



BSI Standards Publication

High-voltage direct current (HVDC) systems — Guidance to the specification and design evaluation of AC filters

Part 5: AC side harmonics and appropriate harmonic limits for
HVDC systems with voltage sourced converters (VSC)

National foreword

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TECHNICAL REPORT



**High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters –
Part 5: AC side harmonics and appropriate harmonic limits for HVDC systems with voltage sourced converters (VSC)**

INTERNATIONAL
ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –

Part 5: AC side harmonics and appropriate harmonic limits for HVDC systems with voltage sourced converters (VSC)

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

The language used for the development of this document is English.

A list of all parts in the IEC 62001 series, published under the general title *High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters*, can be found on the IEC website.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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INTRODUCTION

The IEC TR 62001 series is structured in five parts:

IEC TR 62001-1 – Overview

This part concerns specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters, permissible distortion limits, harmonic generation, filter arrangements, filter performance calculation, filter switching and reactive power management and customer specified parameters and requirements.

IEC TR 62001-2 – Performance

This part deals with current-based interference criteria, field measurements and verification.

IEC TR 62001-3 – Modelling

This part addresses the harmonic interaction across converters, pre-existing harmonics, AC network impedance modelling, simulation of AC filter performance.

IEC TR 62001-4 – Equipment

This part concerns steady-state and transient ratings of AC filters and their components, power losses, audible noise, design issues and special applications, filter protection, seismic requirements, equipment design and test parameters.

IEC TR 62001-5 – AC side harmonics and appropriate harmonic limits for high-voltage direct current (HVDC) systems with voltage sourced converters (VSC)

This part concerns specific issues of AC filter design related to VSC HVDC systems. The rapid proliferation, increasing power, and technical advances of voltage source converter (VSC) HVDC technology in recent years has had a revolutionary impact on large-scale electrical power transmission. In the sphere of harmonics and filtering, the introduction of VSC technology has been highly significant. The harmonic signature of these converters is not only smaller in magnitude than equivalent line commutated converter (LCC) HVDC schemes, but also radically different in nature. Due to the switching and control methods which may be used for VSC, the generation of non-integer harmonics (interharmonics) may be an inherent characteristic of the conversion process. The frequency range of interest has also extended upwards.

The existing national and international regulations and recommendations governing harmonics were originally written considering the types of converters and associated harmonics relevant at the time of their production. With the arrival of new conversion technologies, the guidelines available are proving inadequate to deal with new harmonic profiles. Individual regulatory bodies are hastening to adapt their practices to the new technology and this document aims to aid them by providing a firm basis of appropriate technical knowledge.

The implications of VSC transmission for harmonic generation are perhaps not widely enough understood throughout the industry in terms of the frequencies and magnitudes produced and the necessity (or otherwise) of having dedicated filters. The modelling of a VSC as a harmonic voltage source rather than a current source may also not be fully appreciated in its implications for regulatory methodologies. The generation of interharmonics due to the control techniques used by some VSC HVDC converters also has profound implications.

A further topic of interest is the effect of VSC installations on pre-existing (background) harmonics. Some designs of VSC now produce a waveform so clean that it is quasi-sinusoidal and in many applications harmonic filters may not be required for mitigation of the harmonics generated by the converter. However, the converter will have a harmonic impedance as seen from the network, and it is important to be able to assess this harmonic impedance and calculate its impact in terms of possible amplification (or damping) of the pre-existing network harmonics. In some instances, this amplification of pre-existing harmonics may be the only reason for having to install filtering for a HVDC VSC.

The above aspects mainly refer to steady-state power quality issues. A separate topic is the interaction of the VSC HVDC control system with physical resonances in the connected power system. Electric power grid development is tending towards an increasing installation of underground and submarine cables, especially in the context of dispersed renewable generation. In addition, the phase-out of conventional generation together with the increasing installation of new generation sources coupled via converters and the changing characteristics of network loads will result in a reduction of harmonic damping in the system. Some converter control loops can have a bandwidth of several hundred hertz, and thus are able to interact with grid resonances. As a consequence, oscillations related to system harmonic resonances might appear and new mitigation techniques and assessment methods may become a challenge. Depending on system damping, such oscillations may be damped, sustained in steady-state or increase until some form of tripping or shutdown occurs. This phenomenon has become widely known as "harmonic stability" and although the suitability of this name may be questioned, it has been adopted in this document.

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –

Part 5: AC side harmonics and appropriate harmonic limits for HVDC systems with voltage sourced converters (VSC)

1 Scope

This part of IEC TR 62001, which is a Technical Report, provides guidance on the state-of-the-art of VSC technology in relation to harmonics and predicted future developments, on the harmonic profile of present and predicted future VSC architectures and how they are characterised and modelled – as voltage sources, current sources, or otherwise. It also assesses the harmonic impedance of VSC and the possible impact on pre-existing background harmonics emanating from loads or generation units in the supply network and considers how VSC harmonics are assessed under current IEC standards and national regulations, and identify areas where improvements could be made, research can be needed, or other bodies consulted, for example when considering interharmonics. This document can be a reference source on the subject, which will also contain recommendations for use by those charged with modifying existing standards to adapt to VSC HVDC systems.

Issues relating to harmonics on the DC side of the converters, including DC grids, are deliberately not covered in this document, but are addressed by a separate CIGRE Technical Brochure [1]¹.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 TR 62543, *High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)*

IEC 62747, *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62543 and IEC 62747 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>

¹ Numbers in square brackets refer to the Bibliography.

- IEC Electropedia: available at <http://www.electropedia.org/>

3.1.1

harmonic

integer harmonics and interharmonics

Note 1 to entry: The terms "harmonic" and "interharmonic" are used to describe components of a periodic time domain signal in the frequency domain. To do this, the periodical signal is expressed as a Fourier series. From a physical point of view, harmonics and interharmonics are indistinguishable – they are merely signals of different frequencies.

Due to the fact that definitions of the terms "harmonic" and "interharmonic" differ slightly in various standards, it is essential to clarify the definitions used in this document in relation to those standards.

The International Electrotechnical Vocabulary [2] defines in IEV 161-02-18:1990 a harmonic as "a component of order greater than one of the Fourier series of a periodic quantity". The harmonic order is defined in IEV 161-02-19:1990 as "the integral number given by the ratio of the frequency of a harmonic to the fundamental frequency".

IEC 61000-4-7 [3] excludes other reference frequencies and connects the definition of the IEV specifically to the power system frequency. Due to this, a harmonic becomes a "frequency which is an integer multiple of the fundamental frequency of the power system". Furthermore, IEC 61000-4-7 states that, "for brevity", the RMS value of a harmonic component is simply called a "harmonic".

The same aforementioned standards define the term "interharmonic" as the components of a periodic quantity whose order is non-integer.

To avoid constantly referring to "harmonics and interharmonics", throughout this document the term "harmonics" is used to cover both integer harmonics and interharmonics, except where it is desired to distinguish some aspect which is particular to either one.

3.2 Abbreviated terms

Acronym	Phrase
DC	direct current
DFIG	doubly-fed induction generator
EHV	extra high voltage
EM	electro-magnetic
EMC	electro-magnetic compatibility
EMT	electro-magnetic transient
EN	european norms
FCC	forced commutated converters
FDM	frequency division multiplexed
FACTS	flexible alternating current transmission system
FFT	fast fourier transform
GTO	gate turn-off thyristor
HVDC	high voltage direct current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEV	international electrotechnical vocabulary
IGBT	insulated gate bipolar transistor
IGCT	integrated gate-commutated thyristor
ITU	International Telecommunication Union
LCC	line commutated converter
LTI	linear time invariant
MIMO	multiple input multiple output

Acronym	Phrase
MMC	modular multi-level converter
MOSFET	metal-oxide-semiconductor field-effect transistor
MV	medium voltage
NLC	nearest level control
OPWM	optimized pulse width modulation
PCC	point of common coupling
PLC	power line carrier
PLL	phase-locked-loop
PM	phase margin
POTS	plain old telephone service
PTC	positive train control
PSPWM	phase shifted pulse width modulation
PWM	pulse width modulation
RLC	resistance (r), inductance (l), capacitance (c)
SCR	short circuit ratio
SM	sub-module
SSR	subsynchronous resonance
THD	total harmonic distortion
THFF	telephone harmonic form factor
TIF	telephone influence factor
TOV	transient over voltage
TSO	transmission system operator
UHF	ultra high frequency
USA	United States of America
WECS	wind energy conversion system
VHF	very high frequency
VSC	voltage source converter

4 Basic aspects of VSC HVDC harmonics

4.1 General

Clause 4 provides an introduction to the harmonic aspects of VSC HVDC, setting it in the context of line commutated converters (LCC) technology and including a preliminary overview of some topics which are elaborated upon later in the document. The subjects covered are the following:

- summary of the differences between the harmonic behaviour of VSC and LCC technologies;
- particular issues relating to harmonic aspects of VSC;
- range of frequencies pertinent to VSC HVDC;
- equivalent circuit of the VSC converter from which a harmonic analysis can be performed;
- impact of connecting a VSC to the network, both as a harmonic generator and as a harmonic impedance.

4.2 Differences between VSC and LCC harmonic behaviour

HVDC converters may be defined in two distinct categories. Until the late 1990s, all HVDC projects utilized line commutated converters (LCC) which consisted of 12-pulse thyristor bridges (or earlier 6- and 12-pulse mercury-arc bridges). Such converters depend on the AC line voltage to commute the current between phases and to turn off the thyristors, hence "line commutated".

From the late 1990s, very fast development of HVDC voltage source converters (VSC) has taken place. These use IGBTs (insulated-gate bipolar transistors) in various possible bridge configurations with capacitors for energy storage. These converters are classed as forced commutated converters (FCC), that is, they can be switched on and off at any point in the line voltage cycle as required by the converter control. The many advantages of this type of converter include independent controllability of real and reactive power, black start capability, and the elimination of the need for separate capacitive reactive compensation at the converter stations. Progress in valve design and control techniques has resulted in the rapid increase of converter power ratings and reduction in switching losses.

The main differences between LCC and VSC concerning harmonics are as follows:

- a) Reactive power: LCCs consume reactive power, i.e. have a lagging power factor, due to the phase difference between the applied voltage and the current, caused by both the control angle delay and the commutation (overlap) effect. In order to control the interchange of reactive power with the network, shunt capacitive compensation is installed such that the net reactive power exchange with the network is limited within specified bands. Typically, an LCC HVDC scheme may require the installation of shunt reactive power compensation of around 40 % to 60 % of the value of the rated active power.

This shunt compensation is typically implemented as a number of separate banks and sub-banks, which are switched in steps determined by the reactive power consumption of the converter and the net reactive power interchange goal established by the system operator.

Normally, most of this shunt compensation is tuned at various frequencies to form harmonic filters. The land area required for these filter and capacitor banks, as well as their associated circuit breakers, is a very significant part of the total converter station area.

VSCs for HVDC systems may be designed such that the active and reactive power consumption or generation are controlled independently. Normally, no additional shunt reactive compensation is required.

- b) Harmonic generation: LCCs generate a highly distorted AC current, which, for the usual 12-pulse configuration, contains large amounts of the characteristic harmonics (11, 13, 23, 25, 35 etc.), as well as smaller levels of many other non-characteristic harmonics. The magnitudes of those harmonics decrease rapidly with increasing frequency. Typically, statutory limits are applied only up to the 50th harmonic order, as LCC-generated frequencies higher than that are regarded as having negligible impact on the power system. No interharmonics are generated, unless the frequencies at the two ends of the DC link are different (in such a case, cross-modulation effects will produce a spectrum of interharmonic current from both converters). As a working approximation, the converter may be regarded as a harmonic current source at characteristic harmonic frequencies, as the current generated is reasonably independent of the AC side impedance, although at low order harmonics the cross-modulation effects between the AC and DC sides should be considered.

VSCs for HVDC systems generate a much less distorted AC side current waveform. Depending on the converter topology and the control methods employed, the network side voltage generated by the converter may approach a clean fundamental frequency sinusoid. The converter may be considered as a harmonic voltage source behind an internal impedance, rather than a current source as for LCCs, as it is the generated harmonic voltage which remains independent of load. The harmonic levels may be extremely low compared to LCCs, but due to the adopted switching regime may have a significant frequency range much higher than for LCCs, and may contain significant levels of interharmonics, which are a product of the control strategy adopted.

- c) Harmonic filters: LCCs require the installation of large filter banks to mitigate the harmonic distortion imposed on the connected AC network. At fundamental frequency, these filters supply reactive power to the AC grid, as explained above. Filtering is mainly provided at the characteristic (and possibly low order) harmonic frequencies, but should also consider the mitigation of intermediate non-characteristic harmonics by introducing resistive damping in the filter design. Interaction of shunt filtering with the pre-existing harmonics of the AC system should be taken into account, to avoid unacceptable levels of amplification.

VSC using switch type valves generally requires a very small amount of AC harmonic filtering. VSC using controllable voltage source type valves or using multi-level converter topologies however generate such low levels of harmonics that passive AC filtering of converter emission is usually deemed unnecessary.

4.3 Issues relating to VSC harmonics

The perception and marketing of VSC HVDC technology has rightly emphasised that one of the benefits of this technology is the considerable reduction, or even elimination, of the requirement for AC filters and their associated switching. While this is true, it does not mean that issues related to harmonics can be completely disregarded. Careful analysis of the harmonic generation and the impact of connecting the converter station to the AC system is still required during the converter station design. Studies are still necessary to show that the harmonic levels will be within specified limits and that the converter will not unacceptably amplify pre-existing harmonics. Moreover, harmonic generation affects the stress levels to which converter-related equipment will be exposed.

The fact that VSCs generate harmonics in frequency ranges above 2,5 kHz to 3 kHz (for 50 Hz to 60 Hz systems respectively) and have wide frequency spectra may give also rise to harmonic related issues. Particular topics concerning harmonics, which have been addressed in existing VSC HVDC projects include the following:

- the possible need for small AC filters, either for mitigation of emissions or to limit the amplification of pre-existing harmonics;
- generation of voltage and current waveforms with harmonic frequencies that are unusual for an AC system, and which in practice may have a negligible physical impact. However, these may nevertheless violate some low grid code limits which were originally formulated in the context of different harmonic spectra typical of older technologies. Such frequencies include interharmonics and even harmonics;
- resonance issues in isolated AC systems with high cable content, as typical of windfarms, particularly those located offshore;
- harmonic interaction with other converter systems and filters, for example between wind turbines and the associated VSC HVDC interconnector.

Assessment of VSC harmonic related issues requires detailed understanding of the VSC's harmonic generation and the specific application of the VSC under assessment. Different techniques are applied by VSC suppliers to generate the voltage output, each resulting in different harmonic generation. Clause 4 describes the mechanisms of harmonic generation by different topologies of VSCs and give some illustrative examples of their frequency spectra.

Often VSCs are not the only source of distortion but are part of a larger system that may experience harmonic issues. For instance, offshore VSC applications (i.e. connection of offshore wind farms to onshore grids through HVDC links using VSCs), or connection to very weak AC networks or DC grid applications, are classic examples where the VSC HVDC generated harmonics are not necessarily the source of the problem. In such applications, small harmonic magnitudes generated by other converters, for example wind turbines, may be amplified due to resonances between inductive and capacitive impedances in the system. This, together with low damping in the system, may result in high harmonic voltage distortions at the point of evaluation.

4.4 Range of frequencies considered

The electromagnetic compatibility (EMC) IEC 61000 series classifies harmonics and interharmonics as low frequency conducted phenomena (e.g. IEC 61000-1-2 [4]). According to the International Electrotechnical Vocabulary (IEV or IEC 60050 series [2]) "low frequency" is defined as "frequency up to and including 9 kHz" (IEC 60050-161:2014, 161-01-26). Nevertheless, most standards (for example IEC TR 61000-3-6 [5], EN 50160 [6] or IEEE Std 519-2014TM [7]) only regulate harmonics and interharmonics for frequencies up to and including the 40th or 50th harmonic (2 kHz or 2,5 kHz respectively for a 50 Hz fundamental and 2,4 kHz or 3 kHz respectively for a 60 Hz fundamental). Many grid codes adopt a limit of 50th harmonic for the assessment of harmonic power quality, and this has been the range normally considered for LCC HVDC.

Harmonic magnitude limits for frequencies between 2,5 kHz or 3 kHz to 9 kHz are not standardised and are considered on a case by case basis when necessary.

This document takes into account that VSCs can use pulse-width modulated control (synchronous or asynchronous to the power system fundamental frequency), or other switching technologies, which may generate higher frequencies than the traditional power quality limit of the 50th harmonic order.

Considering VSCs as nonlinear devices, the converters will create non-sinusoidal waveforms. Generated frequencies other than the fundamental are unwanted and are the result of non-ideal conversion.

Figure 1 shows the range of frequencies which may be contained in the voltage waveform generated by a VSC in a typical HVDC scheme, with an indication of which phenomena are responsible for the generation of frequencies in different bands. These are further discussed in subsequent paragraphs.

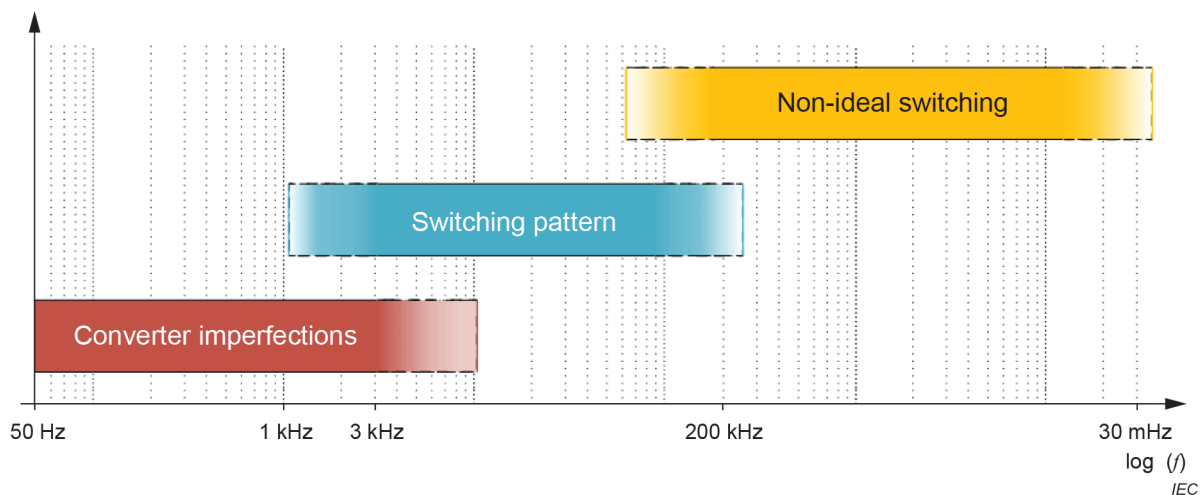


Figure 1 – Frequency range of VSC waveform

In the lowest frequency range, the generation is a result of so-called converter imperfections, such as measurement tolerances, component tolerances, and non-idealities in the control system. The impact of the imperfections can be seen up to higher frequencies but the magnitudes decrease strongly with increasing frequency.

The switching pattern is dependent on the converter topology and the applied modulation strategy. For converters of the cell type such as MMC, the generated frequencies are strongly dependent upon the number of submodules – the more submodules, the higher are the frequencies of the spectrum. For a classical two-level topology, the switching frequency and its integer harmonics will dominate the spectrum in the switching pattern range. With higher frequency, the impact of the pattern typically decreases by approximately 20 dB per decade, eventually becoming negligible.

The effect with greatest impact on the highest frequency range is the non-ideal switching of the power electronic devices. The commutation of the current from one device to another will lead to voltage and current overshoots, which result in even higher frequency content than caused by the switching patterns.

The main focus of this document is the frequency range up to 50th harmonic order covered by the standards listed above in 4.4, because most issues in regard to harmonics (e.g. power quality issues or control interactions) have their origin in this frequency range.

However, where it is helpful to explain certain phenomena resulting from the converter operation, a wider frequency range will be considered. When harmonic generation remains at a significant level at frequencies above around 3 kHz, it may be desirable to consider the power quality implications. Calculation of the rating stresses of converter components should also take such frequencies into account.

It should be considered that modelling of the connected AC system becomes more uncertain with higher frequencies, as secondary effects (such as stray capacitance, skin effect and eddy-current losses) become influential and so the analysis of the system to be investigated becomes progressively more complex.

4.5 Equivalent circuit of the converter for harmonic analysis

Converter representation for harmonic analysis – Figure 2 a) – and an equivalent circuit of the converter for harmonic analysis – Figure 2 b) – based on [8] are presented in Figure 2 below.

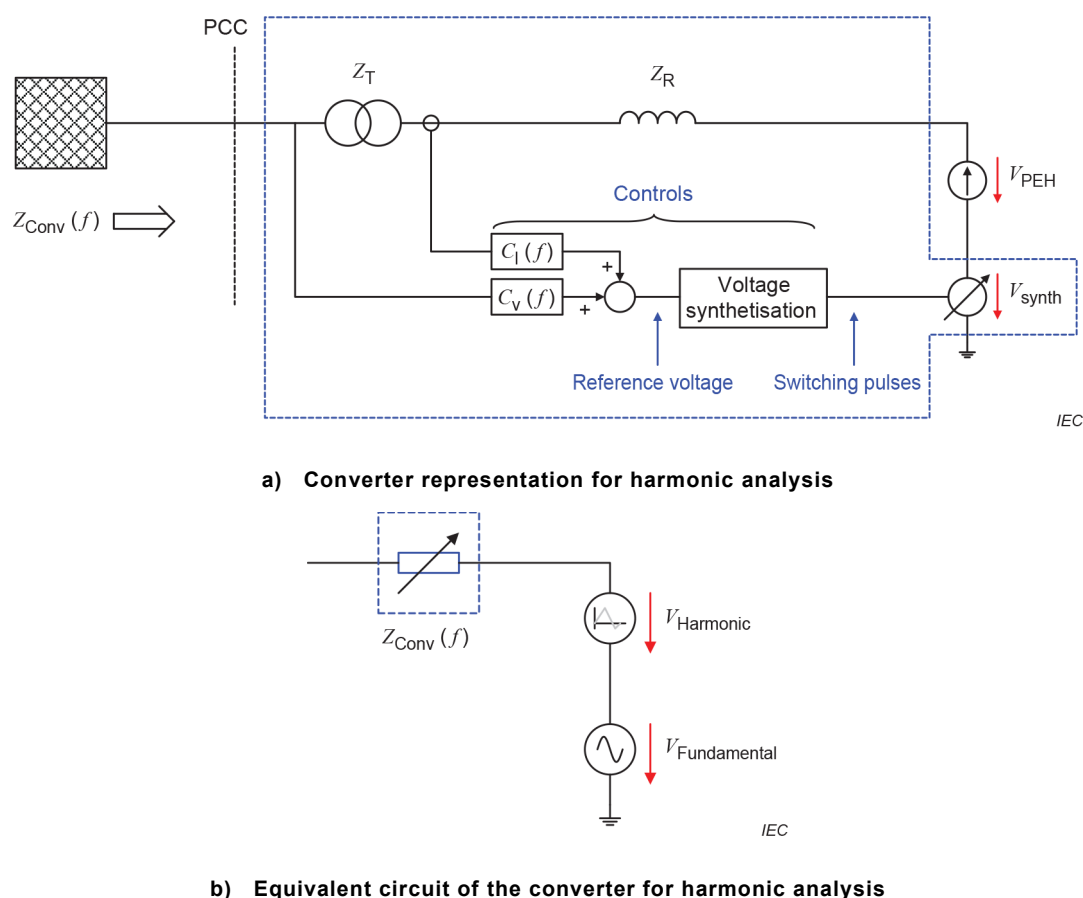


Figure 2 – Harmonic representation of a VSC station for harmonics analysis

The converter is represented by a voltage source consisting of two parts. The voltage V_{synth} represents the synthesization of the reference voltage signal. The reference voltage includes not only the fundamental voltage, but may also be active in the higher frequency range, in defining the impedance of the converter. V_{PEH} represents the voltage created by the non-ideal behavior of the power electronics hardware (e.g. voltage drop across the semi-conductor devices).

The reference signal for voltage synthesization is defined by the transfer function of the current controller $C_i(f)$ and the voltage feedback transfer function $C_v(f)$. The transfer functions also include current and voltage transducer representation, control hardware sampling, delays and all other relevant parameters.

The converter impedance consists of passive and active converter impedance. The passive impedance is defined by transformer (Z_T) and reactor (Z_R). The impedance of any passive filter should also be included. The active impedance depends on the converter control. Determination of the converter impedance is presented in Clause 6.

4.6 Dual impact of a VSC converter on harmonic distortion at PCC

4.6.1 General

To determine the total harmonic distortion at the point of common coupling (PCC) caused by a VSC HVDC converter, two aspects have to be considered:

- converter-generated harmonic emission;
- pre-existing (background) harmonics, including their possible amplification by the converter.

The way to study and treat the total harmonic generation caused by these factors is very similar to that for LCC HVDC converters (or any non-linear load). However, there are two significant differences between LCC and VSC in this respect. Firstly, a LCC HVDC station has extensive passive shunt filtering and reactive compensation, which have the effect of largely masking the harmonic impedance of the converter itself. Secondly, for VSC HVDC, the converter generated harmonics tend to be less significant, and so the possible amplification of pre-existing harmonics becomes a relatively vital aspect. The complex behaviour of the VSC in response to harmonics in the supply system should be understood and taken into account.

In the calculation of the overall harmonic distortion, the network and converter harmonic sources can generally be considered as independent from each other. This assumption allows separate analysis of both effects, using different models and tools, and is valid for most purposes.

In the following, the network is represented as an ideal harmonic voltage source along with its impedance $Z_{\text{Net}}(f)$. The same harmonic impedance is used for the calculations of both the emissions and the amplification of the pre-existing AC network harmonics. Appropriate assumptions regarding what magnitude of pre-existing harmonic voltages and what values of AC network impedance should be used in such calculations is a complex issue which is equally relevant to LCC converters and is discussed at length in [9], [10] to [14].

4.6.2 Converter generated harmonics

The impact of the converter harmonic contribution on the overall harmonic distortion at PCC can be analyzed by use of the model shown in Figure 3.

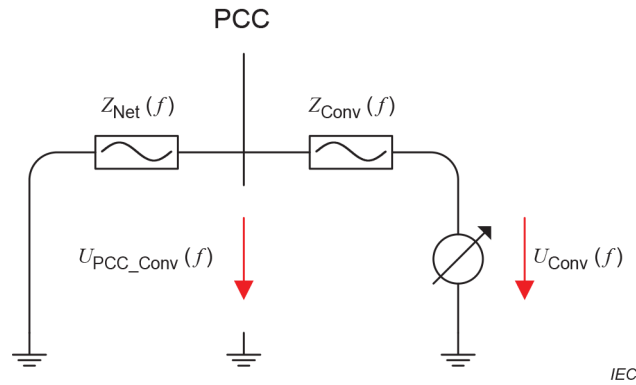


Figure 3 – Harmonic contribution by the converter

The converter is represented as an ideal harmonic voltage source $U_{Conv}(f)$. In a typical design study, the converter impedance $Z_{Conv}(f)$ is defined by the HVDC manufacturer and the network impedance $Z_{Net}(f)$ would be provided by the network operator for the relevant frequency range. The network impedance may have a wide range of possible values depending on configuration and load levels. A suitable calculation algorithm is required to determine the worst-case network from specified network impedance loci, i.e. that impedance which maximizes the distortion at the PCC for each individual frequency.

The harmonic distortion at the PCC is then calculated by:

$$|U_{PCC_Conv}(f)| = \left| \frac{z_{Net}(f)}{z_{Net}(f) + z_{Conv}(f)} \right| \times |U_{Conv}(f)| \quad (1)$$

or, expressed in terms of admittance, as:

$$|U_{PCC_Conv}(f)| = \left| \frac{y_{Conv}(f)}{y_{Net}(f) + y_{Conv}(f)} \right| \times |U_{Conv}(f)| \quad (2)$$

NOTE An equivalent (Norton) current source model could be used, with an internal impedance located in parallel with a harmonic current source. However, such a model offers no particular advantages for most applications and is not referred to in subsequent analyses in this document.

4.6.3 Pre-existing harmonics

The impact of pre-existing (background harmonics) on the total harmonic distortion at PCC can be analyzed by use of the model shown in Figure 4.

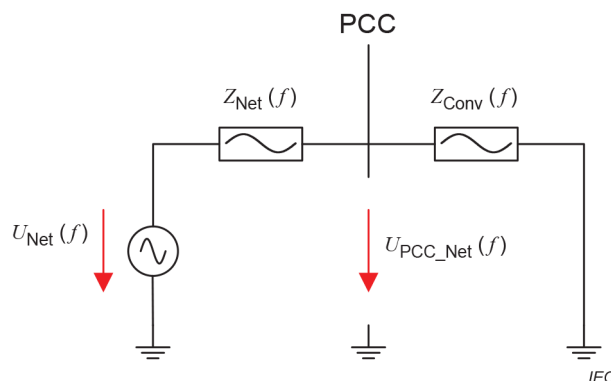


Figure 4 – Amplification of the background harmonics

$Z_{\text{Conv}}(f)$ represents the impedance of the converter, and is discussed in detail in Clause 6 and Clause 10. The harmonic voltage distortion at the PCC due to pre-existing harmonics is then defined by:

$$|U_{\text{PCC-Net}}(f)| = \left| \frac{z_{\text{Conv}}(f)}{z_{\text{Net}}(f) + z_{\text{Conv}}(f)} \right| \times |U_{\text{Net}}(f)| \quad (3)$$

4.6.4 Combining the effects of converter-generated and pre-existing harmonics

There is no fixed relationship between the phase angles of the converter-generated harmonics and the pre-existing harmonics. Therefore, an assessment of harmonic performance at the PCC needs to consider the summation of the two taking into account their random phase relationship. An aggregate harmonic distortion may be calculated by adding the harmonic voltages at the PCC resulting from converter generation and those resulting from modification of the pre-existing harmonics by methods based on the relevant standards, for example the "general summation law" presented in IEC TR 61000 3-6 [5], as expressed in Formula (4):

$$U_{\text{hPCC}}(f) = \sqrt[\alpha]{\sum_i U_{\text{hi}}^\alpha} = \left(|U_{\text{PCC-Conv}}(f)|^\alpha + |U_{\text{PCC-Net}}(f)|^\alpha \right)^{\frac{1}{\alpha}} \quad (4)$$

where the suggested indicative values of the exponent α are frequency-dependent, as shown in Table 1.

Table 1 – Indicative summation exponents

Harmonic order	α
$h < 5$	1
$5 \leq h \leq 10$	1,4
$h > 10$	2
SOURCE: IEC TR 61000-3-6 [5]	

It can be noted however that [5] emphasizes that these values should only be used in the absence of more specific information. If there is any technical reason why some harmonics should have a more, or less, coincident phase relationship than implied by these exponents, another more appropriate summation may be applied.

In IEC TR 61000-3-6 [5], the general summation law and the above exponents are only specified for integer harmonics. Since the interharmonics from the converter and from the network are assumed to be uncorrelated, similar to the higher frequency harmonics, it is reasonable to consider that an exponent of $\alpha = 2$ can be used for interharmonics. This approach corresponds to the method used in IEC 61400-21 [15] for power quality characteristics of grid connected wind turbines.

For assessment of the rating of affected components, a more conservative approach may be desirable. It should be considered that the phase angles of some individual harmonics from the converter and the pre-existing harmonics could be coincident. If any individual harmonics have significant amplitude with respect to rating of any components, their possible phase coincidence should be considered appropriately.

5 Harmonic generation

5.1 General

VSCs are devices that can ideally generate any set of three phase voltages by following a reference signal as a result of some primary control strategy. The reference signal is typically a continuous function, for example a three phase fundamental frequency sine function.

A VSC typically attempts to follow the reference signal by switching in and out capacitors. This will result in an output voltage which is a stepped function. The deviation of the stepped waveform from the continuous reference will result in integer harmonics in case of repetitive patterns, or inter-harmonics if the same pattern is not repeated every fundamental period. Consequently, in order to correctly capture the interharmonics in the analysis of the resulting waveforms, it is important to consider a suitable time window for the fast Fourier transform (FFT) analysis, which may be longer than one fundamental frequency period [3].

A number of different topologies and switching strategies can be used to create the desired high voltage outputs. Subclause 5.2 presents the principal factors influencing harmonic generation common to all topologies. Some of the existing ones are discussed in 5.3 which describes the harmonics generated by different VSC topologies and switching patterns. Subclause 5.4 discusses aspects of the generation of interharmonics, while 5.5 considers the impact of various non-ideal conditions.

VSCs, regardless of their topology and switching pattern, generate harmonics in a wide frequency range. In order to show the nature of the harmonic generation, an extensive spectrum of harmonic frequencies is shown in Clause 5. This should be treated as general information to describe the nature of the given harmonic spectrum, for example, to illustrate where the highest magnitudes in the frequency range are located for a certain switching pattern. By comparing different topologies or switching patterns, it can be concluded that different frequency ranges are required to show the nature of their respective harmonic spectra. Therefore, in the following subclauses, different frequency ranges may be shown for different converter types and switching techniques.

The frequency range to be considered for practical harmonic power quality analysis is generally much more restricted. Nevertheless, it is recommended that the HVDC manufacturer provides the "big picture" to the customer, i.e. a general overview of the range of harmonic generation. This has the benefit of creating mutual understanding on the topic between the HVDC supplier and the customer. Additionally, the customer is informed and therefore capable of addressing any possible future issues that may arise due to harmonics being generated outside the standard harmonic analysis range.

Knowledge of the harmonic generation "big picture" also enables precautionary measures to be taken in the early stages of a project to avoid any adverse or undesired interactions with sensitive equipment in the AC grid, for example PLC transmitters/receivers having resonance frequencies outside the standard harmonic range or automatic meter reading (AMR) systems. Dialogue between the customer and the HVDC supplier is recommended in order to exchange information on any such sensitive equipment.

The analysis presented in subsequent subclauses refers to the phase values of generated harmonics. The generation from the three phases may be unbalanced, i.e. may contain positive and negative sequence components. Any zero sequence harmonics on the converter side of the transformer will be blocked by the converter transformer configuration (either Yd, or Yy without starpoint grounding on the converter side).

5.2 Factors influencing harmonic generation

5.2.1 General

The influences to be considered in the calculation of harmonic generation are the following:

- converter topology;
- converter control:
 - reference voltage generation;
 - synthetisation of the reference voltage;
- power electronics hardware:
 - interlocking time;
 - semiconductor voltage drop.

The VSC converter topology has the greatest impact on the harmonic generation. Four different converter topologies are presented in 5.2.2, and sample harmonic calculations of these topologies are provided in 5.3.

The harmonics generated due to interlocking time and semiconductor voltage drop are due to physical effects which ultimately depend on the converter topology and semiconductor types. Subclause 5.2.4 describes why these occur and how they contribute to the overall harmonic profile.

The harmonic generation described in most of 5.2 relates to idealized operation conditions of the converter. The effects of non-ideal behaviour, asymmetries, pre-existing harmonics, DC side harmonic interaction, and other factors are discussed in 5.5.

5.2.2 Converter topology

According to IEC 62747, VSC converter topologies can be grouped in two types:

- VSC converter using switch type valves:
 - two-level converter (Figure 5);
 - three-level converter (Figure 6);
- VSC converter using controllable voltage source type valves:
 - modular multi-level converter (MMC) (Figure 7);
 - cascaded two-level converter (CTL) (Figure 8).

The converter topologies differ in the energy storage (capacitor) location and the switching pattern of the semiconductors.

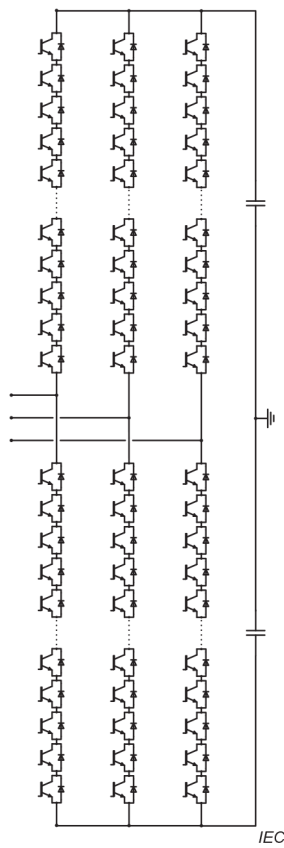


Figure 5 – Two-level converter

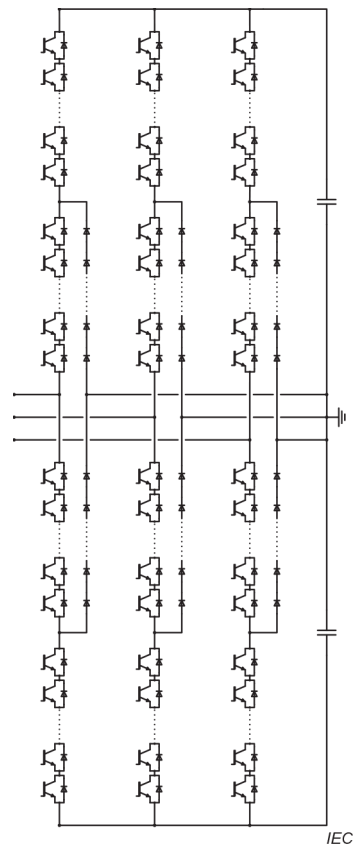


Figure 6 – Three-level converter

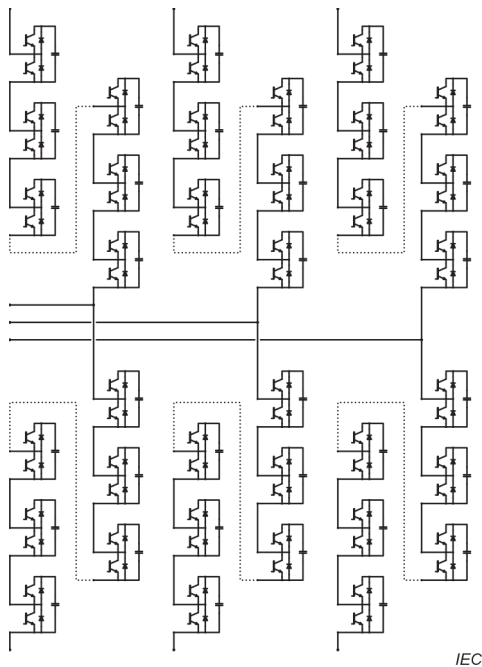


Figure 7 – Modular multi-level converter (MMC)

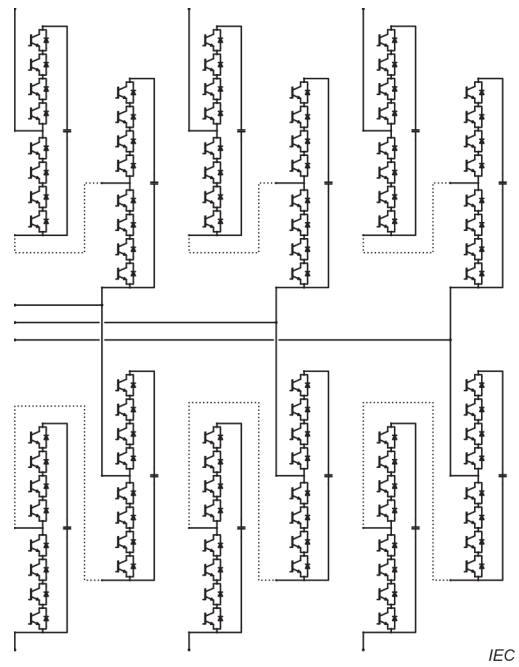


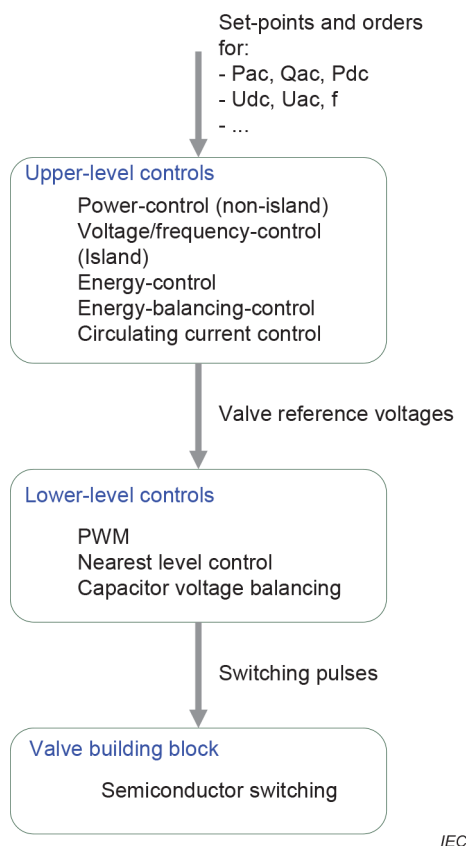
Figure 8 – Cascaded two-level converter (CTL)

5.2.3 Control

5.2.3.1 General

According to the CIGRE Technical Brochure 604 [16], the converter controls which are relevant for harmonic generation can be grouped in three levels as shown in Figure 9:

- upper-level controls;
- lower-level controls;
- valve building block.



SOURCE: [16]

Figure 9 – HVDC VSC converter control structure

The upper-level controls includes the voltage/current control at the converter terminals and the control of the converter internal current and energy-balancing. Since the converter internal current and energy-balancing controls depend on the converter topology, the upper-level controls are topology dependent.

The output of the upper-level controls is the reference for AC or valve voltage. The purpose of the lower-level controls is then to generate a replica of the reference voltage via creation of the semiconductor switching signals. This part of the control system and how it generates harmonics is described further in 5.2.3.3.

In the valve building block, the semiconductor switching may generate noise of a high frequency range; however, that is outside the scope of this document.

5.2.3.2 Upper-level controls (reference voltage generation)

Harmonics generated during the process of reproducing reference voltages are usually caused by the switching of the valves. Both the converter control and the measuring system contribute to the harmonic output. Therefore, both the control software and hardware should be considered in the harmonic generation analysis.

Due to the complexity of the control software and hardware, and intellectual property issues, few publications and only general analysis can be found in the public literature on the subject of harmonics generated by the converter controller. Without detailed knowledge of the system, a general recommendation regarding the required analysis cannot be provided.

As no general rules for harmonic generation analysis can be provided, different converter operating states should be analysed to determine the impact on the converter harmonic generation. Examples of the converter operating parameters and characteristics which might be relevant are

- full range of operation (active/reactive power and operation at different modulation indices),
- negative phase sequence voltage in the AC network,
- control mode active/reactive power or (non-island) or voltage/frequency (island),
- component tolerances,
- influence of measurement filters, and
- cross-modulation.

Due to the high number of relevant operating parameters and possible combinations of these parameters, a comprehensive calculation of harmonic generation for all possible operating conditions may not be practically feasible. Depending on the project requirements and implemented control functions, the HVDC supplier should agree with the customer suitable methods by which a sufficiently high degree of confidence in the calculated harmonic generation may be assured.

In contrast to the effect of other sources, the harmonics generated by upper-level controls can be modified by adjustments to the control software, which can be implemented during the commissioning phase of a project if necessary.

5.2.3.3 Lower-level controls (synthesization of the reference voltage)

Synthesization of the reference voltage is achieved via semiconductor switching according to a switching pattern implemented in the lower-level controls. The switching patterns which are commonly used for VSC HVDC are

- pulse width modulation (PWM),
- phase shifted pulse width modulation (PSPWM), and
- nearest level control (NLC)

Converter topologies with distributed energy storage (MMC and CTL) also require control algorithms for capacitor voltage balancing between the distributed energy storages. Switching patterns and capacitor voltage balancing strategies are highly dependent on the converter topology. An explanation regarding the resulting harmonics is provided in 5.3, where the different topologies are presented.

5.2.4 Power electronics hardware

5.2.4.1 General

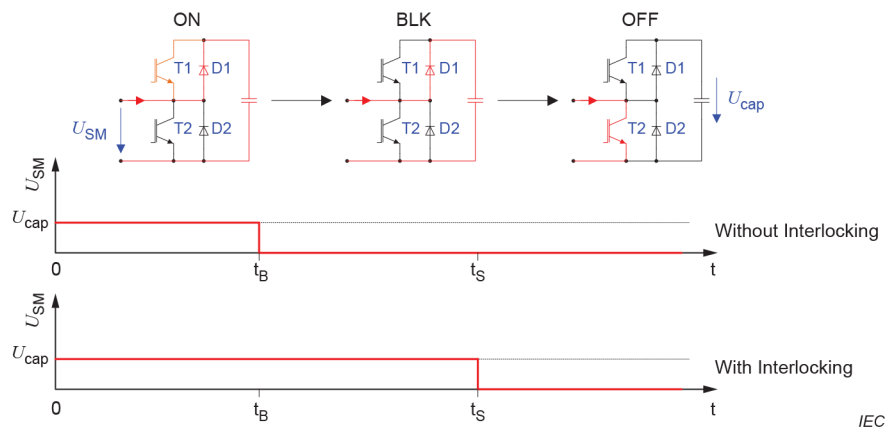
Harmonics created by the power electronics hardware depend on the converter valve voltage and current values. For determination of the worst case harmonic generation, all relevant operating points have to be considered. The HVDC manufacturer is best able to determine which operating points are most relevant for determining worst-case harmonic generation.

The effect of interlocking (blanking) time and semiconductor voltage drops are discussed below.

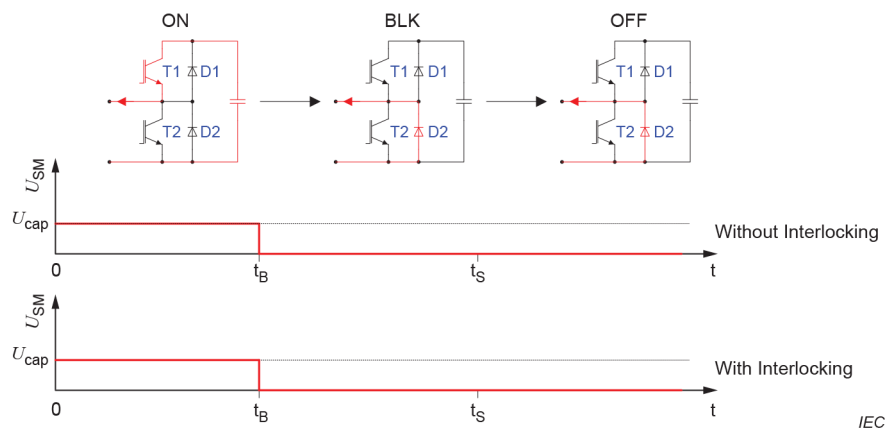
5.2.4.2 Interlocking time

In VSC terminology, "interlocking" describes the time delay (alternatively termed "blanking" time) between the switching events of the individual IGBTs in one half bridge. The interlocking time is required to avoid an unintended short circuit of the capacitor.

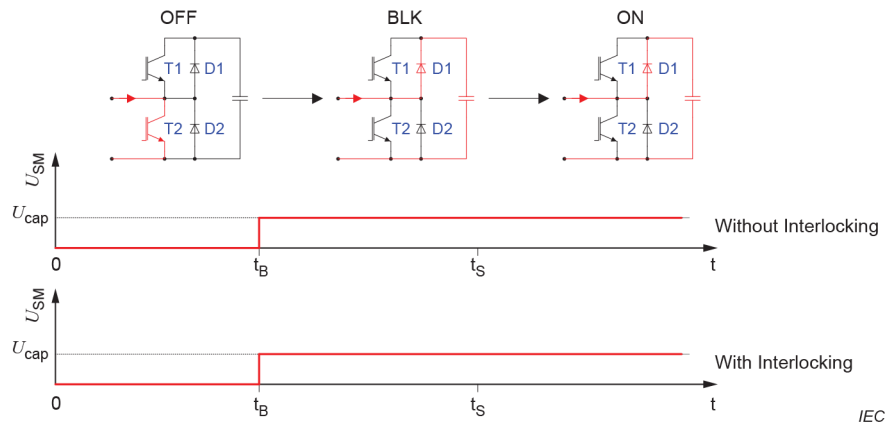
A demonstration of the interlocking time is visualized in Figure 10 (a) to (d). With the current flow through the diode D1, the submodule is considered as turned on, with the capacitor voltage at the submodule terminals. During the diode conduction, the parallel IGBT T1 is in the on-state to allow the current direction change. For turning off the submodule, IGBT T1 is turned off and after a defined blanking time the IGBT T2 is turned on. During the interlocking period, the submodule voltage is applied unintentionally at the submodule terminals.



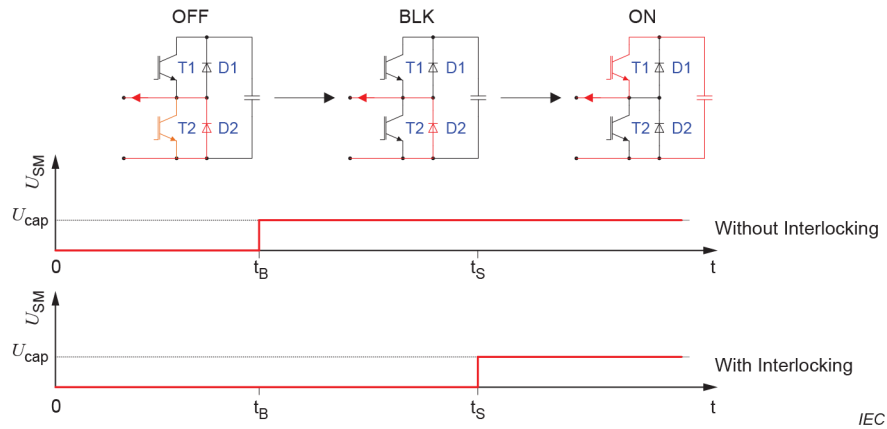
a) Interlocking time during the first part of the transistor switching cycle



b) Interlocking time during the second part of the transistor switching cycle



c) Interlocking time during the third part of the transistor switching cycle



d) Interlocking time during the fourth part of the transistor switching cycle

Figure 10 – Interlocking example

5.2.4.3 Semiconductor voltage drop

Current flow in the module causes a voltage drop at the diode terminals (described as emitter-collector voltage V_{EC}) and a voltage drop at the IGBT terminal (collector-emitter voltage V_{CE}). Although the voltage drop due to these in each individual submodule is very low (0,9 V to 4 V), the summation of the submodule voltages can cause a voltage drop which should be considered in harmonic analysis.

The total voltage drop depends on the number of diodes and IGBTs in the current path and therefore on the current direction and operating point of the converter.

Where I_m is the module current and N_{SM_On} and N_{SM_Off} are the number of the submodules in the ON and OFF states, the total voltage drop of the converter module according to Figure 11 is given by:

$$V_{Drop_pos} = N_{SM_On} \cdot V_{EC} + N_{SM_Off} \cdot V_{CE}$$

$$I_m > 0 \text{ A}$$

$$V_{Drop_neg} = N_{SM_On} \cdot V_{CE} + N_{SM_Off} \cdot V_{EC}$$

$$I_m \leq 0 \text{ A}$$

An overview of the states and the resulting voltage drop is shown in Figure 11.

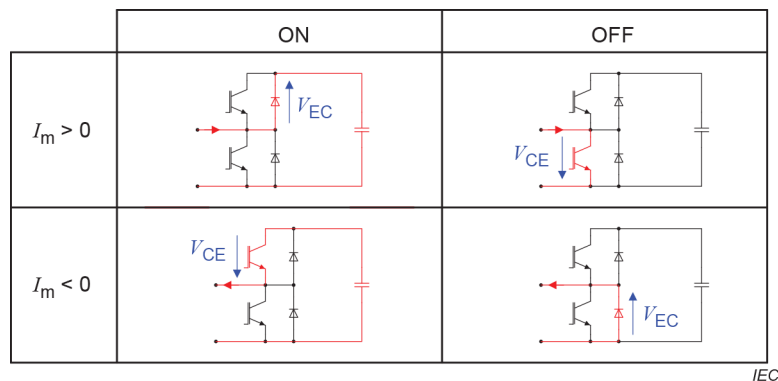


Figure 11 – Semicondutor voltage drop

5.3 Harmonic generation

5.3.1 General

Sample harmonic output profiles for the different types of converters described in 5.2.2 are presented below in 5.3.2 and 5.3.3.

For a better comparison between the different topologies, precise harmonic information might be desirable; however, such information is difficult to provide for VSC technology. The generated harmonics depend mainly on the converter controller which is influenced by many factors. Furthermore, due to the fast development of the VSC technology, any harmonic values provided might be outdated very quickly.

It should be emphasised therefore that these plots should be treated as examples of a wide range of possible harmonic voltage generation, which is dependent on many factors. They should not be seen or quoted as being typical or representative of a certain technology.

All plots show harmonic voltages that are internally generated by the converter valves and are not the harmonic levels expected at the point of common coupling.

In all plots, harmonic voltages are presented in p.u. of direct voltage in order to better visualize the internal harmonic voltage levels generated by the converter valves.

For a better visualization, the plots for two- and three-level converters are shown with a linear scale on the y-axis, and for MMC and CTL converters, the y-axis is shown with a logarithmic scale.

For some plots, the harmonics and interharmonics are indistinguishable. No attempt has been made to make a clearer distinction, as in reality different converters and controllers may create different frequencies from those shown.

5.3.2 Harmonic generation from VSC using switch type valves

5.3.2.1 Two level converter with PWM

A carrier with triangular waves is used. The pulse number is defined as the ratio of the frequency of the carrier and the fundamental frequency. By making the pulse number an odd integer divisible by 3, a symmetry between the three phases is achieved, as well as a symmetry between the positive and negative half period for each phase. This is demonstrated in Figure 12 and Figure 13 which have a pulse number of 9 (such a small number is not typical but is chosen here for a clearer illustration).

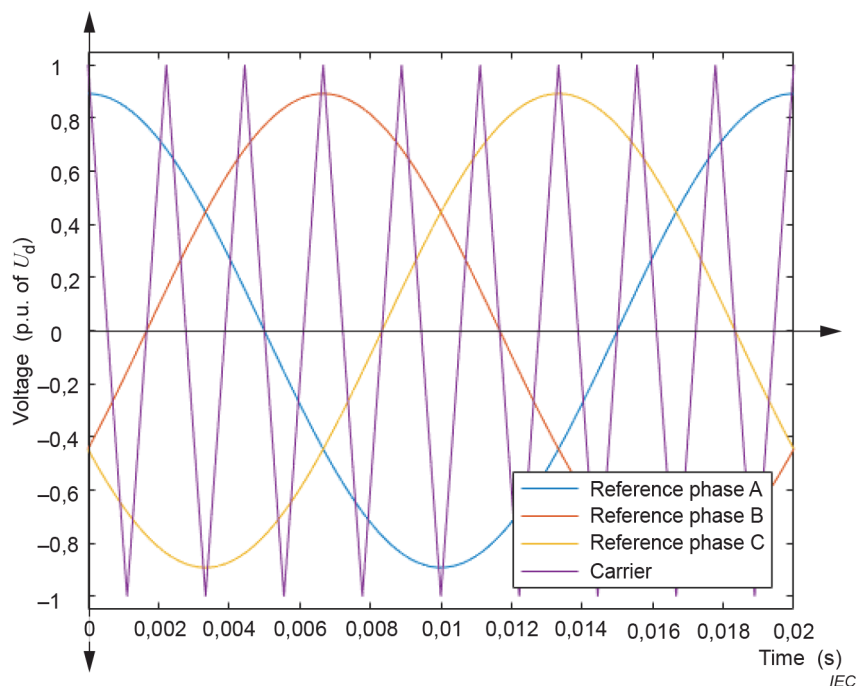


Figure 12 – References and carrier for a two level converter using PWM with pulse number of 9

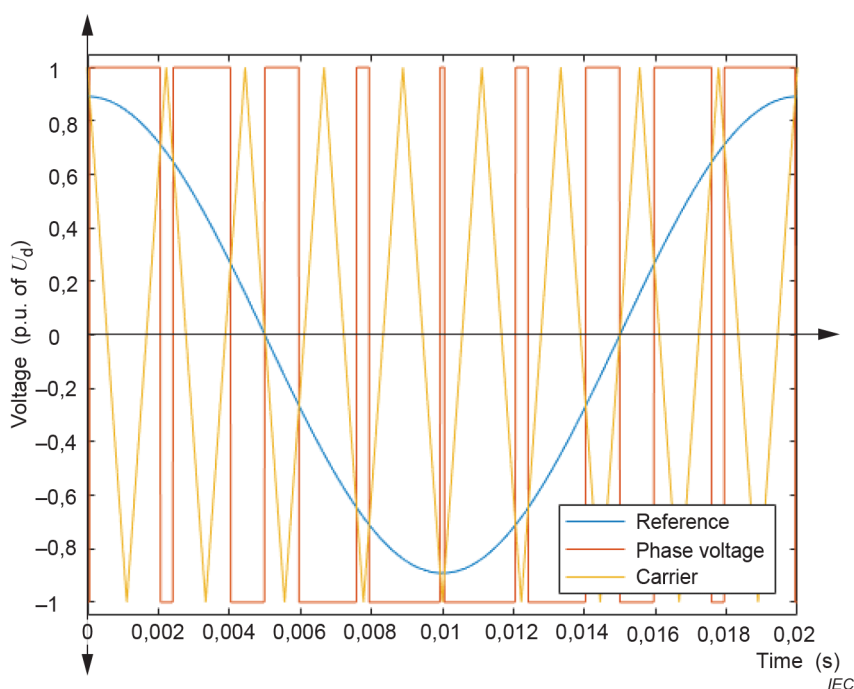


Figure 13 – Reference, carrier and the resulting phase voltage for one phase of a two level converter using PWM with pulse number of 9

The PWM output voltage pattern consists of a fundamental frequency which matches the reference, plus voltage harmonics.

The voltage harmonics when using a pulse number of 39 are illustrated on Figure 14.

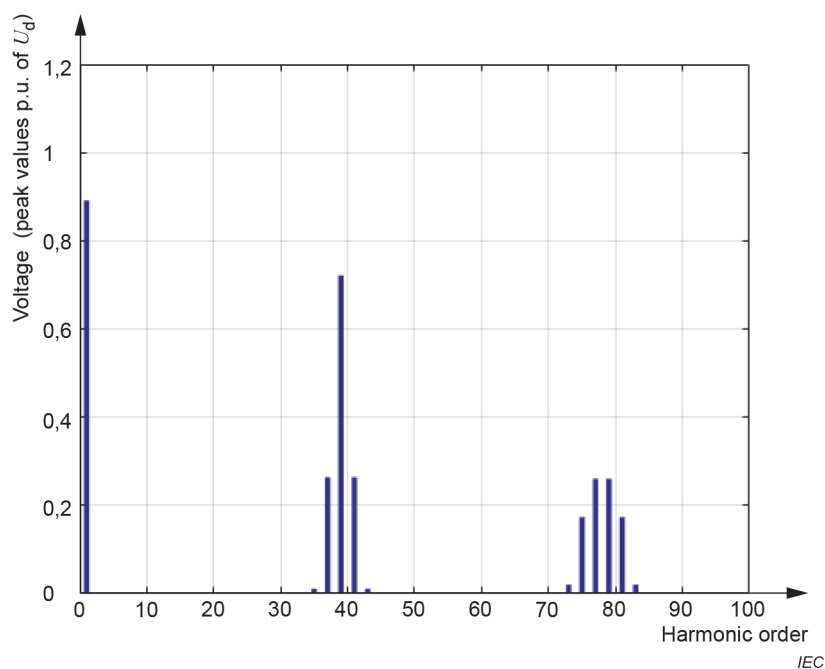


Figure 14 – Harmonic spectrum, phase to ground, of a two level converter using PWM with pulse number of 39

With the given selection of the carrier frequency, symmetry of the three phases is achieved and therefore the generated harmonics divisible by 3 will be of zero sequence.

In Figure 14, it can be noted that the highest peak of the first pulse band after the fundamental is a zero sequence harmonic (39th order). The spectrum of the remaining harmonics without the zero sequence orders is shown in Figure 15.

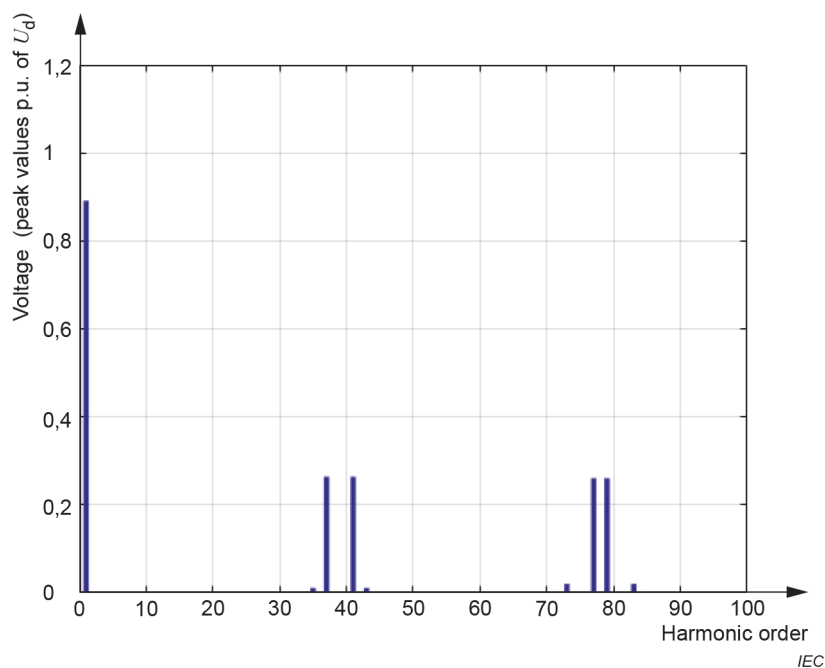
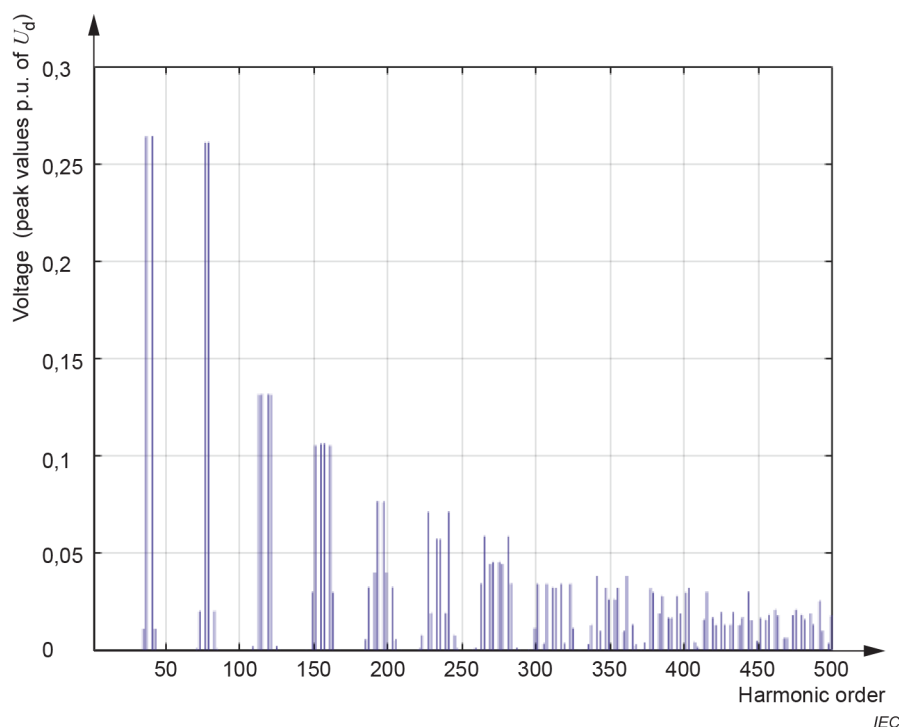


Figure 15 – Harmonic spectrum, phase to ground, of a two level converter using PWM with pulse number 39 after removal of the zero sequence orders

The frequency spectrum continues higher up in the frequency spectrum as illustrated in Figure 16.



NOTE The fundamental is not shown.

Figure 16 – Extended harmonic spectrum of a two level converter using PWM with pulse number 39 after removal of the zero sequence orders

5.3.2.2 Two level converter with optimized PWM (OPWM)

OPWM is a control technique which computes the switching instants so that all unwanted harmonics, up to a specified harmonic order, are eliminated whilst, at the same time, obtaining the correct magnitude for the fundamental voltage. The optimisation lies in using the minimal switching frequency possible to accomplish this; thereby minimising switching losses. The term selective harmonic elimination (SHE) is also used for a similar technique.

With an equivalent pulse number of 23, all positive and negative sequence harmonics up to and including the 31st can be cancelled. The voltages in the time domain and the harmonic spectrum are illustrated in Figure 17 and Figure 18.

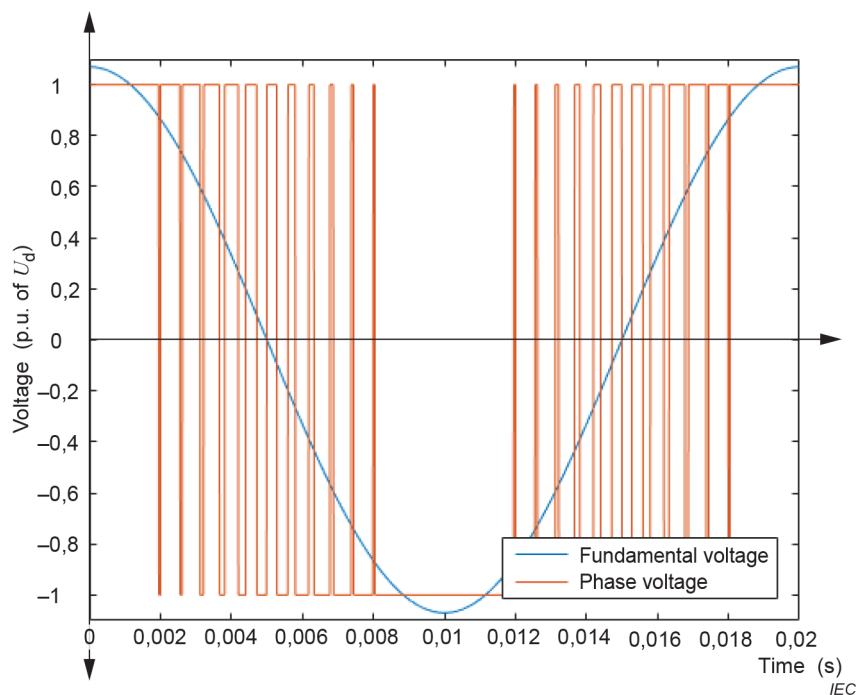


Figure 17 – Fundamental and phase voltage for one phase of a two-level converter using OPWM

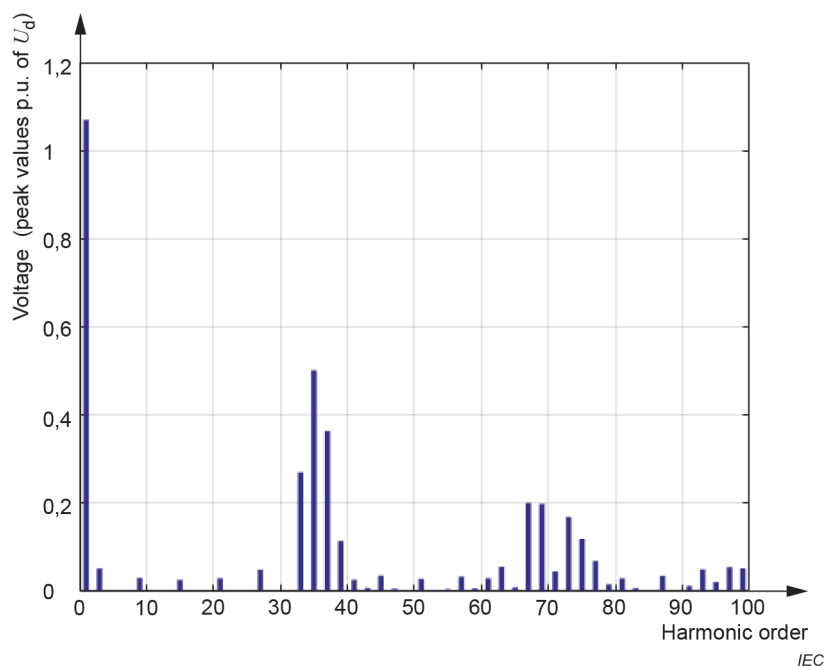


Figure 18 – Harmonic spectrum, phase to ground, of a two-level converter using OPWM

The voltage harmonics below the 35th order, in Figure 18, are of zero sequence. Figure 19 displays the spectrum with the zero sequence removed.

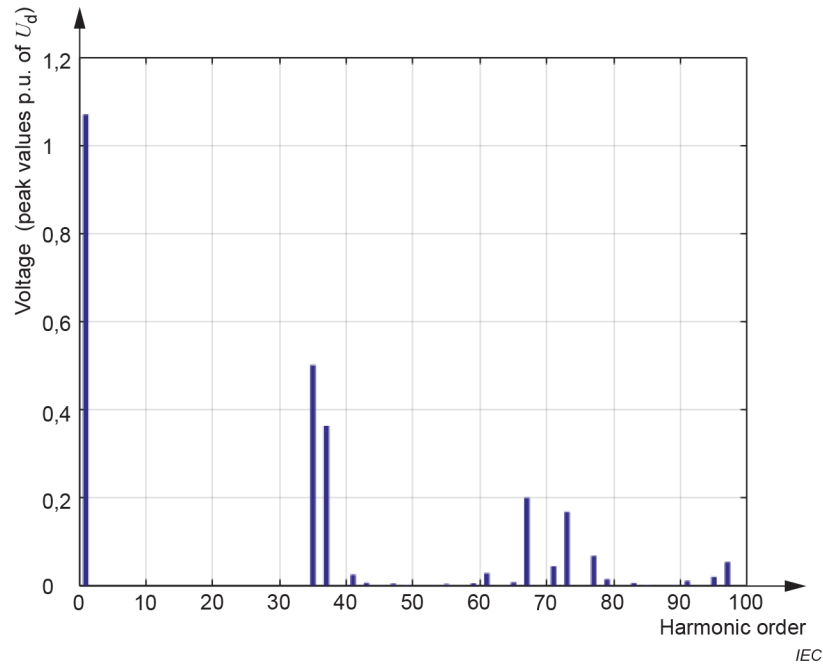
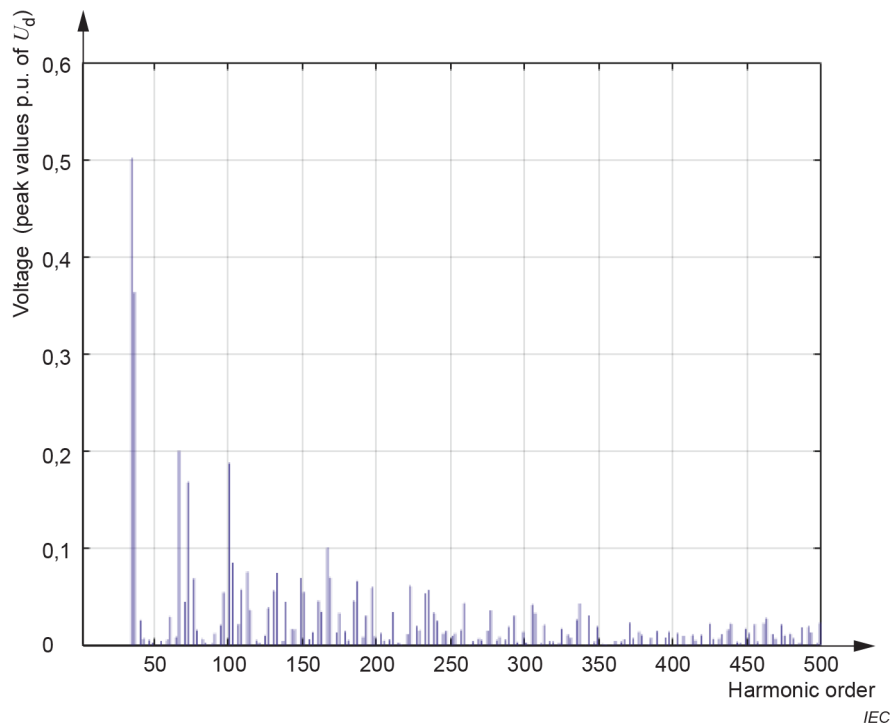


Figure 19 – Harmonic spectrum, phase to ground, of a two level converter using OPWM after removal of the zero sequence

The harmonic spectrum up to order 500 is displayed in Figure 20.



NOTE The fundamental is not shown.

Figure 20 – Extended harmonic spectrum, phase to ground, of a two-level converter using OPWM after removal of the zero sequence

5.3.2.3 Three-level converter

The topology difference from a two-level converter is that each phase can be connected to the positive pole, the midpoint or the negative pole, so at any time there are 3 different voltage levels that each phase can attain.

A separate carrier for the upper part and the lower part is used. The phase voltages are switched between U_d and 0 during half of the fundamental period and between $-U_d$ and 0 during the other half.

A third harmonic signal is typically also added to the reference voltage in order to increase the amplitude of the fundamental voltage in relation to the direct voltage. The resulting third harmonic voltage generated is of zero sequence and therefore does not penetrate to the AC system.

The principle is illustrated in Figure 21 for pulse number 9.

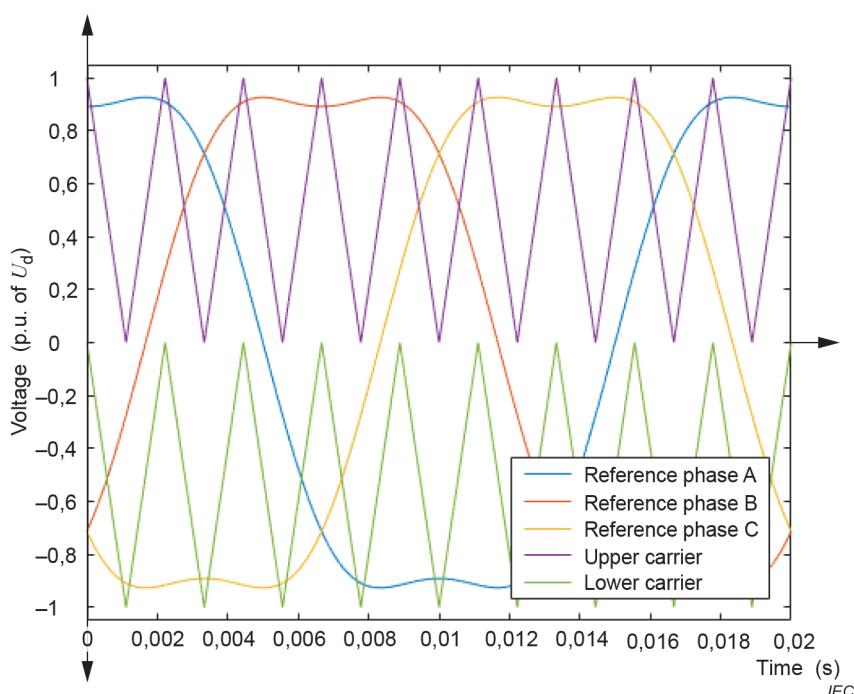


Figure 21 – References and carriers for a three level converter with pulse number of 9

As seen in Figure 21, the three-level converter has the same symmetries, between the phases and the upper and lower half waves as a two-level converter. Therefore, only natural harmonics, i.e. the 5th, 11th, 17th,... negative sequence harmonic and the 7th, 13th, 19th,... positive sequence harmonic will be generated on the AC side. Harmonic orders that are divisible by 3 are of zero sequence and will be blocked by the transformer. Figure 22 shows the resulting voltage for one phase.

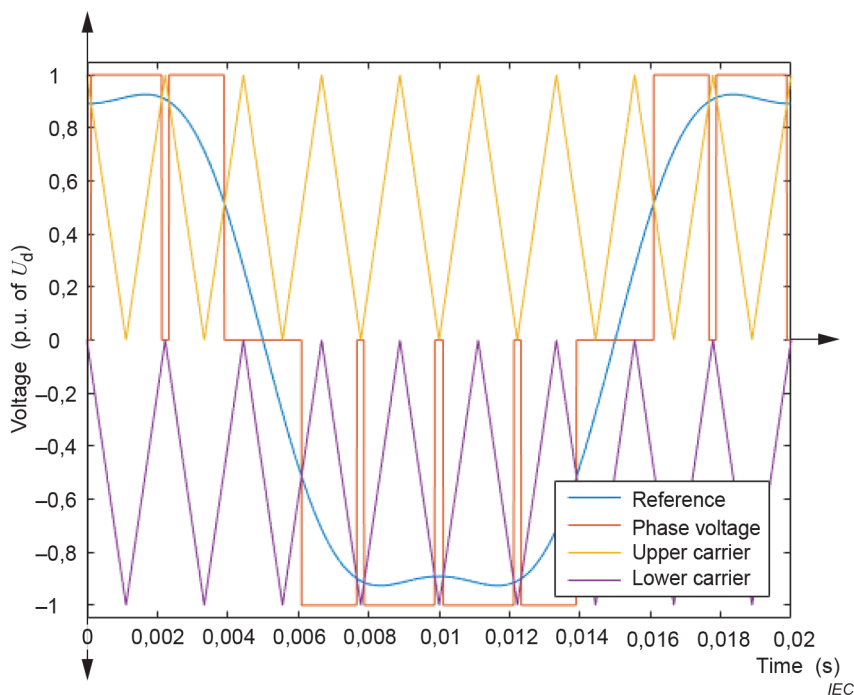


Figure 22 – Reference, carriers and the resulting phase voltage for one phase of a three level converter with pulse number of 9

For the same pulse number as for the two level converter with PWM in 5.3.2.1, i.e. 39 (Figure 14), the voltage spectrum is shown in Figure 23.

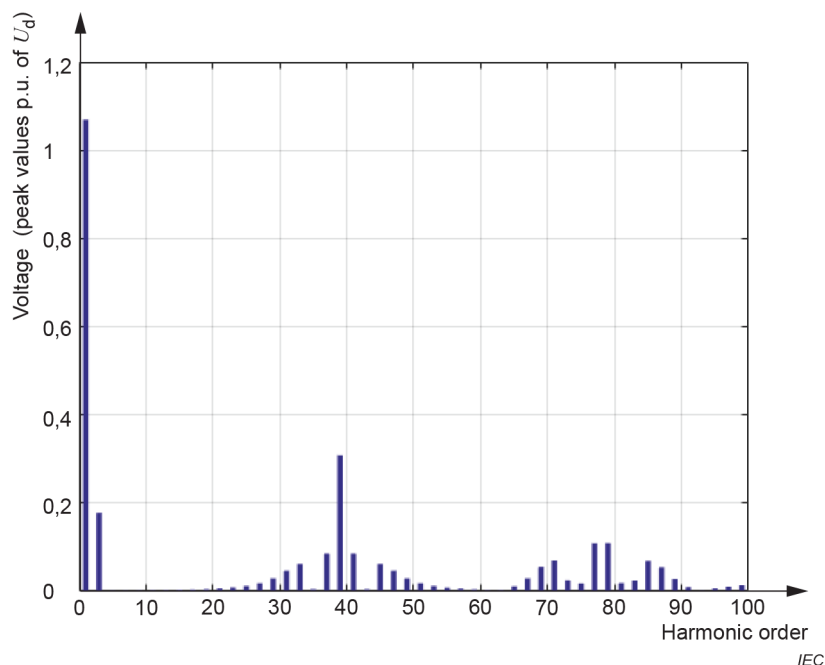


Figure 23 – Harmonic spectrum, phase-ground, of a three level converter, pulse number of 39

The highest peaks are again zero sequence. Figure 24 shows the spectrum after removing the zero sequence.

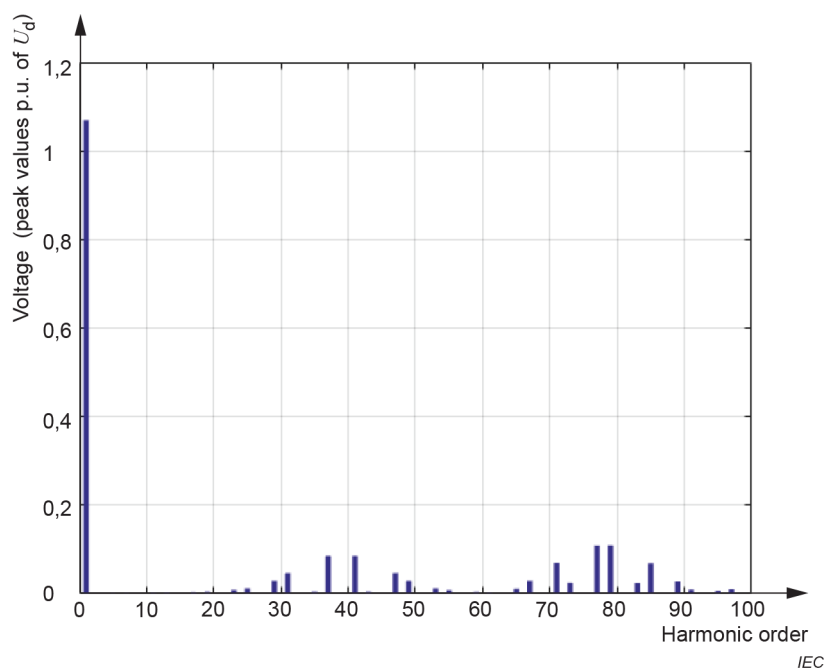


Figure 24 – Harmonic spectrum, phase to ground, of a three level converter with pulse number of 39 after removal of the zero sequence

The broader frequency range is illustrated in Figure 25.

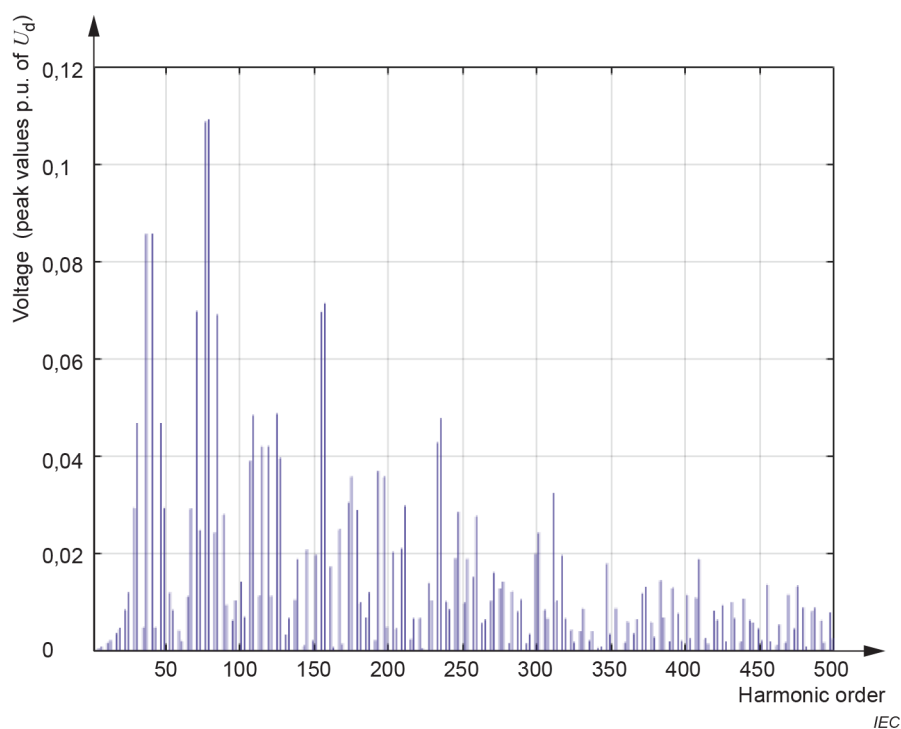


Figure 25 – Extended harmonic spectrum, phase to ground, of a three level converter with pulse number of 39 after removal of the zero sequence

5.3.3 Harmonic generation from VSC using controllable voltage source type valves

5.3.3.1 General

Due to the distributed converter energy, a VSC of the controllable voltage source type can be represented by six independent voltage sources as shown in Figure 26. Additionally to the main purpose of establishing AC and DC voltages for the purpose of active and reactive power flow, the voltage source control can be used for other objectives such as AC harmonic damping or converter energy balancing.

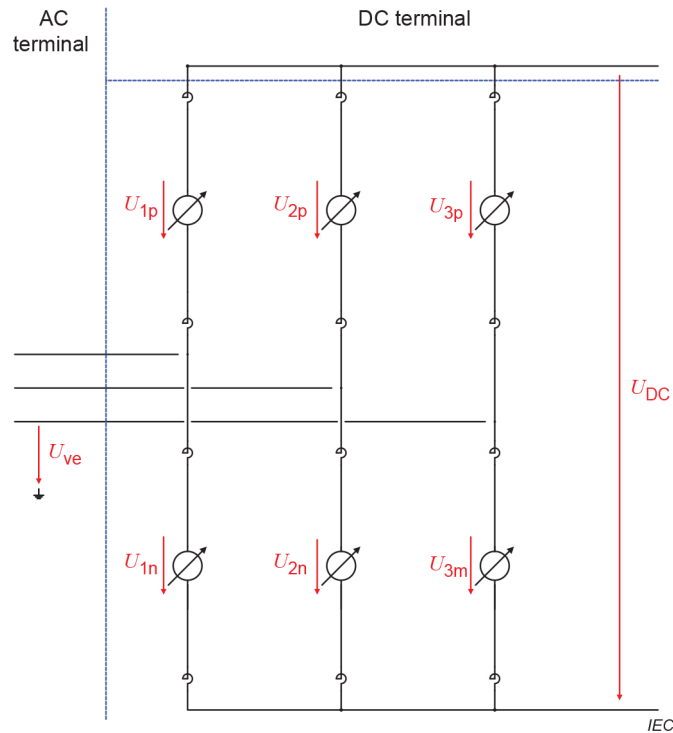


Figure 26 – Voltage source representation of the MMC

The required voltage level for every individual voltage source is created by the converter control (term as defined in IEC 62747 [16]) and sent to the valve control unit.

5.3.3.2 Derivation of harmonics at the converter terminals

For harmonic analysis, every converter valve has to be considered as an independent harmonic voltage source. For the harmonic determination at the converter AC and DC terminals, the voltage sources can be transferred using a transfer matrix, $T_{B6-Terminal}$, as seen below:

$$\begin{pmatrix} U_{ve_1} \\ U_{ve_2} \\ U_{ve_3} \\ U_{DC_1} \\ U_{DC_2} \\ U_{DC_3} \end{pmatrix} = [T_{B6-Terminal}] \cdot \begin{pmatrix} U_{1p} \\ U_{2p} \\ U_{3p} \\ U_{1n} \\ U_{2n} \\ U_{3n} \end{pmatrix}$$

5.3.3.3 Modular multi-level converter (MMC)

Every voltage source has its own valve control unit which can work completely independently from other control units. The main purpose of the valve control unit is to set up the required voltage level by switching of the submodules. The decision to switch is based on the implemented pattern algorithm. The switching signals are then send to the valve base electronics which switches the individual semiconductor.

The converter control can influence the harmonic generation of the MMC converter. Usually, converter control is used to improve the harmonic performance by cancelling out specific harmonics at the AC terminal of the converter. Due to the limited operating speed of the converter and valve unit control, the maximum order of harmonics which can be influenced by converter control is limited. This limitation is a function of the control hardware and therefore has to be defined by the converter supplier.

A common switching pattern technique used for converter control of MMC converters is nearest level control (NLC). The NLC technique can evaluate complex criteria for submodule switching, which allows the improvement of the converter behaviour in terms of, for example, losses or harmonics.

To describe the MMC performance with NLC, the NLC algorithm and the following parameters are required for the harmonics generation evaluation:

- time step of the converter control operation Δt_{CC} ;
- time step of the valve control operation Δt_{VC} ;
- submodule voltage during switching actions V_{SM} .

The results of the voltage generation by MMC converter is demonstrated in Figure 27. The ideal voltage reference signal (red line) is approximated by the converter control reference signal (blue line) depending of the sampling rate used in the control hardware. The module voltage itself (green line) is created with switching of the submodules by valve control.

In Figure 27, it can be seen that the converter control and valve control operate at different time steps. The maximum number of switching events during one converter control operation time step depends on the converter and valve control hardware.

Depending on the submodule state and current direction, the submodules can be either charged or discharged. Therefore, the module voltage does not stay constant between the switching operations, but changes depending on the number of submodules being turned on and the module current.