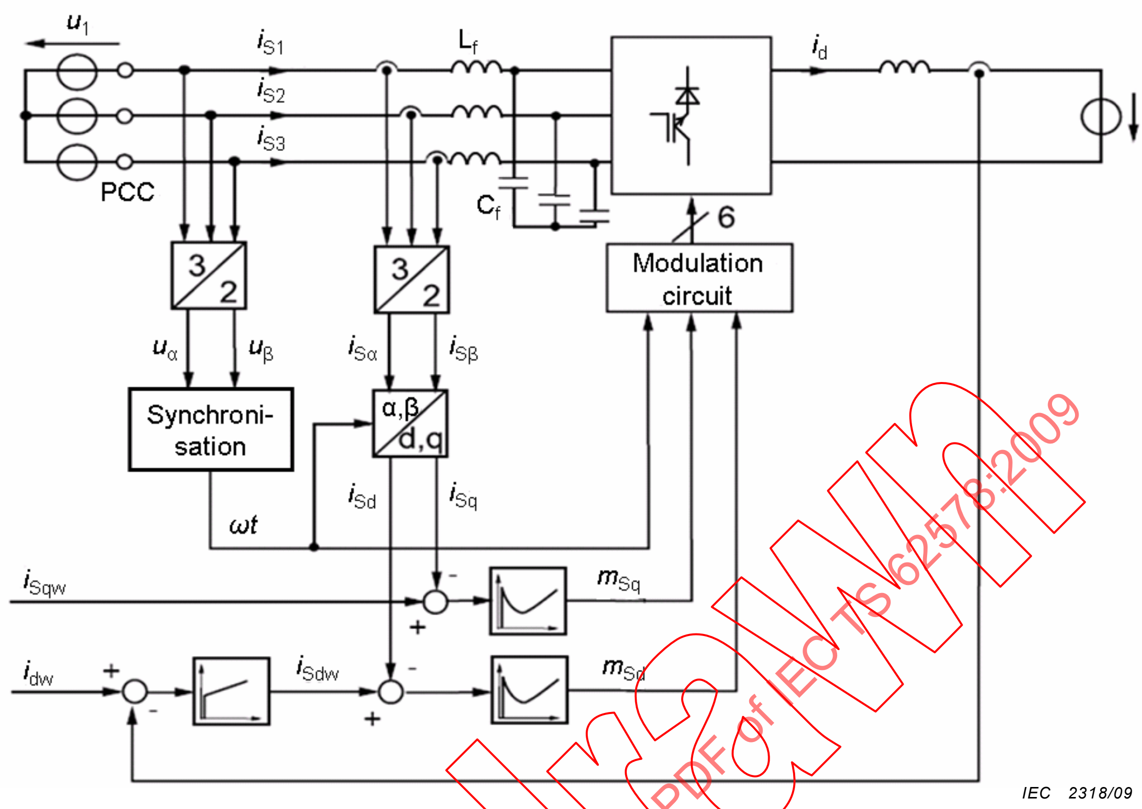


Figure 38 – Typical block diagram of a current source PWM AIC

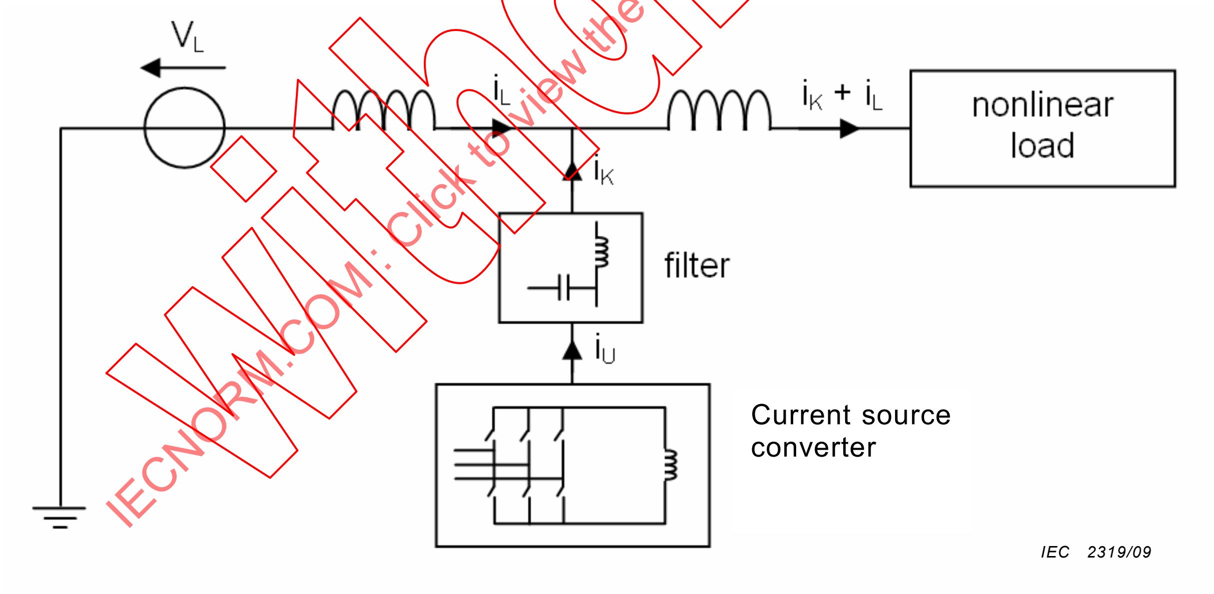


Figure 39 – Current source AIC used as an active filter to compensate the harmonic currents generated by a nonlinear load

In case of high pulse frequency, the current source converter posses real active filter capability for a wider range of harmonics. Figure 39 shows a possible connection for a shunt active filter featuring a current source converter. The current reference corresponds to the harmonic content of the electrical power supply system current that should be compensated. The current i_K is controlled in such a way that the harmonics in current I_L are controlled down to zero.

10.3 Dynamic performance

The control performance is characterized by high dynamics.

Figure 40 shows the performance of a realized current source AIC for a step response of the current.

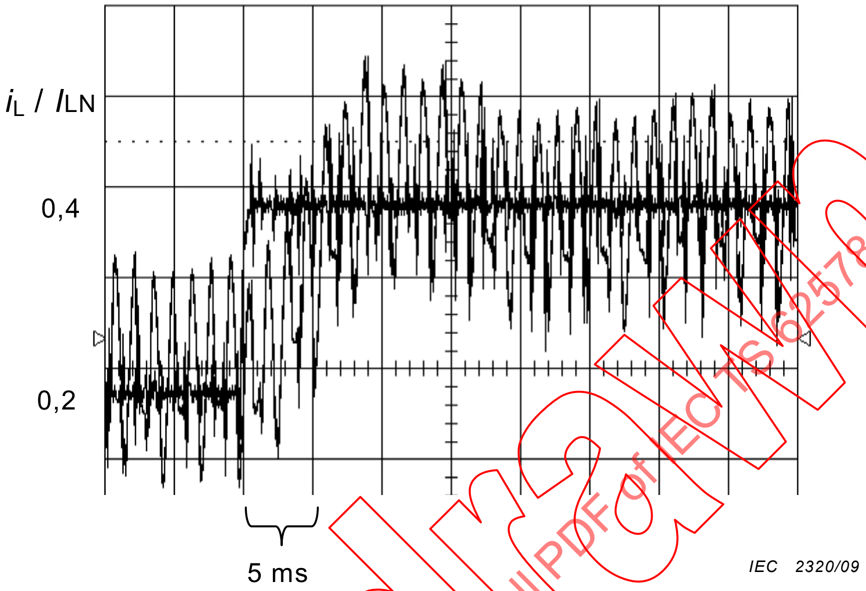


Figure 40 – Step response (reference value and actual value) of current source AIC with low switching frequency [10.9] – I_{LN} equals the rated current of the AIC

10.4 Mains interference

Current source AICs are used in the medium and high power range with GTOs and thus with low switching frequencies. If asynchronous PWM is used, only low harmonic amplitudes in the range of the pulse frequency are typically present. However, by using optimized synchronous pulse patterns for selective harmonic elimination [10.4], [10.8] these a.c. side low frequency harmonics can be further decreased. In both cases harmonics near the resonance frequency of the filter have to be avoided.

Attention should be paid to the harmonics already existing in a distorted electrical power supply system which may cause resonances of the filter and additionally may distort the electrical power supply system current.

10.5 Operation in active filter mode

The current source PWM AIC can be controlled in a way to compensate selected low frequency harmonics present in the a.c. electric power supply system and/or to avoid selected low frequency harmonics.

This can be done by suitable pulse width modulation or by control of the harmonics. For example in the case of medium and high power GTO converters by means of synchronous PWM with optimized pulse patterns. This can be realized similarly to the VSC [10.4]. The maximum harmonic order that can be eliminated depends on the pulse frequency.

10.6 Availability and system aspects

The current source AIC is used in industrial applications for current source converter PDSs. As such it can be used as an alternative to the line commutated thyristor converters. The application of such drives is in the range at medium to high power above 1 MW and at voltages above 1 kV.

Annex A
(informative)

Control methods for AICs

A.1 Control methods for AICs in VSC (Voltage Source Converter) topology

Several control methods exist. Some are time-domain methods, partly instantaneous, based, e.g., on the original instantaneous p-q-theory or on the so-called FBD-theory. Others use filters or sliding integration over a period to generate quasi-stationary control signals out of the above-mentioned instantaneous quantities. Other control schemes apply frequency-domain techniques, either based on FFT algorithms, treating all harmonics simultaneously, or on the determination of selected frequencies.

Amongst PWM-based schemes also a line flux oriented control scheme is know: The indirect stator-quantity control (ISR)-based scheme guides the converter flux on a basically circular track curve. A reference voltage vector is calculated for each period of pulse frequency. This reference voltage is then realised using a PWM scheme. Many of the control schemes are based on a.c. machine control schemes, because the structure of the line and the structure of an a.c. machine are quite similar.

Another control scheme is similar to the direct self control method (DSC) or direct torque control (DTC) that is commonly known to control electrical machines.

The supply network including the filter is treated in these cases like a big electrical machine and its estimated torque and flux (often referenced as "virtual") are controlled by hysteresis control.

The torque reference is produced by the d.c.-link voltage control and the flux magnitude reference is calculated from the reactive power or reactive current reference.

It is also possible to estimate the active and reactive power of the AIC and control these directly with hysteresis control.

The advantage of synchronous pulse patterns results from the property of being synchronous to the line frequency. Stationary, all periods are identical. As a result, all harmonics are known and depend only on the pulse pattern. No interharmonics occur. Dynamic changes require carefully precalculated changes between the pulse patterns.

In case of PWM schemes the pulse pattern is generated automatically for steady-state and dynamic operating conditions. Reference values for fundamental and controllable harmonic components can easily be generated. The generated harmonics to be expected are known but can no longer be influenced. If the triangular reference of the PWM circuit is synchronous to the line frequency, no interharmonics are to be expected. Otherwise, interharmonics in the frequency region of generated harmonics are generated.

Line flux oriented pulse pattern generation schemes (DSR and DSC like) provide the advantage of quick dynamic reaction and optimum utilisation of switching, combined with reduced amplitudes of harmonics. However, harmonics leak from the sharp lines associated with fixed pulse patterns, leading to interharmonics. This effect can also be reached by modifying the base period of space vector modulation and PWM based pulse pattern generation schemes randomly. Then the pulse frequency is not constant, but varies slightly around its mean value. Such methods are known under the name of random PWM.

It is important to note that the total amount of distortion, measured as the r.m.s value of all components in a frequency band in the region of generated harmonics, is constant for all