

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)**

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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.

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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.

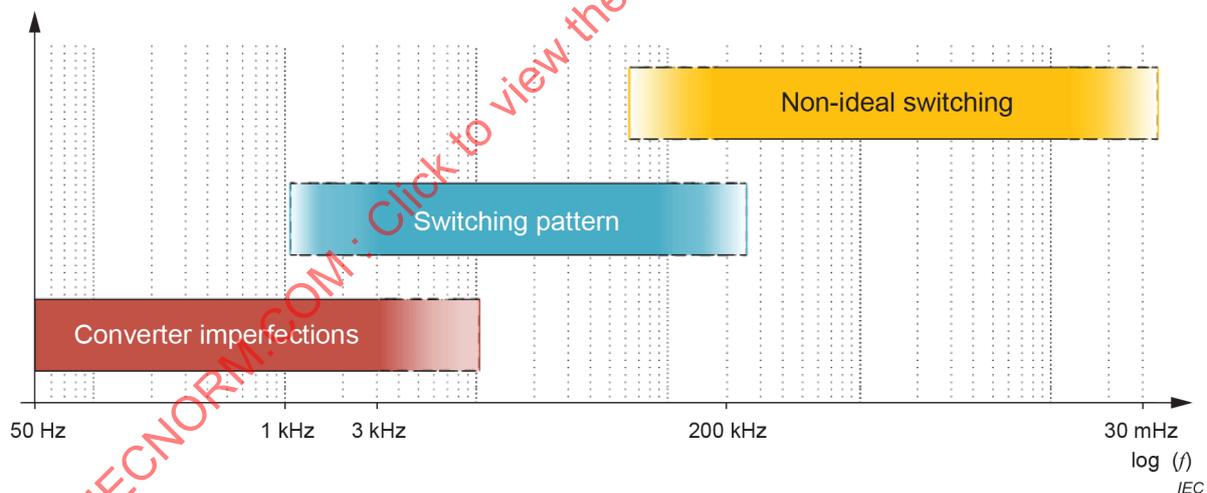


Figure 1 – Frequency range of VSC waveform

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.

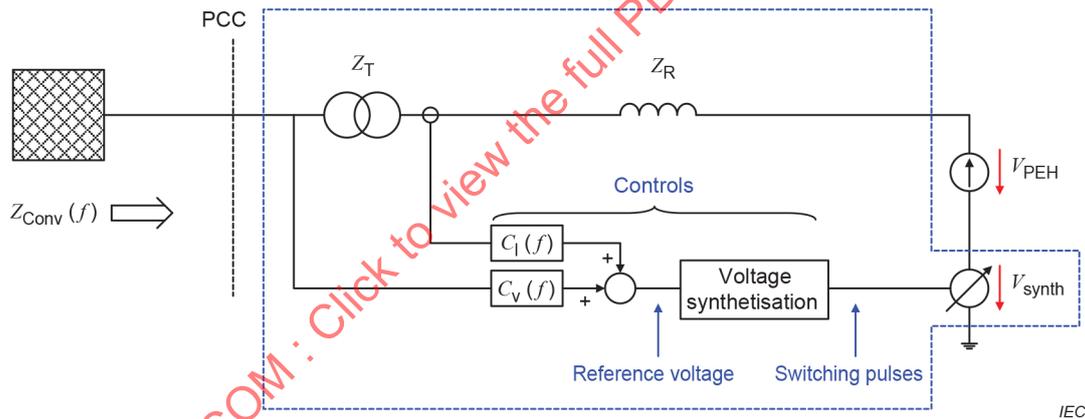
The main focus of this document is the frequency range up to 50th harmonic order covered by the standards listed above in 4.4, because most issues in regard to harmonics (e.g. power quality issues or control interactions) have their origin in this frequency range.

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.

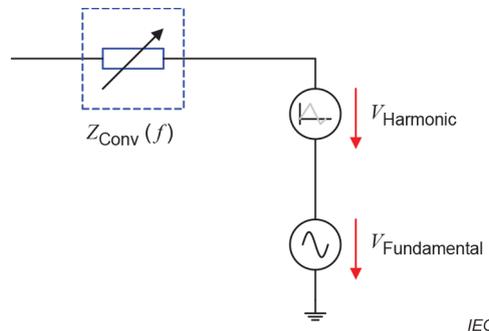
It should be considered that modelling of the connected AC system becomes more uncertain with higher frequencies, as secondary effects (such as stray capacitance, skin effect and eddy-current losses) become influential and so the analysis of the system to be investigated becomes progressively more complex.

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.



a) Converter representation for harmonic analysis



b) Equivalent circuit of the converter for harmonic analysis

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.

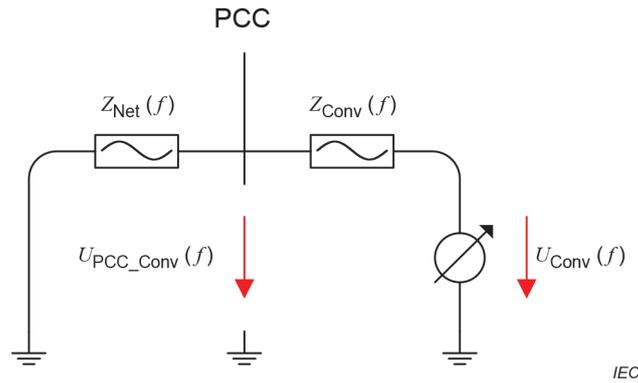


Figure 3 – Harmonic contribution by the converter

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:

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

or, expressed in terms of admittance, as

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

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.

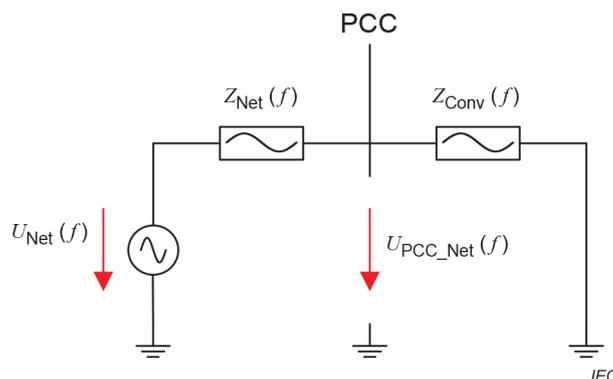


Figure 4 – Amplification of the background harmonics

$Z_{\text{Conv}}(f)$ 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.

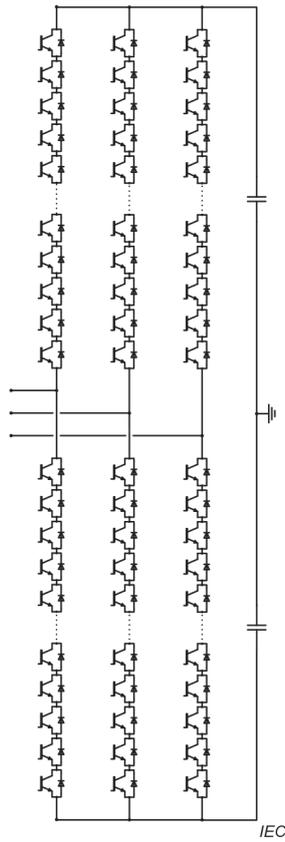


Figure 5 – Two-level converter

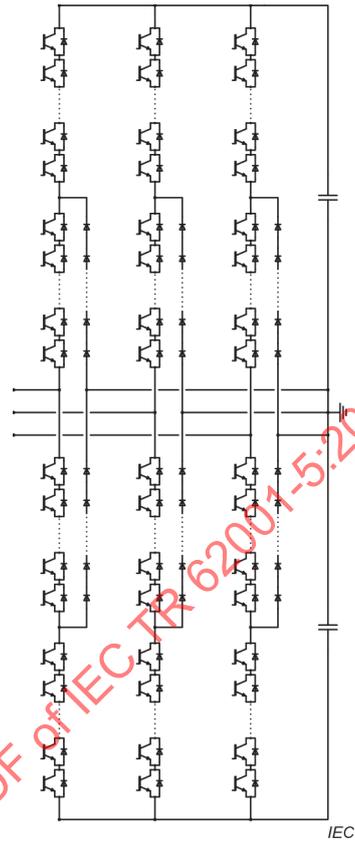


Figure 6 – Three-level converter

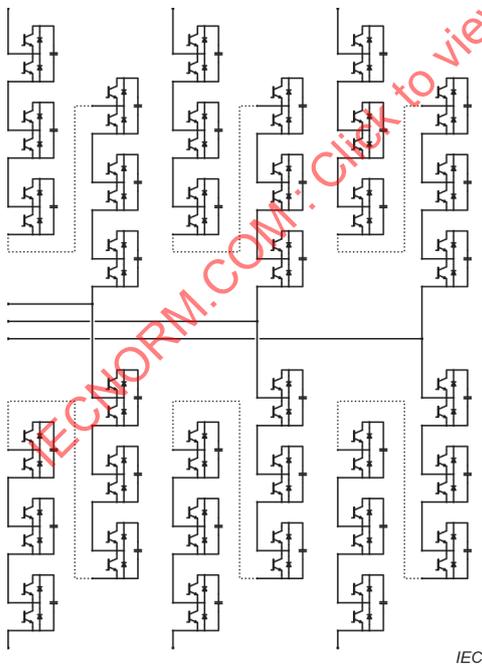


Figure 7 – Modular multi-level converter (MMC)

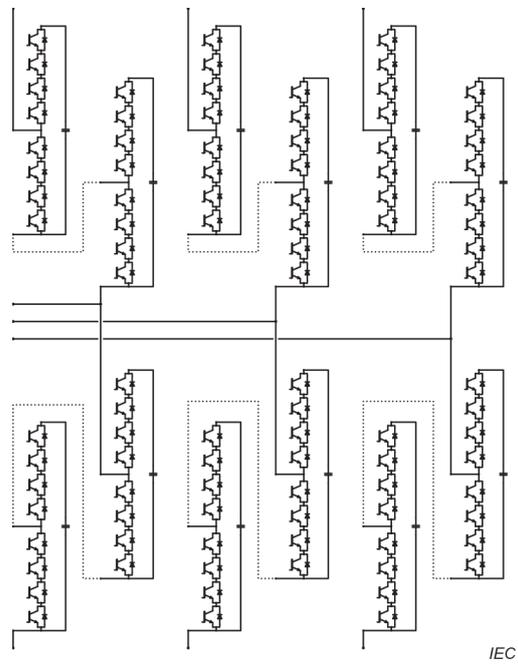


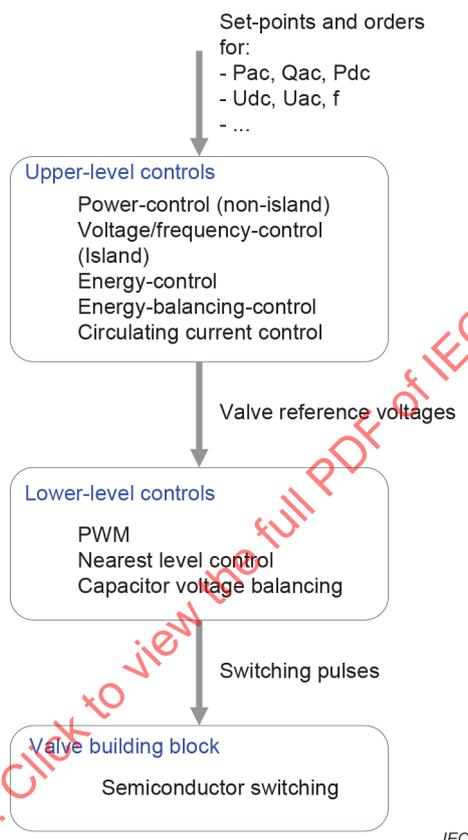
Figure 8 – Cascaded two-level converter (CTL)

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

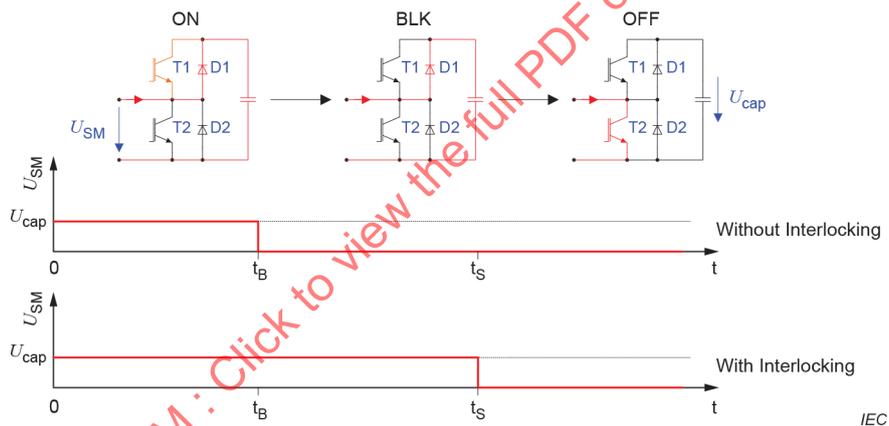
Harmonics created by the power electronics hardware depend on the converter valve voltage and current values. For determination of the worst case harmonic generation, all relevant operating points have to be considered. The HVDC manufacturer is best able to determine which operating points are most relevant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

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

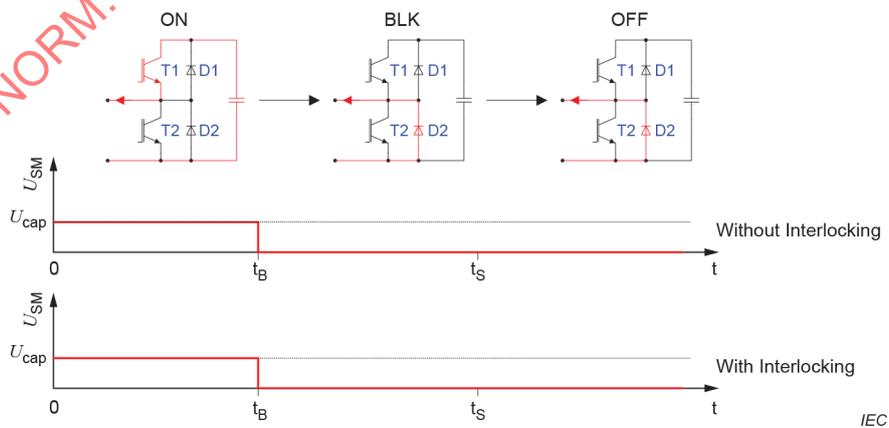
5.2.4.2 Interlocking time

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.

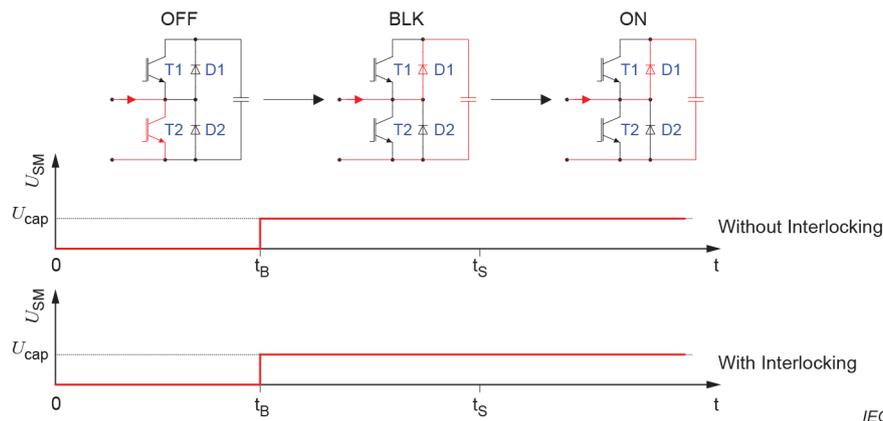
A demonstration of the interlocking time is visualized in Figure 10 (a) to (d). With the current flow through the diode D1, the submodule is considered as turned on, with the capacitor voltage at the submodule terminals. During the diode conduction, the parallel IGBT T1 is in the on-state to allow the 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.



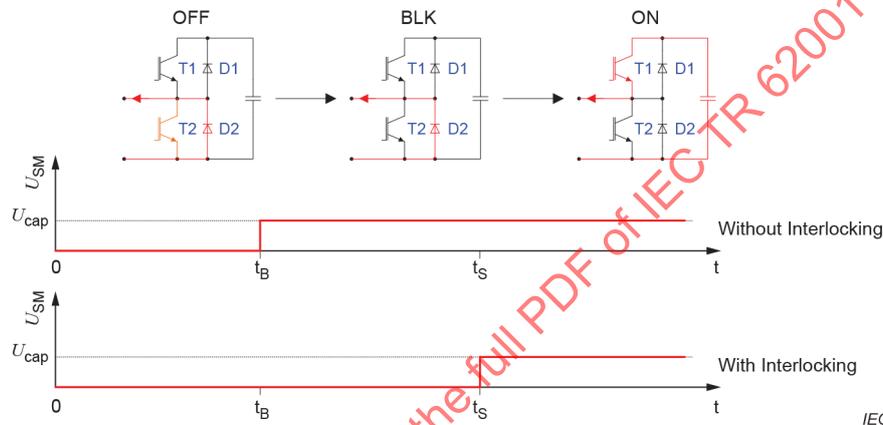
a) Interlocking time during the first part of the transistor switching cycle



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:

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

$$I_m > 0 A$$

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

$$I_m \leq 0 A$$

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

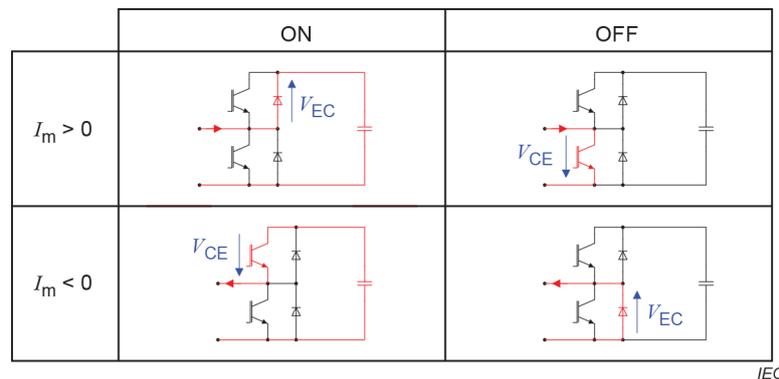


Figure 11 – Semiconductor voltage drop

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).

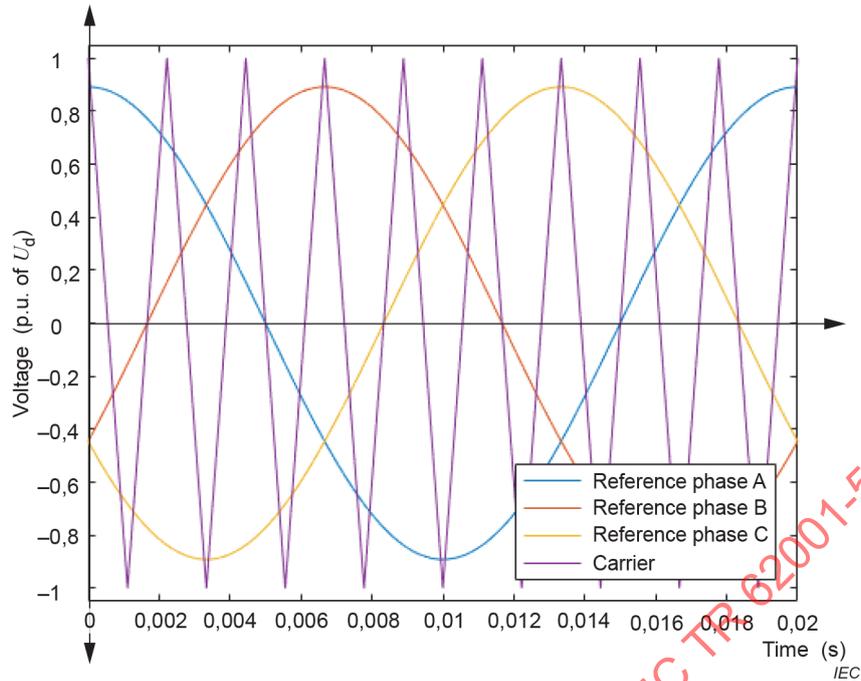


Figure 12 – References and carrier for a two level converter using PWM with pulse number of 9

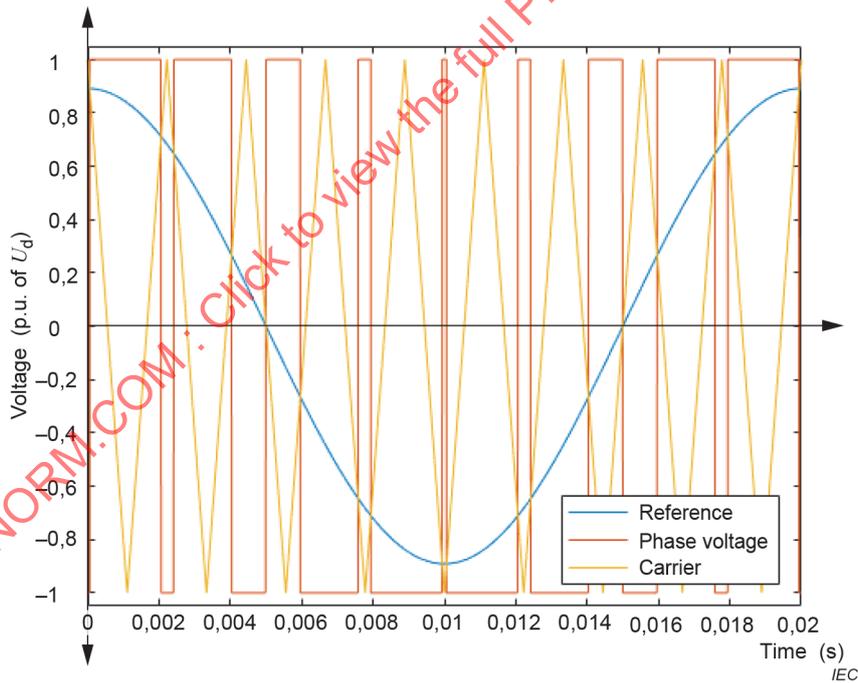


Figure 13 – Reference, carrier and the resulting phase voltage for one phase of a two level converter using PWM with pulse number of 9

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.

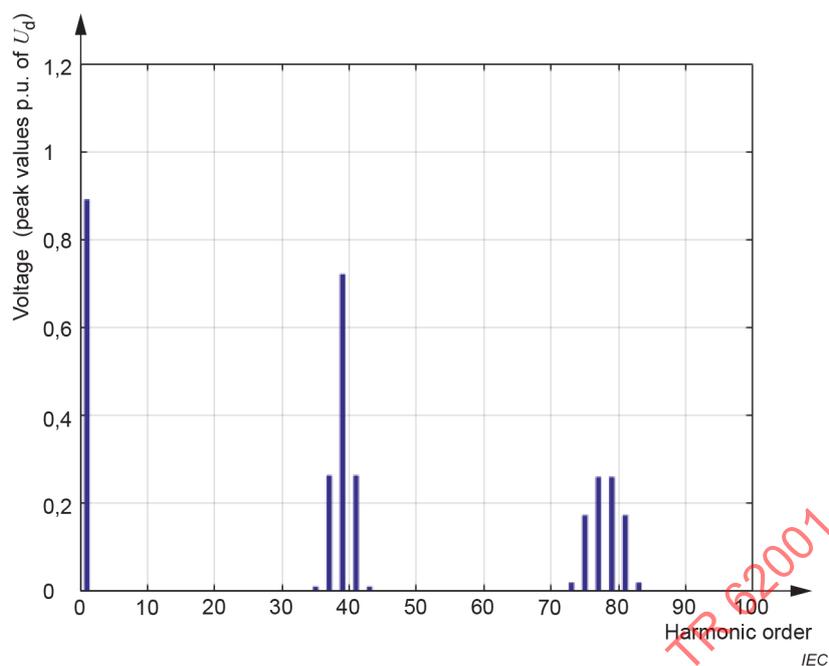


Figure 14 – Harmonic spectrum, phase to ground, of a two level converter using PWM with pulse number of 39

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.

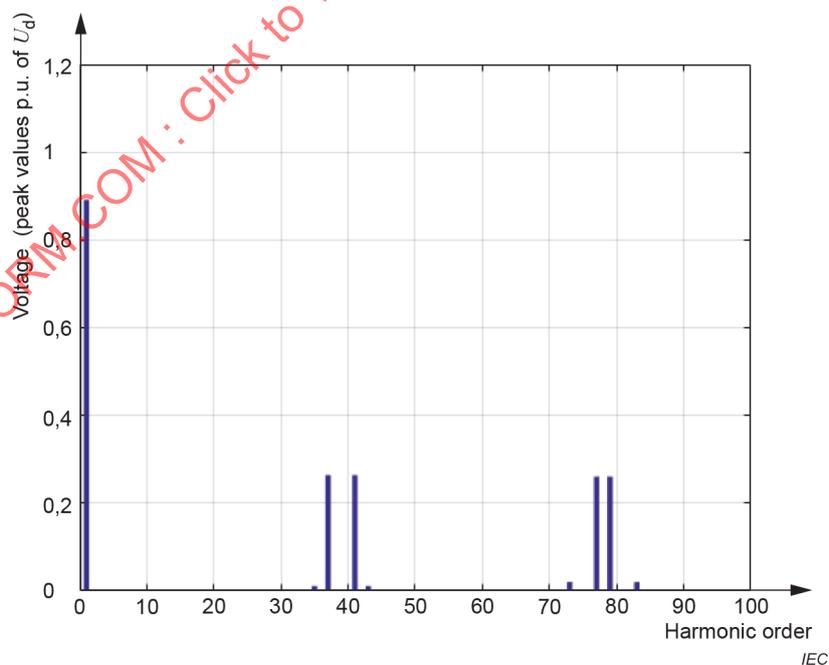
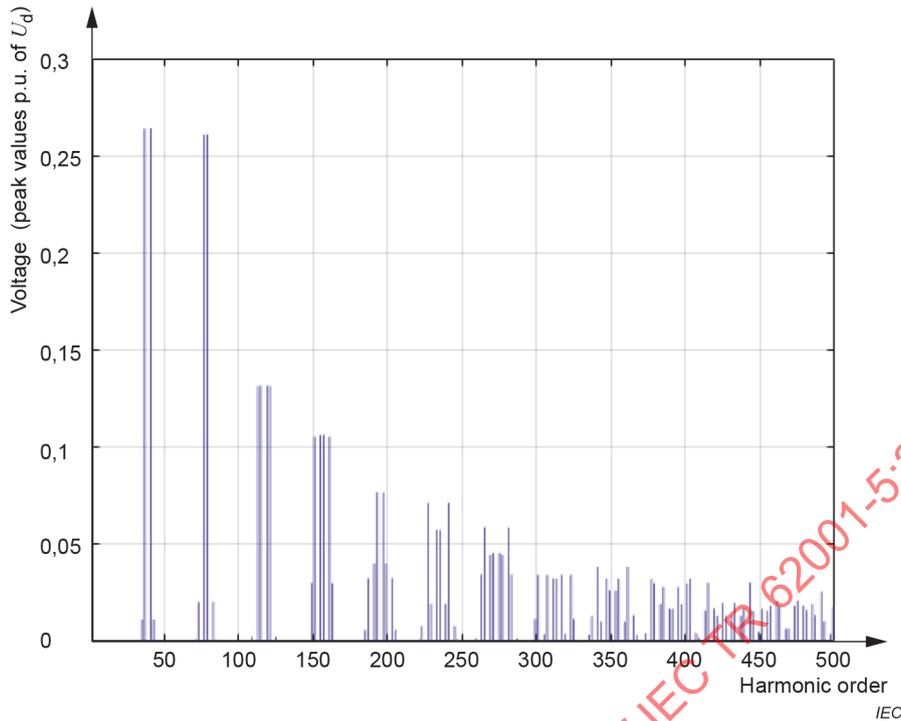


Figure 15 – Harmonic spectrum, phase to ground, of a two level converter using PWM with pulse number 39 after removal of the zero sequence orders

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.

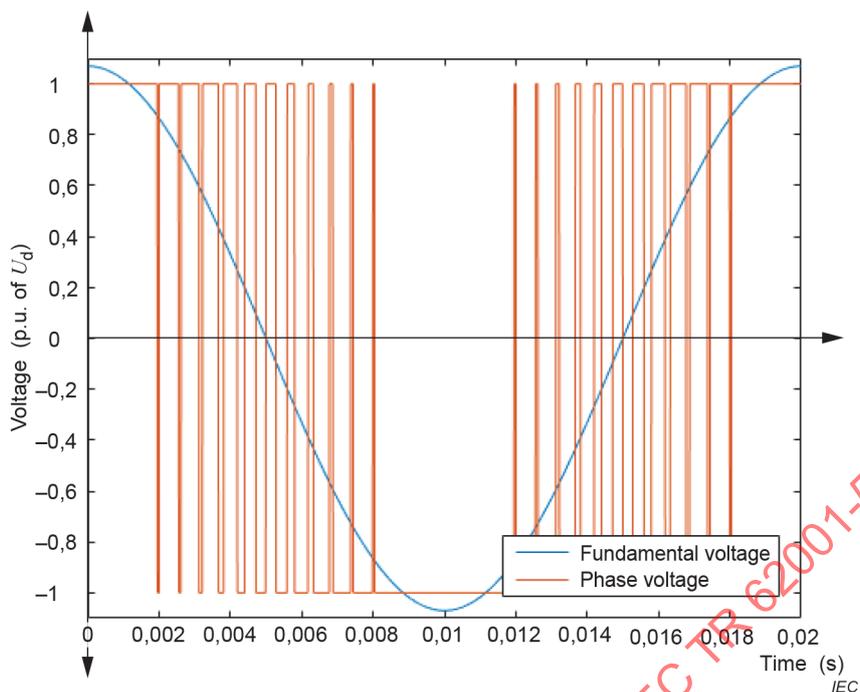


Figure 17 – Fundamental and phase voltage for one phase of a two-level converter using OPWM

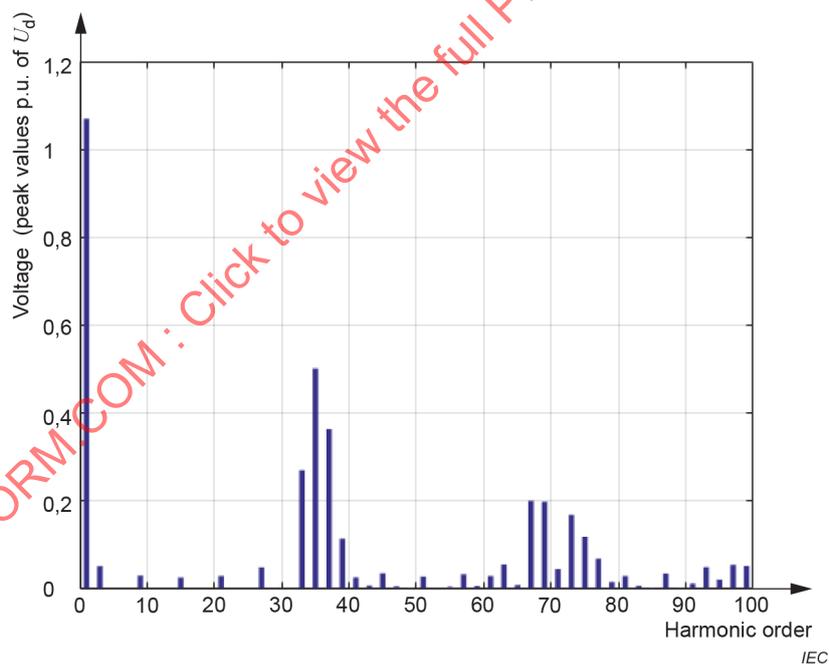


Figure 18 – Harmonic spectrum, phase to ground, of a two-level converter using OPWM

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

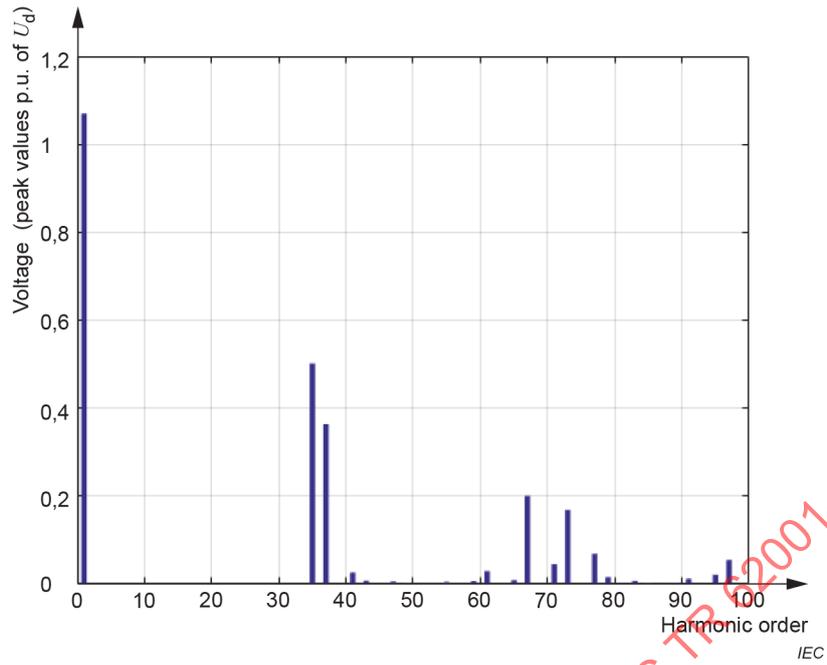
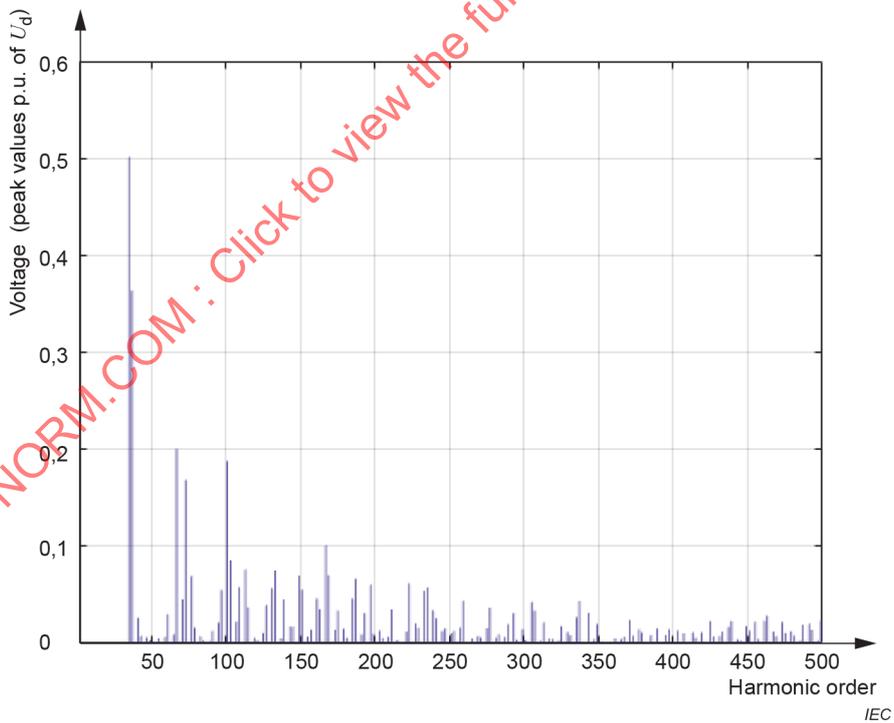


Figure 19 – Harmonic spectrum, phase to ground, of a two level converter using OPWM after removal of the zero sequence

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.

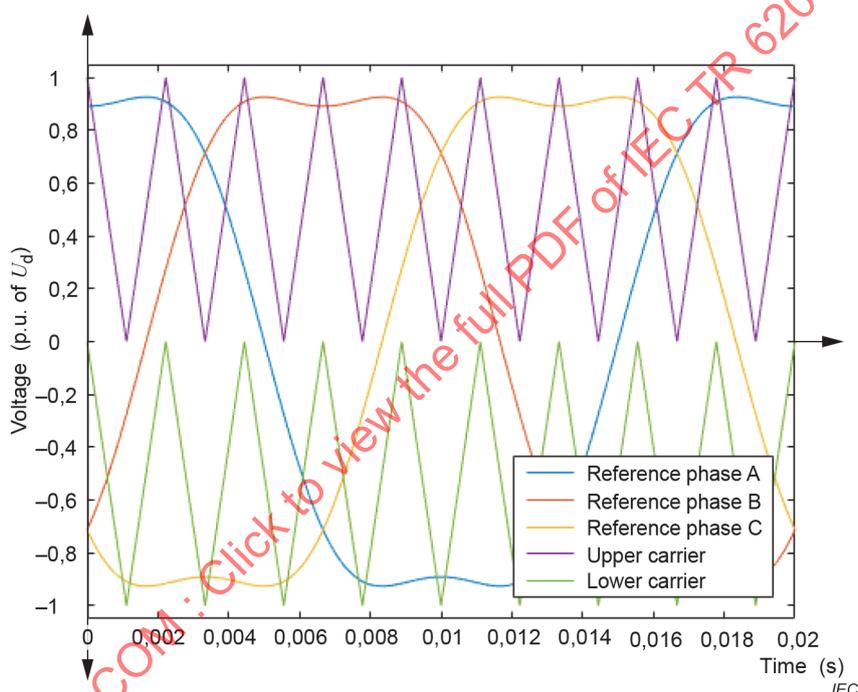


Figure 21 – References and carriers for a three level converter with pulse number of 9

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.

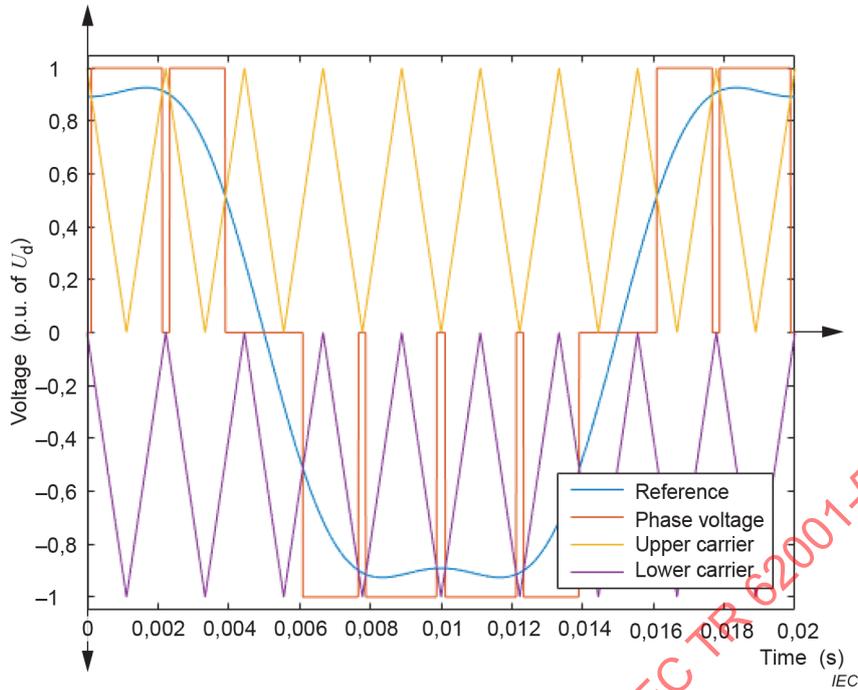


Figure 22 – Reference, carriers and the resulting phase voltage for one phase of a three level converter with pulse number of 9

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.

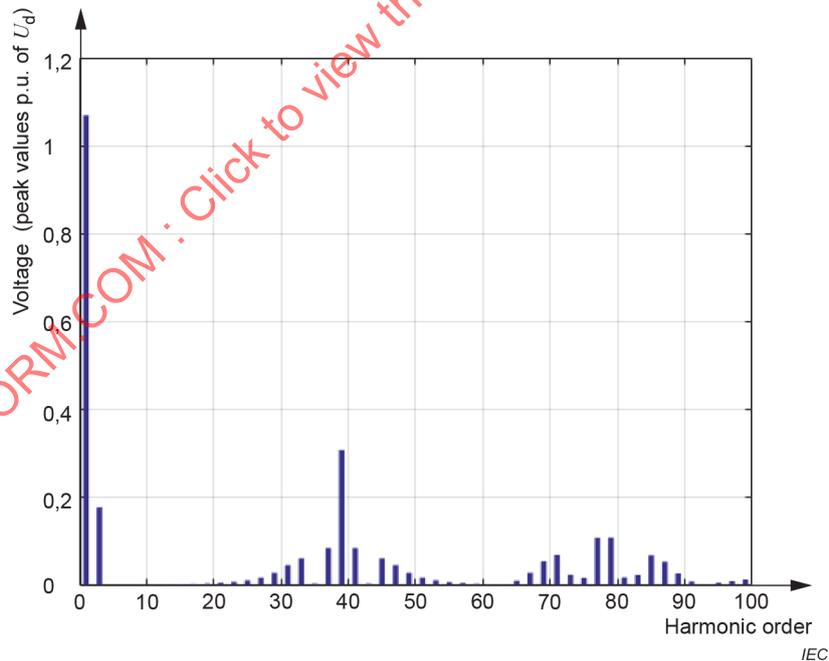


Figure 23 – Harmonic spectrum, phase-ground, of a three level converter, pulse number of 39

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

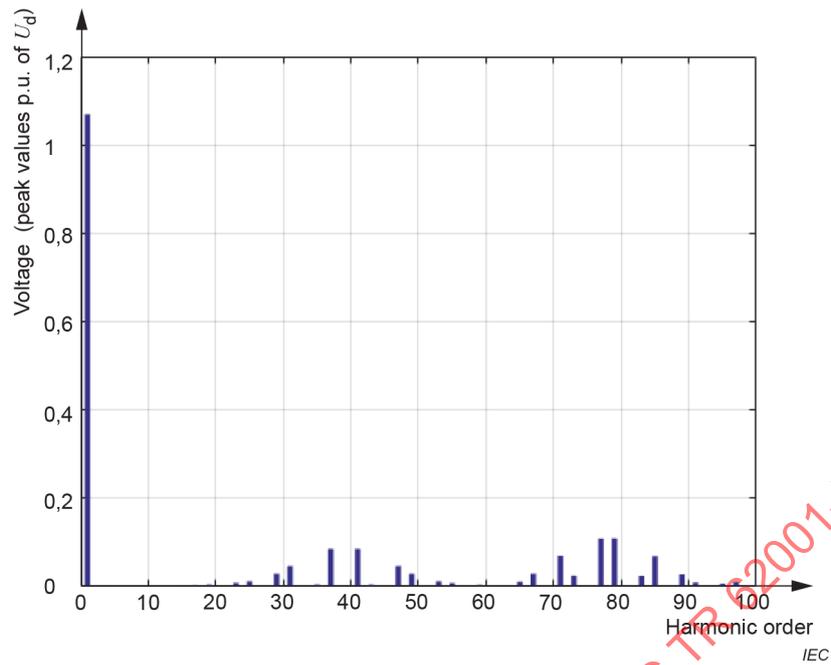


Figure 24 – Harmonic spectrum, phase to ground, of a three level converter with pulse number of 39 after removal of the zero sequence

The broader frequency range is illustrated in Figure 25.

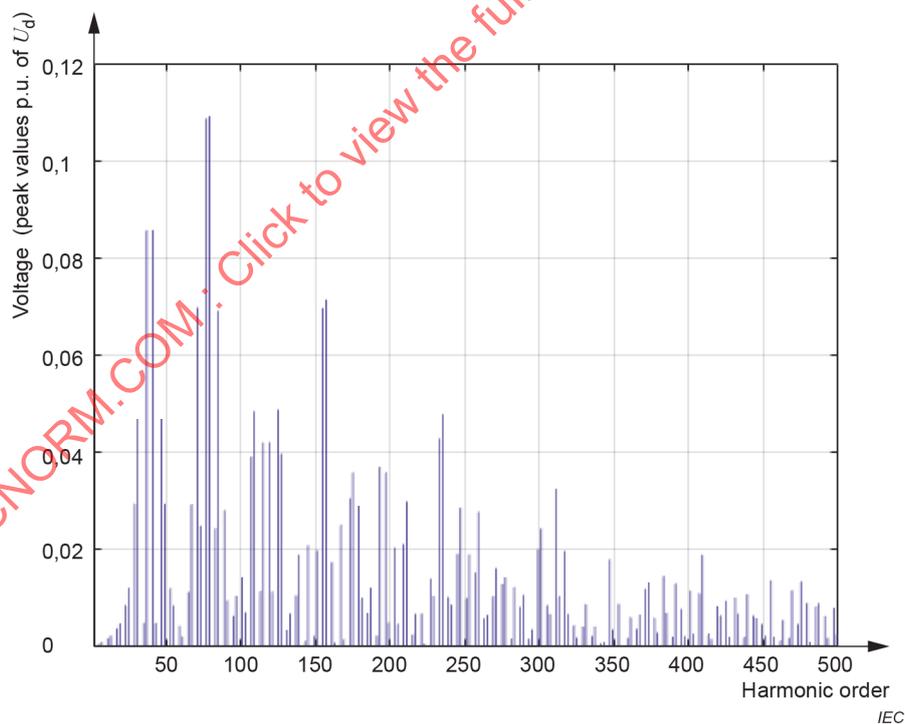


Figure 25 – Extended harmonic spectrum, phase to ground, of a three level converter with pulse number of 39 after removal of the zero sequence

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.

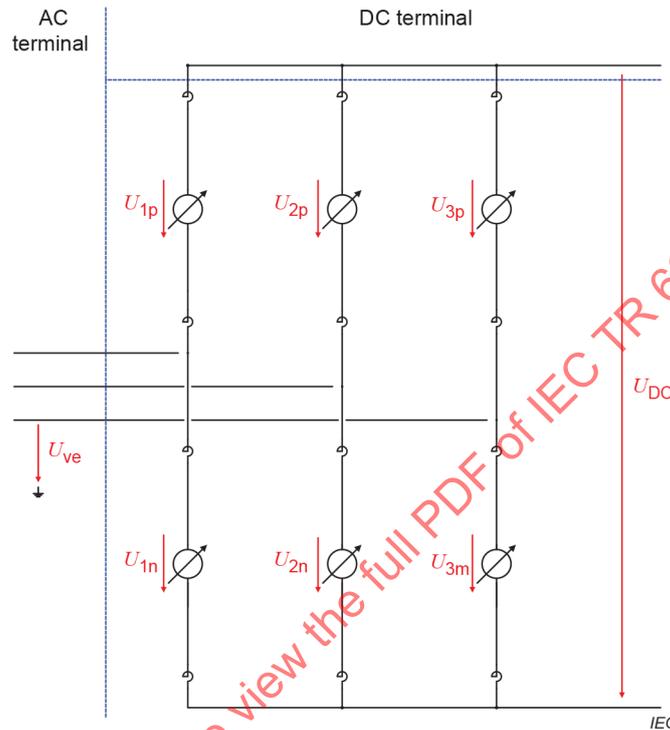


Figure 26 – Voltage source representation of the MMC

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 sent 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.

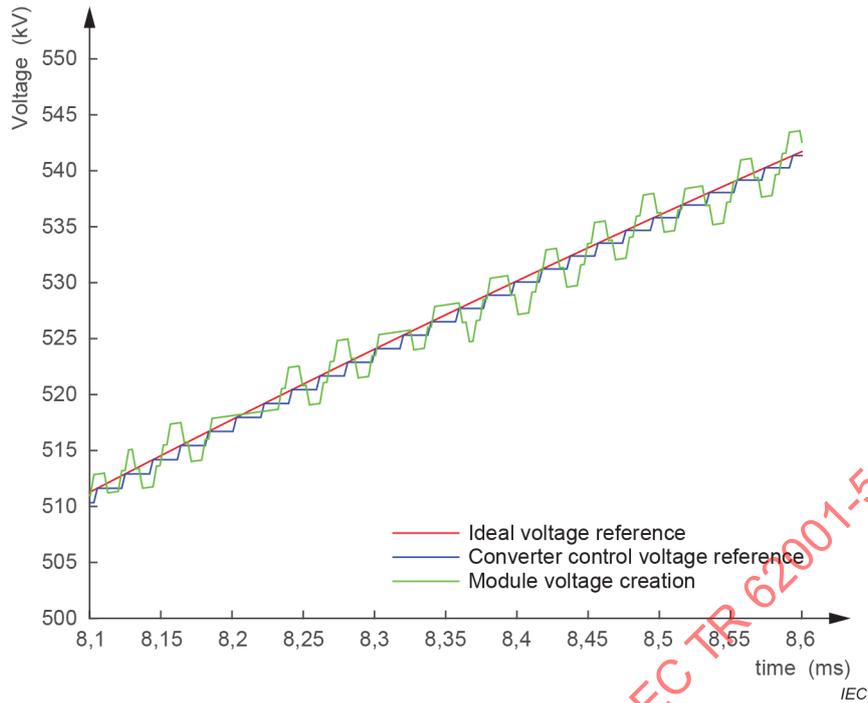


Figure 27 – Valve voltage generation

For the demonstration of the module voltage generation, a very simple NLC method is used. The submodules are switched whenever the absolute difference between the reference voltage and converter valve voltage is reduced. The resulting harmonic spectrum of the converter module voltage (U_{1p} according to Figure 26) is shown in Figure 28 and for a higher frequency range in Figure 29. The increased peaks for the harmonic order > 500 are the characteristics of the particular MMC converter and depend on the valve control.

The presented harmonic values show only the harmonic created by the converter model with the simplified control and neglecting all damping elements in the circuit.

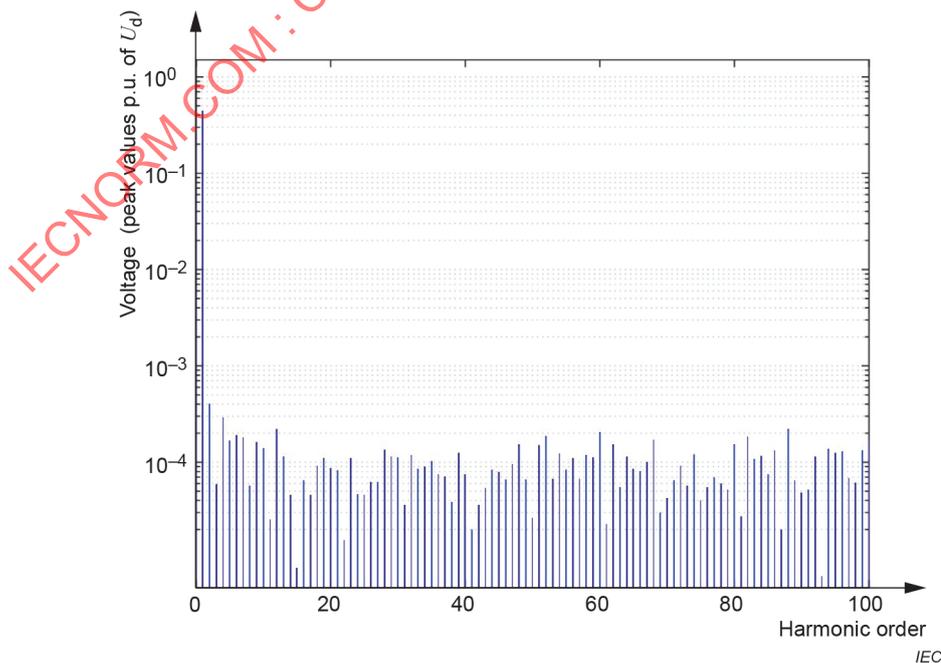


Figure 28 – Harmonic spectrum for one arm of the MMC converter

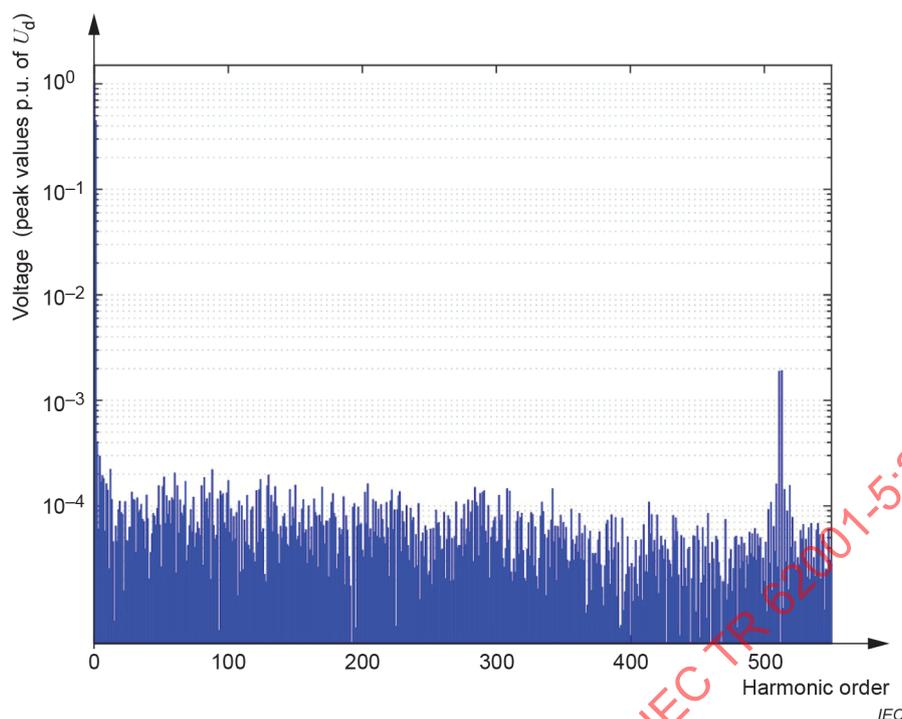


Figure 29 – Harmonic spectrum for one arm of the MMC converter (extended frequency range)

5.3.3.4 Cascaded two-level converter (CTL)

5.3.3.4.1 General

Below is a simplified description of a multilevel converter with N cells which is switched according to a carrier based PWM, where the phases of the carriers for the cells in each arm are phase shifted in respect to each other. This description is for a symmetric monopole, but the principle is the same for asymmetric monopole and for a bipole, where two asymmetric monopoles are combined. The text describes a converter built up with half-bridge cells.

5.3.3.4.2 Basic topology

This description assumes a symmetric monopole setting, where the positive DC terminal has voltage $+U_d$, and the negative terminal has voltage $-U_d$. The converter consists of 6 arms, and each arm has N cells. See Figure 26. In this simplified description, it is assumed that all cells have the same cell voltage, which is assumed to be the constant value $2 \times U_d / N$. A cell can either be inserted or bypassed. The total voltage over a valve arm is the sum of all inserted cells in that arm. Each cell which is inserted contributes with its cell voltage of $2 \times U_d / N$, so the total voltage over an arm can vary between 0 and $2 \times U_d$. Since each arm is either attached to the positive or negative DC terminal, the AC side of the valve arm can attain values between $-U_d$ and U_d with N steps.

5.3.3.4.3 Switching principles and harmonic spectrum

The converter controls the voltages for the AC side of the valve arms. As described above, these voltages can obtain values between $-U_d$ and U_d . Each phase has a reference voltage, which typically has a third harmonic added in order to be able to have the peak value of the fundamental component bigger than U_d . For this simplified converter with constant cell voltages, the optimal choice for the reference is

$$u_{\text{ref}}(t) = U_d m_4 / \pi \left(\cos(\omega_1 t + \varphi) - \frac{1}{6} \cos(3(\omega_1 t + \varphi)) \right) \tag{5}$$

where

m is the modulation index, defined here to be the quotient, scaled with a factor of $\pi/4$, of the peak value of the fundamental component and U_d .

Each phase has two arms. Each arm has its own modulation reference. Furthermore, each cell in an arm has its own triangular carrier. When the carrier and the modulation reference intersect, the corresponding cell switches from inserted to bypassed or from bypassed to inserted. The modulation reference r for an arm is a variable that can take values in the interval $[-1, 1]$, where $r(t) = 1$ means that the voltage should be as positive as possible and -1 as negative as possible. For this simplified model, the modulation reference for an arm is the voltage reference where U_d has been factored out.

$$r(t) = m_4 / \pi \left(\cos(\omega_1 t + \varphi) - \frac{1}{6} \cos(3(\omega_1 t + \varphi)) \right) \tag{6}$$

The phases of the carriers for the different cells in one arm are distributed evenly. Figure 30 shows the reference for one arm and the carriers for three adjacent cells for that arm over one fundamental period.

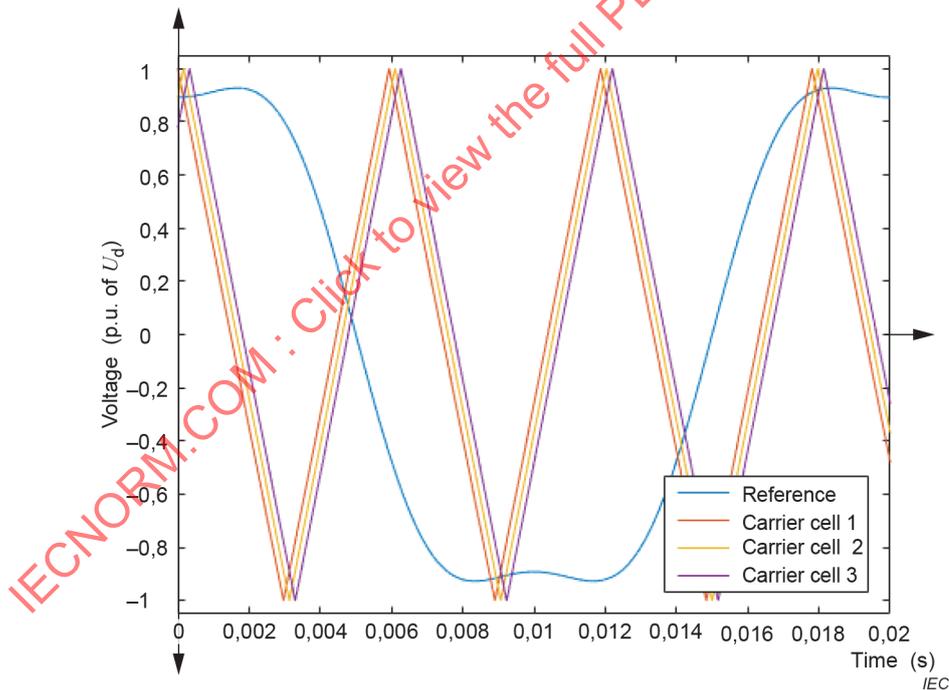


Figure 30 – Reference and carriers for three adjacent cells

In Figure 31, which is a zoomed in version, the resulting normalized voltage is also shown.

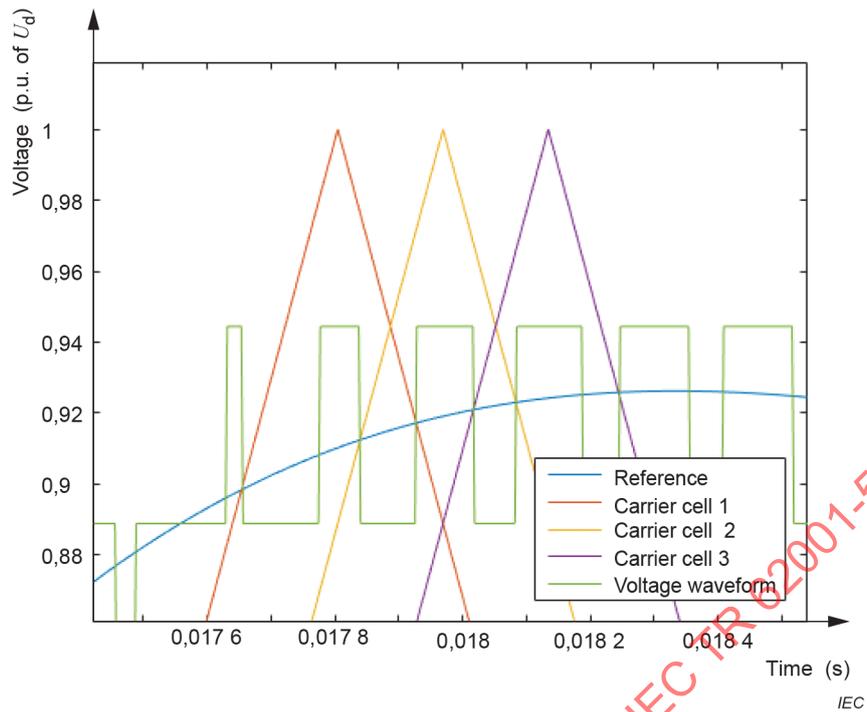


Figure 31 – Zoomed – reference and carriers for three adjacent cells and resulting voltage

As seen in Figure 32, the resulting waveform follows the reference by switching in and out cells.

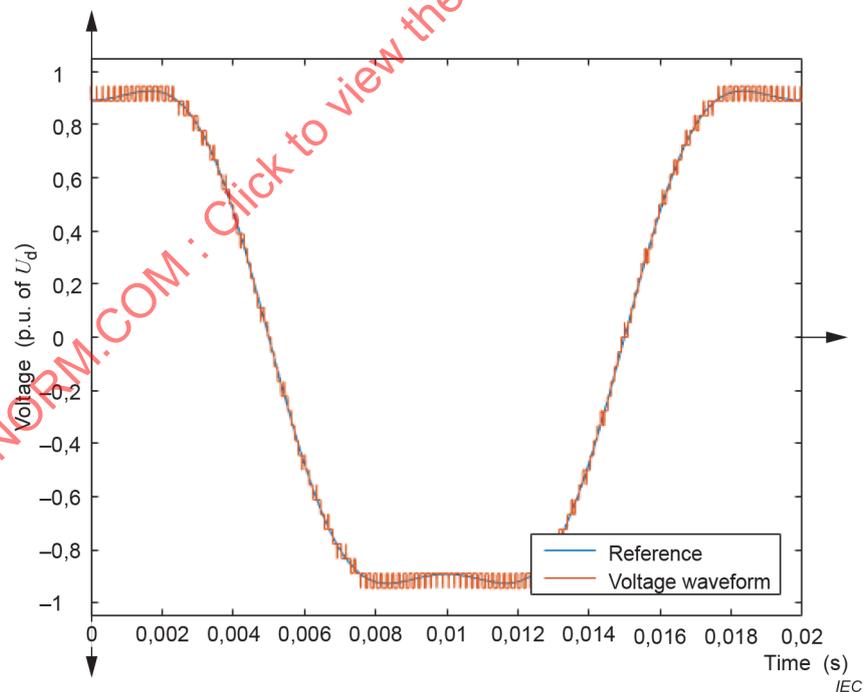


Figure 32 – Reference and voltage for one arm

The voltage spectrum for this arm is shown in Figure 33.

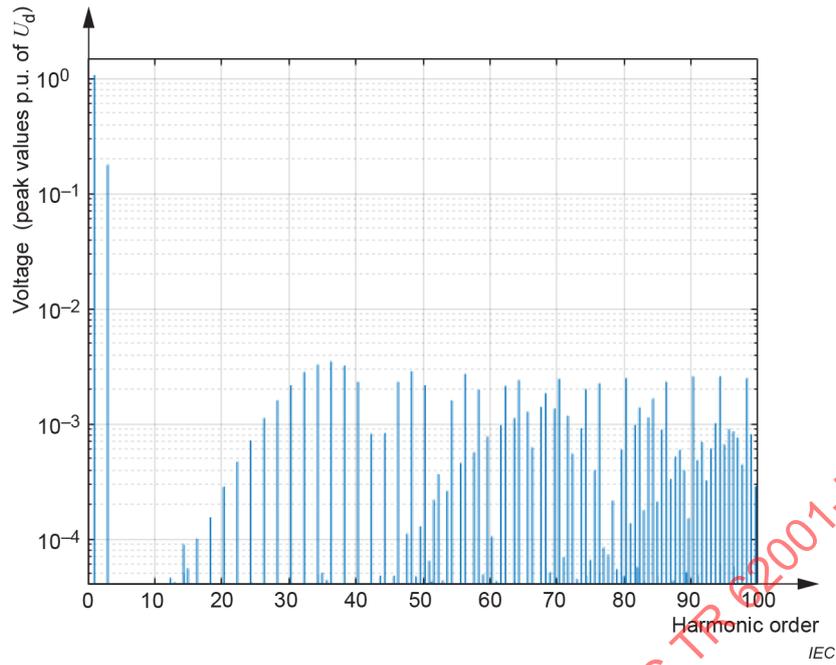


Figure 33 – Harmonic spectrum for one arm of a CTL converter

In Figure 34, the frequency range has been extended.

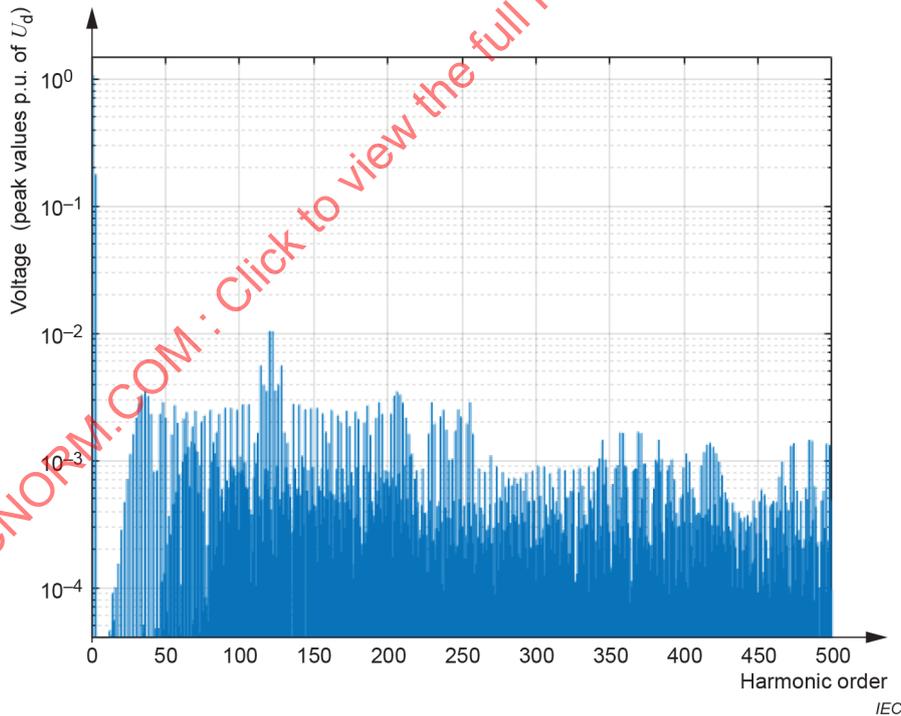


Figure 34 – Harmonic spectrum for one arm of a CTL converter – extended frequency range

5.4 Interharmonics

Besides the basic interharmonic generation related to the carrier frequency, further factors will affect whether the spectrum includes interharmonic frequencies.

The digital implementation of the controls calls for discretization in time and value. As shown in 5.3.3.3, the time-wise discretization, or in other words the sampling frequency, will have an impact on the spectrum. If the sampling frequency is a non-integer harmonic of the fundamental frequency, the switching instances of the modulation will differ between two adjacent periods of the fundamental, which results in non-integer harmonic components within the spectrum.

The impact of the sampling decreases with increasing sampling frequency. But this does not mean that the non-integer components are shifted to a higher frequency range with higher sampling frequencies. The components generated by this effect are spread over the frequency range but have a decaying magnitude for higher sampling frequencies.

As described in 5.3.3.3, a common switching pattern technique used for MMC is nearest level control. Parameters used in a simple NLC are

- time step of the converter control operation Δt_{CC} , and
- time step of the valve control operation Δt_{VC} .

Harmonics at the AC terminal of the converter (U_{ve} in Figure 26) with optimized NLC time steps are shown in Figure 35. The resulting harmonics are of integer type only and no interharmonics appear.

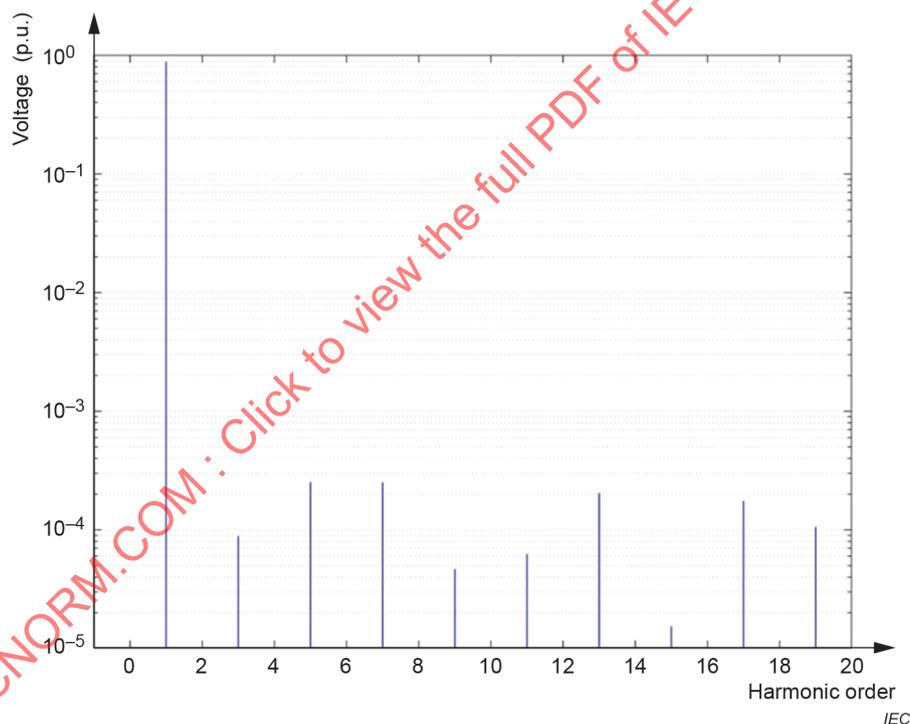


Figure 35 – Voltage synthesis with optimum time step of the valve control operation

A change of Δt_{CC} and Δt_{VC} can change the generated harmonics as shown in Figure 36. The resulting harmonics levels are slightly changed and interharmonics can appear.

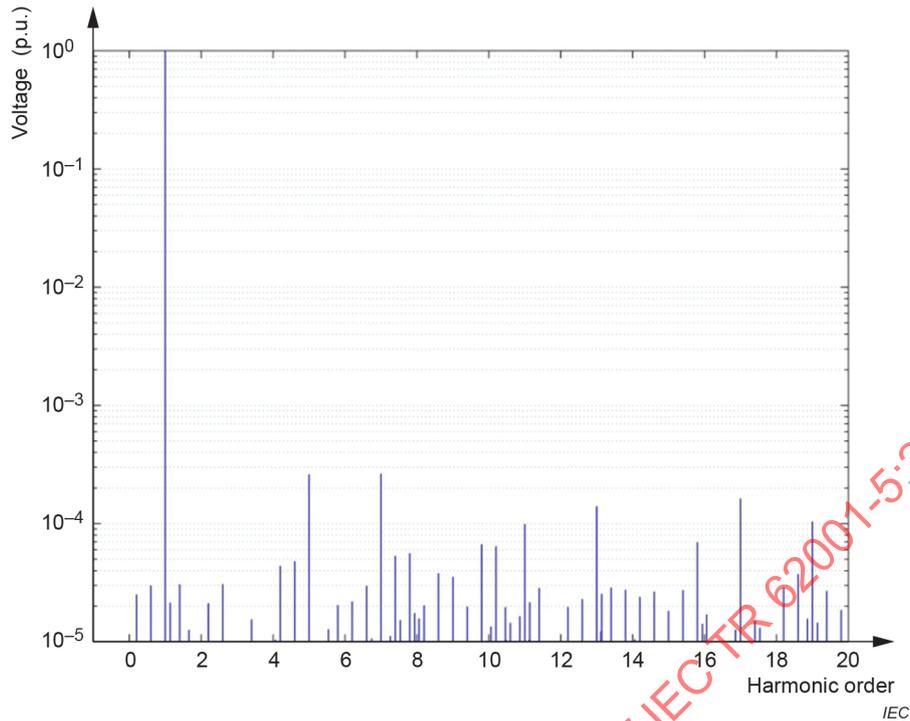
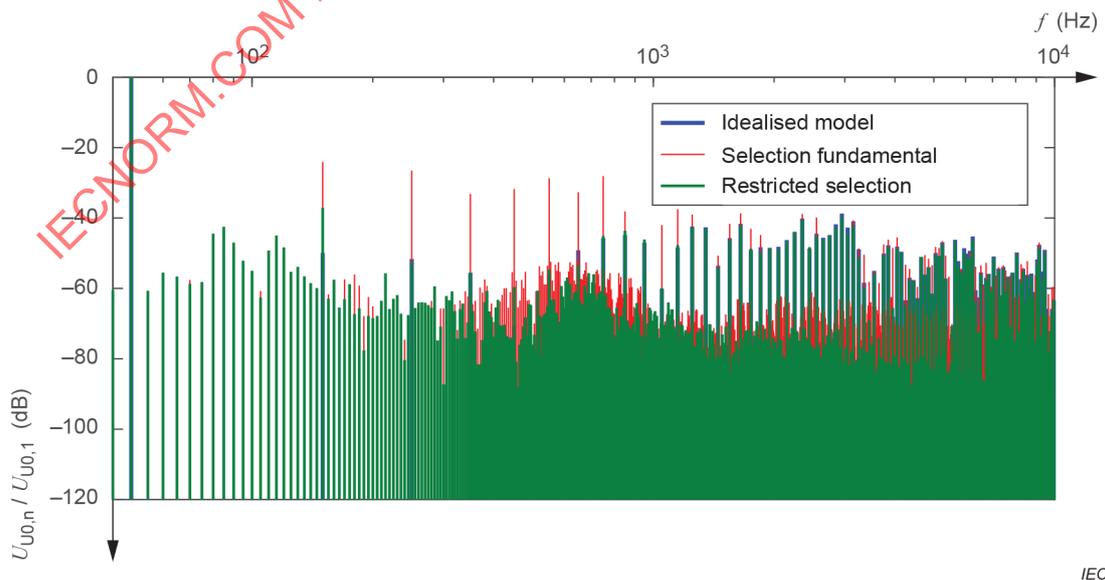


Figure 36 – Voltage synthesisization with an alternative time step of the valve control operation

For converters of cell type (e.g. MMC), the chosen sorting and selection algorithm used for voltage balancing of the cell capacitors will further influence the composition of the spectrum due to the impact on the capacitor voltages. Assuming the capacitor voltages are perfectly balanced – which does not mean that the voltages have a fixed value –, the changing capacitor voltages have an impact on the magnitude of integer harmonics. If a voltage balancing or sorting and selection algorithm is used to decrease the number of switching events, the deviation of the capacitor voltages will increase with a direct relation to the magnitude of non-integer harmonics (Figure 37). This effect can be explained in that a change of the submodules utilized to shape the output voltage may differ in adjacent fundamental periods.



SOURCE: [17]

Figure 37 – Illustrative impact of sorting and selection algorithms on interharmonic generation

Figure 37 should be understood as an illustration of the effects of a particular control implementation, and not as typical of any real system. The key implies the following.

- Idealised model: No capacitor voltage change considered -> No interharmonics.
- Selection with fundamental: Sorting carried out once in a fundamental cycle -> Selection done whenever the arm current changes its direction.
- Restricted selection: Sorting and selection are done each time the converter changes the required number of voltage levels (for PWM schemes, once per switching cycle). The restriction means that only one submodule can be turned on or off.

These two examples show that the generation of interharmonic frequencies is dependent upon many different factors. The prediction of the impact of some of these factors requires a very deep knowledge about the hardware and software used for a particular installation. As such knowledge is intellectual property, a detailed analysis can only be done by HVDC manufacturers.

5.5 Impact of non-ideal conditions on harmonic generation

Subclause 5.5 discusses the effect on harmonic generation of non-ideal conditions in the converter and supply network. The harmonic generation described in previous subclauses considered "ideal" conditions – namely that

- the AC network supply voltage is sinusoidal at fundamental frequency (no pre-existing harmonics),
- the AC network supply voltage is balanced among phases,
- there is no source of AC currents (fundamental or harmonic) on the DC side,
- the converter phase reactances are exactly balanced, and
- there are no tolerances or slight inaccuracies in the converter control system.

In reality of course, it is likely that few, if any, of these conditions are fulfilled. Small variations in the above parameters will normally occur.

In the context of HVDC line commutated converters, these small non-idealities are the source of the "non-characteristic" harmonics. In the past, much effort has been put into the correct calculation of the impact of these non-idealities for LCC, as, although the non-characteristic harmonics may be mostly of small magnitude, they may nevertheless become significant cumulatively, or if they coincide with anti-resonance frequencies of the filter plus network impedance. Most significant is the generation of 3rd harmonic as a result of network supply voltage unbalance, which may require the installation of 3rd harmonic filters.

In LCCs, the impact of such non-idealities on the generated harmonics may be straightforwardly analysed from the switching function of the converter, as the converter control functions act at lower frequencies and so have a very limited influence on harmonic generation.

When considering harmonic generation from HVDC VSCs, it is therefore reasonable to consider what impact these non-idealities would have. It is an obvious question for those with previous experience of LCC technology.

The answer is, however, not straightforward. As will be explained below, the ability of VSCs to be controlled in response to different parameters allows compensation for these non-idealities to be provided, if necessary. In general, it can be stated that a large part of the generated harmonics are caused by the control action. Therefore, the effect of non-idealities on the harmonic output content is directly influenced by the capability of the control to either filter out and reject the non-ideal conditions or to provide a new response in order to mitigate them. The control bandwidth of a MMC extends over a wide spectrum of frequencies and potentially, within that bandwidth, it has full controllability of the synthesized voltage in each of the phases. But these control actions may have side-effects, and an optimum solution may require a compromise judgement.

One approach considered for 5.5 was to demonstrate and compare calculations for harmonic generation both with and without the presence of non-ideal parameters. This simple concept however proved difficult to implement, as it would mean determining what was the standard converter configuration and base control system to be used, from many possible options in service or under development. To show one example would not be typical and could in fact be misleading. The action of control in mitigating such harmonic generation could be inherent or deliberate, and very much dependent on the particular VSC design and project.

As an overview however, it can be stated in general terms that the impact of the non-idealities is not greatly significant and certainly not comparable to their impact in the case of LCC. In support of this, it can be considered that

- the versatility of VSC control permits compensation, either natural or deliberate, for different factors,
- the internal energy storage within a multi-level VSC tends to mitigate harmonic interaction (cross-modulation) between AC and DC sides,
- the harmonic generation without considering non-idealities is itself much lower than for LCC and therefore the impact of small deviations from the considered ideal conditions should be correspondingly lower,
- these non-idealities are generally omitted in the standard harmonic calculations used for VSC design, with no evident deleterious impact in practice and
- field experience has not indicated any practical problems attributable to these non-ideal factors.

Any significant possible adverse effects of non-idealities on harmonic generation should be possible to mitigate by means of a suitable VSC control feature. This is however assuming that the scheme is designed with control margins to allow for such feature.

6 VSC HVDC as a harmonic impedance

6.1 General

In network harmonic studies, such as conducted by utilities, it is necessary to model converters as harmonic loads in cases where, for example, the harmonic flow originated from harmonic sources in an AC network is evaluated, or the AC harmonic impedance seen from a certain point is calculated.

Correspondingly, the HVDC manufacturer has the objective of designing converters such that they do not exceed harmonic distortion limits under multiple AC network scenarios (i.e. for different harmonic impedances of the network to which the converter is connected). The AC network impedance is typically given as an impedance sector in the impedance complex plane. The design verification is then typically performed in the frequency domain using a circuit that includes the harmonic impedance of the converter and the AC network impedance.

Therefore, for the purposes of TSOs, utilities and HVDC manufacturers, there is a need to model the converter harmonic impedance, either as a circuit equivalent or as a Thevenin, or Norton, equivalent.

In the future, a similar requirement to model the converter impedance as seen from the DC side will be applicable in the context of DC grids.

The overall impedance of the converter station may be envisaged as consisting of passive and active elements, as illustrated in Figure 38, where Z_T is the transformer impedance, Z_R the phase reactor impedance and C_V and C_I the transfer functions of respectively the voltage and current control loops.

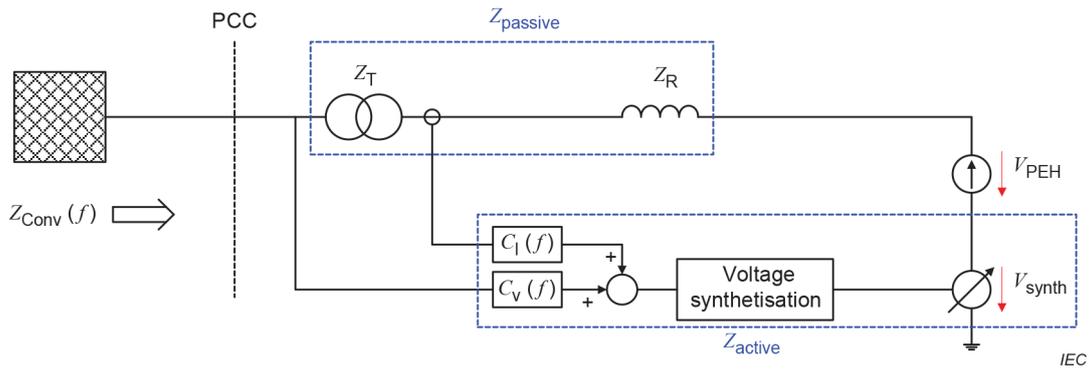


Figure 38 – Active and passive impedance elements

6.2 Passive impedance

The first approximation of the converter impedance is to simply use the passive impedance. The component impedances should be calculated appropriately with respect to the frequency range considered, i.e. the impedances should reflect for example increased losses with frequency, etc.

For the AC side of the VSC, the passive impedance would mainly be determined by the impedances of transformer, phase or valve reactor and, where applicable, impedances of AC filter branches. If there are no AC filters in the scheme, such a model would be inductive for all frequencies, for example the converter could be modelled as an EMF behind an inductance with a series and/or parallel connected resistance to represent losses as a function of frequency.

Should the converter transformer be equipped with an on-load tap-changer, the impact of different ratios should be considered as these may change both the impedance and harmonic voltage magnitudes. If there are filters in the scheme, these should preferably be modelled explicitly.

If there are particular requirements on residual (zero sequence) harmonic current injection into the network, either on the DC or AC side, and there is significant degree of zero sequence harmonic components in the line-to-earth voltage on valve side of converter transformer, the various parasitic paths (such as stray capacitances) of zero sequence currents should be considered in the design. However, they may not need to be considered when modelling converter impedance in general as they can be expected to be of high ohmic values.

6.3 Active impedance

6.3.1 General

Modelling the converter as a passive impedance as described above will have its limitations. However, to include the impact of control in the converter impedance model can give rise to difficulties, unless generic assumptions can be made. The difficulty in providing such generic assumptions is that almost all VSC HVDC schemes have an individual design of the control as they are adapted to the specific requirements of a given project. Typically, such controls will be finalised through system studies made at a late stage in the design process, which may further complicate the assessment of the converter impedance for study purposes.

The active impedance may be defined as a frequency-dependent impedance influenced by the converter control and representing the small-signal behaviour of currents and voltages.

6.3.2 Ideal VSC behaviour

Clause 10 demonstrates in detail how the control can impact the harmonic impedance of the converter. The discussion below is simplified and as such only intended to be illustrative.

Figure 39 shows a simplified scheme for a converter using a controllable voltage source valve. In an actual scheme, the control strategies are far more detailed, but here two basic control principles are considered:

- the current into the AC network is controlled (I'); or alternatively
- the voltage of the AC network is controlled (U').

The first would resemble what could be expected when controlling active and reactive power exchanges with the AC network and the second would apply during passive, island or similar operating conditions. The converter may be expected to act differently from a harmonic point of view for these two control strategies.

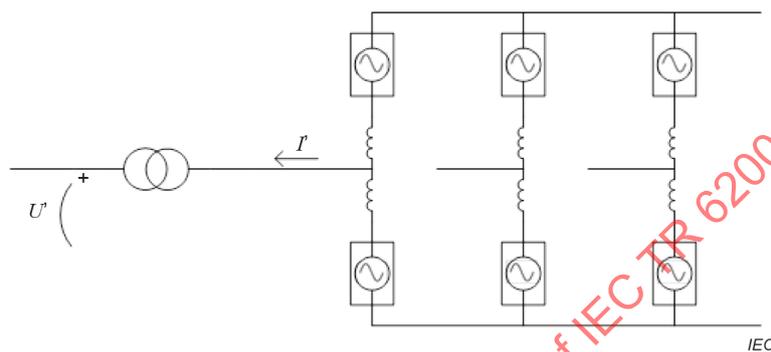


Figure 39 – Control of AC voltage or current

If the current into the AC network is controlled, then ideally the converter would inject a current consisting of a fundamental frequency positive sequence component only. If this theoretical assumption were true, then the converter control would suppress any imbalance current component in the transformer and any harmonic current components. Expressed in simplified way, the converter would appear as a high impedance for any harmonic voltage components or any asymmetry either caused by the converter itself or existing in the AC voltage at the point of common coupling, PCC.

If the voltage of the AC network at the PCC is controlled through U' , then ideally the converter would keep the voltage, at this point, to a target fundamental frequency positive sequence component only. If this, theoretical, assumption were true, then any imbalance component and any harmonic components in the AC network voltage would force a current, determined by the component source level and the AC network impedance up to PCC, into the converter. Expressed differently, the converter would appear as a short circuit at PCC for any harmonic voltage component or any asymmetry appearing in the AC network.

An actual control would be more complicated than the idealised ones above, and may combine the above two principles to various degrees. Further, no actual control, even if implemented as described, could be ideal due to various practical limitations and considerations in the overall system. The outcome would be dependent on the dynamic response of control, measuring system and so forth.

6.3.3 Impact of practical control system features

The active impedance of the current and voltage controller depends on the measuring system, discrete delays due to the control hardware and due to the delay in the voltage synthesization. Measuring system and control hardware are very specific to each HVDC manufacturer, so that general statements are not possible. The functions which might have an impact on the converter impedance are

- control loops,
- current and voltage transducer transfer function,

- current and voltage sampling method and sampling rate,
- analog and digital filters,
- control delay, and
- voltage synthesization delay.

Combining these effects, the impedance can be approximately calculated as shown in [8], and referring to Figure 38:

$$Z_{\text{Conv}}(f) = \frac{C_I(f) + Z_T(f) + Z_R(f)}{1 - C_V(f)} \quad (7)$$

where

Z_T is the transformer impedance;

Z_R the phase reactor impedance;

C_V and C_I the transfer functions of respectively the voltage and current control loops.

Depending on the converter control, the positive and negative sequence impedance might be different. In that case, the harmonic amplification has to be calculated for positive and negative sequence pre-existing harmonics separately.

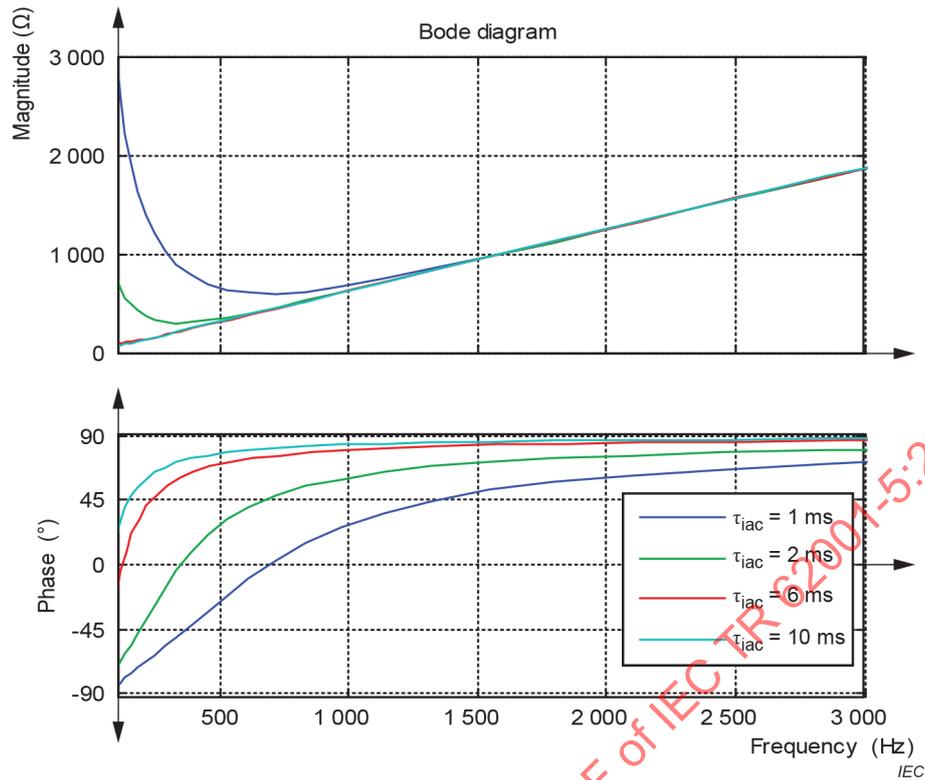
6.3.4 Example of impact of control

In Figure 40 (taken from [18]), the impact of the current control loop on the equivalent impedance is depicted as an example. The other parameters mentioned in 6.3.3 are not considered in this case.

The actual values shown should not be taken as typical – this plot is purely for illustration.

As it can be seen, the effective converter impedance varies depending on the dynamic response performance of the current control. The shorter the settling time, the more significant the active effect on the converter impedance. From Figure 40, it can be seen that at low frequency the effective impedance becomes capacitive due to the control system, whereas at high frequency the inductive behaviour is predominant. This behaviour may change depending on the control system structure.

This result is obtained by simulation with a simple generic model of VSC converter. The transformer and the phase reactors are included in the model. It is interesting to note that the overall impedance, including active and passive elements, can appear as capacitive at lower frequencies, despite the large inductances of the phase reactors and transformer.



SOURCE: [18]

Figure 40 – Illustrative impact of the I-control inner control loop time response (to 5 % relative error) on the positive sequence converter impedance

It is clear from Figure 40 that the active impedance can have a phase angle much lower than 90° – in other words, it appears to have a partially resistive or damping character. It is important however to understand that this does not imply additional energy dissipation within the converter. The resistive characteristic is a result of switching energy storage within the converter itself and does not create any significant additional losses.

6.4 Impact on amplification of pre-existing harmonics

When any new apparatus, in this case an HVDC converter station, is connected to the power supply network, if it exhibits a reactive impedance at a given frequency, then it may resonate with the network harmonic impedance as seen at the point of common coupling (PCC). Consequently, this may result in the amplification of pre-existing harmonic voltages in the supply network.

This is equally true for LCC HVDC installations, and in HVDC projects the issue has often been addressed by imposing particular limits on amplification factors or on the aggregate distortion permitted from the combination of HVDC emissions and amplification of pre-existing sources [9], [12].

For LCC stations however, the harmonic impedance as seen from the PCC is normally dominated by the large shunt filter banks. The harmonic impedance of the converter itself is relatively insignificant, apart from specific issues which may occur at the very low order harmonics.

For VSCs, there are often no such shunt filters, and where they exist, they are generally very small. The harmonic impedance as seen from the PCC is therefore dominated by the internal harmonic impedance of the VSC, both passive and active.

In terms of mitigation, VSCs have the capability to provide some active filtering, or adjust their characteristics so as to provide damping, at lower order harmonics. This may allow the amplification of some specific amplified pre-existing harmonics to be kept within the desired limits, but the upper frequency range of such action is limited by the bandwidth of the control. An additional consideration is that active filtering may reduce the available capacity of the converter for its primary purpose of DC power transmission.

In some VSC HVDC projects, the location of the converter station is at some distance from the TSO's substation which is regarded as the PCC, and the two are connected by some kilometres of AC cables. The capacitance of these cables will tend to interact with the inductive impedance of the AC network at low harmonic orders, resulting in amplification of pre-existing harmonics.

If the length of cable is sufficiently long that the series impedance at the frequency range of interest is significant, there may be no effective action that can be taken at the converter station, neither by passive filters nor by using active techniques, to significantly reduce any excessive amplification at the PCC. Installation of passive filters, or modification of the controls, being at the remote end of the cable, has relatively little impact on the resonance of the cable with the network impedance at the PCC.

Passive filtering at the PCC end of the cable rather than at the converter station itself can be more effective, but it is often impossible to install such filtering due to considerations of space, cost, or issues of ownership. Even so, it may be difficult to damp resonances due to the large capacitance of a long cable by using a relatively small filter.

This problem of amplification due to AC cables connecting the VSC station to the AC network can be of very high significance and should be considered at an early stage of planning such an HVDC project, as, if the level of amplification of pre-existing harmonics due to the cable connection alone is unacceptable to the TSO, and filtering at the PCC is not permissible, then the feasibility of the complete transmission project may be questioned.

7 Adverse effects of VSC HVDC harmonics

7.1 General

In 7.2 and 7.3, various possible adverse effects of harmonics will be discussed. These subjects have been widely covered in literature and standards, in the context of harmonics generated by LCC technology and other harmonic polluting sources. A comprehensive discussion may be found in [19]. A brief summary of these effects will be presented but the focus will be on potential consequences specific to VSC HVDC.

The aspects of VSC transmission which could possibly result in adverse harmonic effects come under the headings of

- extended range of higher frequencies generated by the converters,
- generation of a wide range of interharmonics, often inherently as a consequence of the valve switching strategies,
- generation of even order harmonics, and
- use of dedicated AC cables or overhead lines within the scope of some VSC HVDC projects to connect new converter stations to existing main substations, with the consequent risk of interference to telecommunication cables sharing an adjacent route.

Reference is made throughout Clause 7 to the above aspects and the relevance of each to the affected system in question.

7.2 Telephone interference

7.2.1 General

Formerly, the risk of interference to analogue telephone communication due to inductive coupling from power system harmonic currents was a major issue to be considered. However, telephone communication technology has developed rapidly in recent years, with traditional analogue communication at audio frequencies over copper cables being replaced by digital, optical and cellular technologies. These technologies are immune to such interference and so the issue is of constantly diminishing importance. However, there is still at the time of publication a considerable amount of legacy analogue telephone circuitry in operation, particularly in countries which have extensive older telephone networks for consumer connection to local exchanges, and the following refers to such systems where they exist.

The voice range band used in telephony is from about 300 Hz to 3400 Hz, which lies within the range of frequencies typically generated by a VSC converter. Telephone interference criteria exist in order to limit noise which is perceptible by the human ear through telephone equipment to acceptable levels. Such noise may be caused by inductive coupling between the power and the telephone circuits.

The main parameters affecting telephone interference, examples and criteria are detailed in [9] and [10] to [13]. Telephone influence factor (TIF) and telephone harmonic form factor (THFF) are weighted voltage indices derived from the coupling factors and psophometric weighting factors for each frequency. The TIF and THFF criteria might be used as criteria for projects for which no detailed studies are performed, keeping in mind that these criteria give only a rough estimate of telephone interference influence [10]. Other criteria such as the psophometric weighted harmonic current IT or equivalent disturbing current I_{eq} are current-based and give indications of the level of current injected at the point of connection, but they can also be incomplete indicators of possible interference.

Considering the list of distinguishing features of VSC harmonics in 7.1, the following points are relevant in the context of telephone interference.

7.2.2 Extended higher frequency range of VSC harmonics

This should have little impact on perceived telephone interference, due to the diminishing response of the human ear and telephone equipment to higher frequencies. The effective noise level of various frequencies in the voice band can be assessed using one of the two similar weighting systems (psophometric and C-message), which take into account the response of telephone equipment and the sensitivity of the human ear. In countries following European practice, psophometric weighting is commonly used, while the C-message weighting curve is more in use in countries following North American practice. Both have a steep-fall-off in weighting values at higher frequencies. This should ensure that the extended upper range does not create any significant additional telephone interference, even if harmonic generation can still be significant at higher frequencies for some VSC technologies. The relatively low magnitudes of higher frequency harmonics should also ensure that the maximum unweighted induced voltage permissible for safety reasons is not exceeded and that it will not exceed the ratings of telephony equipment.

7.2.3 Interharmonics

There is nothing in the nature of interharmonics which will affect telephone interference any differently to integer harmonics – they are just another frequency. The psophometric and C-message factors are continuous functions over the frequency range, so interharmonics should be considered in the same manner as integer harmonics when calculating telephone interference. Appropriate weighting factors may be derived by interpolation, depending on the grouping methodology adopted. The formula used to define the telephone interference criteria (e.g. TIF, THFF, IT product) should be modified to include all frequencies in the spectrum, not just integer harmonics.

7.2.4 AC cable connecting HVDC station to the PCC

Although telephone interference is typically considered to be an issue along overhead lines, experience has shown that it may cause issues also along underground cables, typically where there is a lengthy exposure with close separation between the AC or DC cables and a telephone system in the same route. Despite the shielding of the power and telephone cables, interference may still occur, especially if single phase cables are used and the separation is close enough for the different distances from phase conductors to telephone cable to become significant, such that the positive or negative sequence harmonic currents can cause interference.

DC side interference is beyond the scope of this document but is covered in depth in [1].

Virtually all LCC HVDC transmission projects are connected to the AC power system directly at a major substation. Telephone interference issues were generally dealt with by the imposition of indicative criteria (TIF, THFF, etc. as described above). However, as the spatial footprint of VSC stations is relatively small, and as converter stations are being located on available sites convenient for DC cable connection and suitable under local planning regulations, such VSC stations sometimes require a dedicated AC overhead line or cable connection to the nearest major grid substation. This connection may form part of the HVDC transmission scheme contract and so the HVDC owner may be completely responsible for ensuring that there is no interference from the cable. An exact assessment of any possible risk of interference from this link should therefore be made.

The possible routing of this AC link may be highly constrained and may have to run close to existing telephony services. An initial infrastructure study should therefore be undertaken at an early planning stage of such a project, to identify any such vulnerable telecommunications circuits.

The following details of any telephone line within the vicinity (at least within 50 m for a power cable, up to 1 km for an overhead line) of a dedicated AC link from the VSC converter site should be identified:

- whether a telephone line is buried cable or overhead line;
- the geographic route of the telephone line, with accurate coordinates. If the separation distance is small (in the range of 10 m or less), then the location accuracy should be correct to within approximately 1 m;
- the nature of the telephone line (e.g. trunk cable or local subscriber);
- the technology of the telephone line (e.g. analogue telephony, ADSL, broadband). Fibre optic may be excluded;
- the type of telephone cable, including definition of any shielding;
- local earth resistivity values.

On the positive side, such an AC cable may provide some degree of mitigation of harmonic currents injected in the remote substation, due to attenuation along the cable length, especially at higher harmonic orders.

7.3 PLC, metering and ripple control

7.3.1 General

Power line carrier (PLC) is a communication method that uses a modulated carrier signal for power line protection and communication purposes. PLC operates in a narrow band with a carrier frequency somewhere in the frequency range of around 30 kHz to 500 kHz. Detailed consideration of this frequency range is well above the scope of this document and possible interference with the performance of PLC belongs to an area of study covered by CIGRE Technical Brochure 15 [20], and is discussed in IEEE Std 643-2004TM, 5.4.3 [21]. The use of PLC on high voltage networks is decreasing as it is replaced by dedicated optical fibre or internet communication, but similar technologies may become more widespread on lower voltage networks in the context of "smart metering".

On some power distribution systems, meters and other apparatus are remotely controlled by means of low frequency PLC or "ripple control" systems which generally operate in the range of 110 Hz to 3 000 Hz and normally use interharmonic frequencies to avoid interference from normal harmonic pollution. On more recently installed systems, the signals are in the range of 110 Hz to 500 Hz. The magnitude of the injected sine wave signal is in the region 2 % to 5 % of the nominal supply voltage, depending on local practice [22]. Both IEEE Std 519 [7] and IEC 61000-2-2 [23] suggest limits for individual voltage interharmonics to protect low frequency ripple control or low-frequency PLC from interference and to account for resonances caused by harmonic filters.

Although becoming obsolete due to their data carrying limitations and advances in other communication technologies, some metering systems such as automatic meter reading (AMR) still use power lines to communicate. Generally, either the current, voltage or both are briefly shorted to ground to send a step signal that is interpreted as a binary bit. Series of bits are interpreted to identify the meter and the information it is sending. Multiple meters can send signals at the same time, but with multiple communication attempts and error checking, communications can be quite reliable. These signals include a wide range of frequencies, but their magnitude generally decreases as their frequency increases. Some systems limit their communication frequencies to less than 1 000 Hz. Signal magnitudes should be kept low enough to prevent flicker, which varies depending on frequency, but could be as low as 0,23 %. (IEEE Std 519 [7]).

From the list of distinguishing features of VSC harmonics in 7.2, only two points are relevant in the context of PLC and ripple control.

7.3.2 Extended higher frequency range of VSC harmonics

Experience of equipment failure in one PLC system near to a VSC converter [24] [25] showed that high-frequency switching transients from a VSC converter, combined with sharp local circuit resonances, can (in abnormal situations) lead to high stresses on some PLC coupling and filtering equipment. The HVDC station design in this instance included AC filters, but these were tuned without a high-pass characteristic. Designers should therefore be aware of the possible effects of high frequency injection into the surrounding AC system, as even low levels of injection at key frequencies subject to resonances may create problems. Some mitigation by means of high-pass AC filters or dedicated high-frequency filters may be desirable.

7.3.3 Interharmonics

In the lower frequency range, interharmonics may need to be subjected to particular limits, if low frequency communication as described above is used within the distribution system. However, where no such ripple control systems exist, which is probably the majority of power systems, there appears to be little justification for applying stringent low limits for interharmonics. Even where low frequency interharmonic ripple systems do exist, the limitations on interharmonic distortion should be restricted to the affected frequencies. Even so, the required limitations may be too low to realistically be achieved on the EHV power system, and mitigation measures within the distribution network may be more appropriate. Higher order interharmonics which do not affect ripple control systems should not be subjected to the same limitations.

The AMR systems described in 7.3.1 are sensitive to interharmonic voltage distortion below 1 000 Hz at about 0,4 % magnitude. This sensitivity does not appear to be particularly frequency dependent, so targeting specific frequencies for mitigation is not applicable in this case.

7.4 Railway signal interference

Railways use a variety of systems for signalling and communication with trains. Possible electromagnetic interference with these systems from external sources, including the electric power system, is of course of paramount importance for safety reasons. Concerns may be raised when an HVDC cable is routed in close proximity to railway communications and signalling, for a long distance. The installation of an HVDC cable in a railway tunnel is a particular case. Rail safety regulations are extremely strict and will insist on rigorous proof that no interference can occur.

Again, DC side interference is beyond the scope of this document but is covered in depth in [1]. However, similar issues may arise from AC lines and cables connecting a VSC station to the grid, if these lie in close proximity to a railway.

Any radio frequency communication issues (for this purpose, above 9 kHz) are outside the scope of this document, and are adequately covered in CISPR, ITU, IEC and EN standards [26] to [29] and CIGRE Technical Brochure 15 [20].

Railway communication systems are necessarily designed with a high degree of immunity from electromagnetic interference. The introduction of low magnitudes of additional higher order harmonics, and of interharmonics, from VSC HVDC converters to the power transmission system will have a negligible impact either in terms of conducted harmonics or inductively coupled interference from parallel AC lines.

A review of all the relevant railway signaling standards in the USA and Canada revealed that there are no harmonic standards that raise significant issues related to interference in the range of frequencies above the 50th harmonic, to approximately 9 kHz. Common modern railway signaling systems do not appear to have any operational impairments from the low level higher order harmonics potentially generated within VSC HVDC systems. In many cases, the major (USA Class-1) railways have moved critical communications and block interlock schemes telecommunication support to fiber optic and microwave based systems. In the USA, the addition of positive train control (PTC) utilizes signaling systems which are radio based (VHF and UHF) bands which utilize much higher operating frequencies than any possible conducted harmonic contribution from VSCs.

Detailed studies of possible interference between steady state harmonic interference of a VSC HVDC transmission cable and the various railway systems in a very long tunnel in Europe have verified that there were no issues of concern.

7.5 Digital telecommunications systems

The conversion of much of the former telephone network to various forms of digital technology has reduced the problem of direct interference with analogue signals at audio frequencies. However, it is still possible that induced harmonic voltages in telephone systems may cause interference with the digital communication. The error checking algorithms which are generally employed may prevent this resulting in false information, but the effect may be significant slowing of the communication. In addition, levels of induction which could cause damage to equipment or risk to personnel should be avoided.

Such risks are therefore related to the magnitude of interfering induced voltages rather than to any specific frequency or harmonic characteristic. Interharmonics and even harmonics will not be more deleterious than integer harmonics. Higher frequencies will be more effectively mitigated by communication cable shielding.

ADSL, POTS (plain old telephone service), and other subscriber services typically share the same copper wire coming into homes and business locations through a frequency division multiplexed (FDM) topology. The typical frequency allocation can be summarized as

- 0 kHz to 4 kHz, voice (POTS),

- 4 kHz to 25 kHz, unused guard band,
- 25 kHz to 138 kHz, ADSL, 25 upstream bins (7-31), and
- 138 kHz to 1 107 kHz, ADSL, 224 downstream bins (32-255).

In the range of 1st to 200th harmonic spectrum where induced harmonic interference from a VSC might occur, the band allocation is either for voice, which is covered by normal telephone interference, or is unused.

It is therefore concluded that the introduction of VSC HVDC harmonic sources should not pose any risks for digital telecommunication systems unless the magnitude of the coupled harmonic voltage is exceptionally high.

8 Harmonic limits

8.1 General

The possible adverse effects of harmonic voltages and currents in electric power systems are well understood and documented. Limits on the acceptable distortion levels to be permitted at different voltage levels of the power system are defined in various national and international standards, and limits on the maximum acceptable harmonic impact of newly connecting non-linear installations are defined in grid codes or by individual TSOs based on these standards.

The above well-known material will not be described here, except where necessary to set the context for further discussion. Instead, the intention is to highlight those areas where the introduction of large-scale VSC HVDC has created issues which are not adequately covered by standards and practices developed in the context of earlier, different technologies.

Clause 8 includes recommendations which may guide the development of future standards and practice. It is recognized that both national and international standards take many years of discussion before they can be revised. However, the "practice" of network operators in interpreting these standards when providing appropriate harmonic limits for new VSC HVDC projects is more flexible. It is hoped that the recommendations included herein will be of assistance in both cases, allowing further penetration of VSC technology in the short- and long-term without undue hindrance, whilst maintaining the essential protection of power systems and their users from deleterious harmonic effects.

One practical issue to be taken into account is that the utility and TSO requirements on harmonic performance and amplification of pre-existing harmonics will have been developed without any knowledge of their resulting implications in terms of the required harmonic mitigation at the converter station. Sometimes limits and conditions may be specified based on somewhat arbitrary criteria. Pre-existing harmonic levels and network harmonic impedances may not be accurate, or may include wide margins. Limits for amplification of pre-existing harmonics may not need to be as strict as initially assumed.

In a collaborative "best for project" working context, it is therefore reasonable for the HVDC supplier, once the initial assessment of required mitigation has been made, to discuss with the utility and TSO whether it is possible to relax or modify certain requirements, in order to achieve a practical mitigation solution which is to the benefit of both parties. Such negotiation would normally occur at the tender stage or initiation of the project implementation stage.

8.2 Deleterious effects of excessively low limits

In principle, harmonic limits should be set low enough to avoid any predictable adverse effects. Specifying sufficiently low harmonic limits at the beginning of the project could prevent difficulties that would arise post-commissioning, incurring additional delays and costs, including possible modifications to the filtering solution.

However, when specifying limits, it should also be considered that requesting unjustifiably low limits could lead to the following possible implications:

- unnecessary filtering being required in the station design. A superfluous filter would result in an unjustified greater design complexity (and therefore lower reliability), increased cost, greater spatial footprint, audible noise and additional losses;
- the introduction of active filtering in the converter control system, increasing complexity and possibly reducing the converter capacity available for power transmission;
- prolonged discussions between the parties during the design stage, with potentially costly implications for the project schedule particularly regarding the civil and mechanical works.

Therefore, setting harmonic limits as high as possible, while avoiding any problem in the actual and predictable future network, would lead to an optimal design. When defining harmonic limits, a network operator should consider why a particular limit or a specific range of frequencies is specified, and ensure that the requirements are pertinent to its network.

It may also be taken into account that, in the event of actual harmonic issues arising at a later time, for example due to changes in the network, some adjustment of the VSC control parameters may be possible to mitigate the problem without the need for additional main circuit equipment. However, the full impact of any such future changes would have to be considered through repetition of appropriate system studies and possibly real-time simulation.

8.3 Standards and practice

An important distinction should be made between "standards" and "practice" in setting harmonic performance limits for an HVDC project (or any similar large installation).

- Standards – IEC TR 61000-3-6 [5], IEEE Std 519 [7] and other national and regional standards define compatibility levels and planning levels which should be respected for the system as a whole. This ensures that all consumers can connect to the system without risk of damage or degraded performance due to harmonics in the supply.

In many cases, these standards also give guidance on the methodology for determining the permitted distortion limits for any new connection to the system.

Such standards are only revised on a long time frame, perhaps every 10 to 20 years. The recommendations of this document may be taken into account in future revisions, but meanwhile network operators should abide by the limits defined in the relevant standards.

- Practice – In practice there are areas where the standards either offer no guidance or where the network operator or HVDC customer has relative freedom of action, while still respecting the requirements of grid codes and other guidelines. Such areas may include
 - defining planning levels, in the case that the relevant standard (e.g. [5]) only gives "indicative" levels,
 - interharmonic limits (where these are not imposed by standards),
 - the definition of THD to include or exclude interharmonics (e.g. they are excluded in IEC TR 61000-3-6 [5]),
 - higher frequency harmonics (above the typical 50th order),
 - allocation to new connections of available "headroom" between planning levels and the pre-existing harmonic background levels, and
 - how to treat amplification of pre-existing distortion. This includes aspects such as representation of the network impedance [9] [12], and the methodology for combining pre-existing harmonics levels with new emission levels.

It is in these areas that the recommendations of this document may have a more immediate effect on industry practice.

8.4 Perception of VSC in setting limits

The introduction of VSC HVDC technology has hugely reduced the harmonic generation of converters compared to LCC technology, and has largely removed the need for dedicated AC filters. The marketing of VSC HVDC has naturally highlighted this aspect, and the resulting beneficial reduction in the physical area of converter stations.

The resulting perception of VSCs as being virtually harmonic-free has had an impact on the way that some TSOs have allocated a proportion of the available headroom to a new VSC HVDC installation. Extremely low levels of permitted harmonic emissions have been specified for some HVDC projects. Similarly, parameters relating to the amplification of pre-existing harmonics have sometimes also been set at very low levels. The understandable reasoning behind this is to preserve headroom for future connections to the system. This is a matter of "practice" by TSOs where they are not bound by standards.

However, such specifications have sometimes led to detrimental effects on the implementation of VSC projects, as outlined in 8.2 above. If harmonic limits are set so much lower than for other types of installation, such that the cost and feasibility of the VSC HVDC project is adversely affected, then it should be questioned whether such limits are of real benefit to any of the parties involved.

It is therefore recommended that, even if TSOs prefer to allocate a smaller proportion of the available headroom to a new VSC connection than would be the case for another non-linear installation of similar size, the limits chosen should take into account the feasible realistic performance of the VSC technology being considered.

8.5 Emission and amplification limits

Two distinct phenomena contribute to the aggregate harmonic distortion at the point of connection of a VSC. One is the harmonic emission from the converter itself. The other is the distortion due to pre-existing sources within the AC network, which may be amplified or damped by the introduction of the new connection and the operational characteristics of the VSC.

Harmonic limits with respect to the converter emissions are discussed in the remainder of 8.5.

Harmonic limits with respect to the possible amplification of pre-existing harmonics are dealt with in different ways in different standards and practices. For the purpose of the present document, it is only necessary to note that there should be nothing different about such limits applied to a VSC connection compared to any other equivalent non-linear connection. However, it is important that the harmonic impedance of the VSC, including the effect of its control system, should be taken into account in calculations, as discussed in Clause 6.

The specification of the network harmonic impedance envelopes is also of vital importance for the correct calculation of the harmonic performance due to both emission and amplification. It is fruitless to calculate the converter performance in great detail if the other principal factor involved in determining distortion, i.e. the network impedance, is inadequately represented. The provision of correctly calculated network harmonic impedance by the customer at the tender stage will facilitate the tender process by permitting comparison of competing designs on an equal basis. It should also facilitate an optimized design of any harmonic mitigation and minimize future risk for all parties. The recommendations of [12] should be followed.

8.6 Relevance of standards for VSC

The underlying philosophy behind the emission limits for individual harmonics in many existing standards is based on allowing high values for those harmonics which are normally prevalent and of the highest magnitude, and low values for harmonics which are not normally significant. Thus a desired total harmonic limit (THD) can be achieved while giving maximum scope for the most common and largest harmonic orders; thereby avoiding imposing excessive requirements on their mitigation. In an industrial and domestic environment dominated by 6 and 12 pulse converters of various types, the harmonics with highest allowed limits are typically odd harmonics that are not divisible by three, i.e. 5, 7, 11, 13 ... while other harmonics and interharmonics are allocated relatively small limits.

Large scale HVDC VSCs however have a completely different harmonic spectrum, and certain emitted harmonics or groups of harmonics may be found to be in infringement of harmonic limits which were originally set in the context of earlier technologies.

The following subclauses 8.7 to 8.15 examine the conflict between typical existing harmonic limits and the requirements of VSC technology for optimal allocation of limits across the harmonic spectrum, and make proposals for improvements to standards and practice in this respect.

8.7 Existing standards

The above-mentioned unsuitability of existing standards for VSC technology may be illustrated by reference to two standards – IEC TR 61000-3-6 [5] and IEEE Std 519 [7]. Many other national standards are based on one of these, or contain many of their features.

IEC TR 61000-3-6 [5] defines firm compatibility levels, which should not be exceeded at any point in the supply system, in order to protect all connected apparatus, together with lower magnitude indicative planning levels which may be used as a basis for the regulation of harmonic distortion. Table 2 shows the planning levels for higher voltage systems.

Table 2 – Indicative planning levels for harmonic voltages (in percent of the fundamental voltage) in MV, HV and EHV power systems

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,8	1,4
7	4	2	9	1,2	1	4	1	0,8
11	3	1,5	15	0,3	0,3	6	0,5	0,4
13	2,5	1,5	21	0,2	0,2	8	0,5	0,4
$17 \leq h \leq 49$	$1,9 \cdot (17/h) - 0,2$	$1,2 \cdot (17/h)$	$21 \leq h \leq 45$	0,2	0,2	$10 \leq h \leq 50$	$0,25 \cdot (10/h) + 0,22$	$0,19 \cdot (10/h) + 0,16$

SOURCE: Table 2 of IEC TR 61000-3-6:2008 [5].

The recommendations of IEC TR 61000-3-6 [5] with respect to interharmonics are described and discussed further below in 8.10.

8.8 Higher frequency harmonics

8.8.1 General

The relevant standards at present give no guidance or recommended limits for harmonics above the 50th order. However, as seen in Clause 5, the range of frequencies with significant harmonic generation from VSCs extends well above the 50th order. To date, some utilities have made attempts to enforce harmonic limits at higher frequencies [30] but there is limited technical reasoning behind these and the choice of limits appears to be arbitrary.

Power electronic components based on turn-off devices such as IGBT, IGCT or MOSFET inject harmonics at higher frequencies than conventional non-linear installations. The harmonic emission is commonly concentrated at frequencies which are multiples of the switching frequencies. For this reason, there is an increasing interest to define limits for harmonic emission in the frequency range from 2 kHz to 150 kHz. Aspects of the frequency range 9 kHz to 50 kHz are addressed by CIGRE TB 799 [31].

Present IEC standards and IEEE guidelines define power quality limits up to the 50th harmonic. However, various bodies are now addressing the need for guidance at higher frequencies. EN 50160 [6] mentions supraharmonics in the application guide for the standard. IEC TS 62749 [32] also addresses the issue. At a national level, only the German standard DE-BDEW for MV installations [33] defines a current emission limitation up to 9 kHz. For the specific interference with power line carrier (PLC) systems, EN 50065 (all parts) [34], CENELEC/EN 50061 [35] and IEC 61000-3-8 [36] addresses this frequency range. CISPR 14-1 [37], CISPR 14-2 [38] and CISPR 15 [39] also address the range above 9 kHz but in the field of EMC interferences.

The presence of this high-frequency component in the network may possibly result in

- potential interference with power-line communication operating in the same range of frequencies,
- amplification of currents and voltages due to resonances, and
- impact of this distortion on end-user equipment such as capacitors.

Setting harmonic emission limits in the range between 2 kHz to 150 kHz at HV level can be considered a means to prevent possible compatibility issues resulting from electromagnetic interference. On the other hand, the quality of the information to perform studies in such a range is extremely limited because existing network models are not accurate up to that frequency range and the measurement of harmonic components in such a range is not necessarily reliable over this whole frequency range. Verification that a new installation actually conforms to limits set in a higher frequency range may not be feasible or accurate using conventional power quality measurement instruments and techniques.

The use of high-frequency turn-off semiconductors is nowadays predominantly seen at low-voltage levels in modern power networks. Therefore, any problems related to high-frequency spectra in the network will first be seen in low-voltage networks. This matter is being currently addressed by, among others, the CIGRE Working Group C4.24 on power quality and EMC issues [40] associated with future electricity networks.

In many VSC converters installed before 2017, no special mitigation measures have been taken to limit harmonics in the frequency range above the 50th order. The harmonic emissions have been at the natural level produced by the installation. There have been no known consequential power quality problems in the connected networks or in network assets or consumer equipment. The only issues which have occurred have been due to particular resonances associated with specific remote items of equipment, and these issues would not necessarily have been prevented by the application of power quality limits on harmonic distortion at the PCC.

It is recommended that, in setting limits for higher order harmonics, the present day VSC technology should not be unduly constrained due to an approach of limiting higher order harmonics as a precaution against unknown future issues. This should be considered in future revisions of the relevant standards.

There appear to be no known justifications for lower limits to be imposed for harmonics above the 50th order than those implemented at and around the 50th order.

It is suggested that, in order to allow at least a qualitative assessment of harmonic issues at higher frequencies, the HVDC supplier is asked to provide the emitted spectra over the full range of frequencies of significant magnitude, where this range will depend on the VSC technology being used.

If future standards aim at considering the range above the 50th harmonic, utilities and industries will have to address the following issues:

- network representations which account for higher frequency phenomena;
- improvements in sensors and measurements in order to obtain reliable data at such frequencies and to verify compliance;
- increased understanding of any harmful and ageing effects these high-frequency harmonics could have on different assets and installations.

8.8.2 IEEE Std 519-2014 [7]

IEEE Std 519 [7] is a "recommended practice" which suggests harmonic limits but does not mandate them. However, harmonic limits established by utilities and TSOs for HVDC projects are often modeled upon [7]. The fundamental assumption of this standard is that the "load" is responsible for current harmonics, and the utility is responsible for controlling voltage harmonics. The limits in this recommended practice represent a shared responsibility for harmonic control among owners, operators and users of a power system.

The load harmonic current limits recommended by [7] for transmission voltage greater than 161 kV and short-circuit ratio of less than 25 (parameters covering almost all conceivable HVDC installations) are shown in Table 3.

Table 3 – Current limits for system rated > 161 kV

$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
1,0 %	0,5 %	0,38 %	0,15 %	0,1 %	1,5 %
SOURCE: Table 4 of IEEE Std 519-2014 [7].					
Key					
TDD total demand distortion, expressed as a percentage of maximum load current					

The above limits pertain only to odd integer harmonics. Even order integer harmonics are limited to 25 % of the values shown.

The voltage harmonic limits recommended by [7] are 1 % of fundamental for individual harmonic distortion of all orders up to 50, and a voltage THD limit of 1,5 %. However, [7] also states that "high-voltage systems can have up to 2,0 % THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user."

Regarding interharmonics, IEEE Std 519 [7] states:

"For interharmonic current components with frequencies which are not integer multiples of the power frequency, users should limit the components to sufficiently low levels so as to not produce undesirable effects on the power system and connected equipment. Limiting values and appropriate statistical indices should be developed on a case-by-case basis starting from the guidance of Annex A and considering the specifics of the supply system, connected user loads, and provisions for other users."

8.8.3 Shortcomings in the context of VSC

Both of standards listed in 8.8.1, and others derived from them, give insufficient or inappropriate guidance with respect to VSC HVDC in the following areas:

- even harmonics;
- higher frequency harmonics (above 50th order);
- interharmonics.

The following Subclauses 8.9 to 8.11 deal with each of these in turn.

8.9 Even order harmonic limits

The even order harmonic limitations of IEC TR 61000-3-6 [5] and IEEE Std 519 [7], except in the low-order range, appear to be without sufficient technical basis. Firstly, note the wide discrepancy in the magnitudes between standards: for example for a transmission level HVDC system, at second harmonic, IEC TR 61000-3-6 [5] gives a limit of 0,8 % voltage distortion while IEEE Std 519 [7] gives 1 % voltage distortion and 0,25 % current harmonic distortion. While the current and voltage limits are not directly comparable between the two standards, there is clearly a significant difference, and considering that the affected consumer and utility equipment should be similar in both environments, the implication may be that the limits in one or both of these standards are unjustified.

The concern that originally drove the limits on even order harmonics is the characteristic of diode rectifiers and LCCs to demodulate even harmonics into direct current, which can then saturate transformers. This is a valid concern for second harmonic. However, because the harmonic current should be driven through a predominately inductive path for this demodulation to occur, the vulnerability decreases with harmonic order. It would take approximately twice the amount of fourth harmonic voltage distortion to cause the same impact as a given amount of second harmonic, and four times the amount of eighth harmonic relative to the second. Thus, this requirement appears to have no basis above the 8th harmonic. Additionally, at the very high harmonic orders characteristic of VSC, the IEEE Std 519 [7] requirement for even order current harmonics to be no more than 25 % of the adjacent odd harmonic limits results in a limit that is practically unmeasurable.

It is therefore recommended that harmonic limits for even order harmonics should be set as high as possible within the boundaries of the relevant standards which have to be respected.

Furthermore, it is recommended that future revisions of the relevant standards should consider that unnecessarily low limits on even order harmonics, particularly at higher frequencies, may be a restricting factor for VSC technology. The rationale for such limits should be reconsidered, and if no deleterious impacts can be identified, then it is proposed that for the higher orders, typical of VSC, the even order individual harmonic limits should be equal to the limit for the adjacent odd harmonic of the next higher order.

8.10 Interharmonics

8.10.1 General

Over recent years, new VSC technologies have been introduced whose harmonic spectrum is often characterised by interharmonics as well as integer harmonics. Considering that VSC HVDC projects and wind power are becoming more numerous worldwide and of higher rated

power, interharmonics can no longer be neglected or be considered on a case by case basis. Interharmonics should be considered as significant as integer harmonics for VSC by utilities and standards organisations.

8.10.2 Treatment of interharmonics in existing standards

8.10.2.1 General

The guidance included in relevant IEC and IEEE standards is outlined below, with discussion of how this might be applied in the practice of TSOs when setting planning levels and allocating limits for VSC HVDC projects.

8.10.2.2 IEC standards

Except for considering the effect of interharmonics as a possible cause of flicker through the modulation that they can cause on the fundamental voltage (a phenomenon which is already addressed by flicker limits), the IEC standards do not define compatibility levels for interharmonics. The main reason given is that existing data collection and analysis were not sufficient to arrive at the necessary consensus to set a standard.

The following reasons justifying the need to restrict the level of interharmonic voltages are given in IEC TR 61000-3-6 [5] and are summarized in Table 4.

- Below twice the fundamental frequency, interharmonics should be limited to 0,2 % to avoid flicker problems with incandescent and fluorescent (thin tubes) lamps. If higher values are permitted, the interharmonic frequencies should not exceed the flicker limit.
- Ripple control receivers may be disturbed if the minimal functional voltage exceeds 0,3 %.
- In the frequency range up to 2,5 kHz, the interharmonic voltages should not exceed 0,5 % if problems of interference with the following items of equipment are to be avoided: television sets, induction rotating machines and frequency relays.
- In the range from 2,5 kHz up to 5 kHz, 0,3 % should not be exceeded in order to avoid audible noise, for example in radio receivers and other audio equipment.
- In order to avoid problems of mechanical resonance, it is necessary to take particular care when interharmonics, mainly sub-harmonics, are present near rotating machines. This can adversely affect steam turbine generators in particular. Sub-harmonic current levels of 0,1 % or less have been sufficient to create problems in the past in some cases involving mechanical resonance. Therefore, the recommended 0,2 % interharmonic voltage limit may be reduced or, alternatively, the generator manufacturer may be consulted to determine if control system design modifications are a possible solution to avoid potential mechanical resonance problems.

Table 4 – Summary of IEC TR 61000-3-6 [5] recommended voltage planning levels

Frequency range	Voltage limit %	Reason
$f < 2 \times f_{\text{fundamental}}$	0,2	Flicker problems with incandescent and fluorescent (thin tubes) lamps
$f = f_{\text{ripple_control}}^{\text{a}}$	0,3	Ripple control receivers may be disturbed
$f < 2,5 \text{ kHz}$	0,5	Interference with: television sets, induction rotating machines (audible noise and vibrations) and frequency relays
$2,5 \text{ kHz} < f < 5 \text{ kHz}$	0,3	To avoid audible noise (e.g. radio receivers and other audio equipment)
^a Single frequency used is generally in the range 100 Hz to 3 000 Hz.		

IEC TR 61000-3-6 [5] then states that, with respect to these effects, a conservative planning level for interharmonics can be set to 0,2 %. This level is certainly conservative, but may be considered unnecessarily so in the context of VSC technology which typically produces interharmonics within the < 2,5 kHz range where, according to Table 4, a 0,5 % limit is considered adequate with the exception of frequencies below the second harmonic and specific ripple control frequencies.

The final point above, regarding mechanical resonance, is only relevant to very low-order harmonics and therefore not of concern for HVDC VSC technology.

Note that [5] does not indicate if these individual limits should apply to every single interharmonic frequency, in the case that there are multiple such interharmonics between two adjacent integer harmonics. It is assumed that the recommendations of IEC 61000-4-7 [3] on grouping of interharmonics (as discussed in 8.10.2.3 below) would apply, and therefore the respective limits would apply to the total value of the grouped interharmonics.

Utilities should also consider that any interharmonic voltage from an installation below 0,1 % is not considered as a disturbance as stated in IEC TR 61000-3-6 [5]. Furthermore, interharmonic limits should not be set to such low values that are almost impossible to measure or that would require installation of unnecessary filtering.

In Annex B of IEC 61000-2-12:2003 [22] (applicable to MV networks), there is a statement that interharmonics should not be allowed to proliferate without any limits, to avoid creating unknown problems which could be difficult to solve thereafter. In that respect, IEC 61000-2-12 [22] suggests limiting the levels of interharmonics in MV networks to reference values not exceeding compatibility levels of the next upper even harmonic (for example interharmonic 4,5 will have the same limit as harmonic 6).

8.10.2.3 IEEE standard

IEEE Std 519 [7] only suggests voltage limits for interharmonics in the range below 120 Hz, where flicker can be an issue. There are no limits and no guidance for higher frequency interharmonics of interest in the context of VSC, except for a general statement that due consideration should be given and limits developed on a case-by-case basis.

8.10.3 Discussion and recommendations

For interharmonics, there is no physical reason to give different limits than for integer harmonics, except where specific frequencies are being used for other applications. Specific examples include metering, ripple control or communication, and automatic meter reading (AMR) systems which could be affected by a wide range of interharmonics. A good understanding of the relevant operational frequencies and the levels of immunity of these systems is essential to prevent interference.

In future years, it is essential that a consensus is reached in standards to address interharmonics as they cannot be neglected for VSCs. One goal of this document is to open the discussion in standard organisations so interharmonics are covered with the same importance as integer harmonics.

In the meantime, utilities may write their own specifications in the absence of official standardized limits. The recommendations based on IEC TR 61000-3-6 [5], outlined above, can be used to prepare the specification.

For example, a Canadian utility has used the following planning levels of interharmonics for the past few years in multiple projects.

- In the frequency range up to 2,5 kHz, the planning levels for interharmonic voltages should not exceed 0,5 % [5] or the planning level of the nearest even order harmonic (inspired by

IEC 61000-2-12 [22]). The individual limits for individual installations are lower than the overall planning levels.

- The flicker limit is believed to be sufficient and no additional limits should be applied for subsynchronous interharmonics (mechanical resonance is typically not a problem for this utility).
- No special limit is necessary for ripple control because it is not used by this utility.

This document makes the following recommendations to assist utilities when specifying interharmonic limits, which balance protecting network users and the practicalities of VSC design.

- The existing international recommendations should be used as much as possible in specifying the interharmonic limits, but interpreted and adapted in accordance with the above discussion.
- Any particularly stringent interharmonic limits should be accompanied by a justification for why such stringency is desired. Discussion between the TSO and the HVDC supplier will facilitate appropriate decision making in the early stages of the VSC design.
- An allowance of some flexibility is recommended among individual interharmonic limits to permit exceptionally high values at some frequencies, possibly at the expense of others.
- Allowance of a flexible approach with regard to minor infringements of particular frequencies.

If the limits for individual interharmonics are to be increased, it may be necessary to consider the introduction of a "total interharmonic distortion" limit to correspond to the normal THD, as interharmonics are not included in the definition of THD in the IEC standards.

Furthermore, it is recommended that future revisions of the relevant standards should consider that unnecessarily low limits or recommendations regarding interharmonics may be a restricting factor for VSC technology. The rationale for any limits or recommendations should be reconsidered, and if no deleterious impacts can be identified, then it is proposed that for the interharmonic orders typical of VSC, no unnecessary restrictions should be applied.

8.11 Interharmonics discretization and grouping methodologies

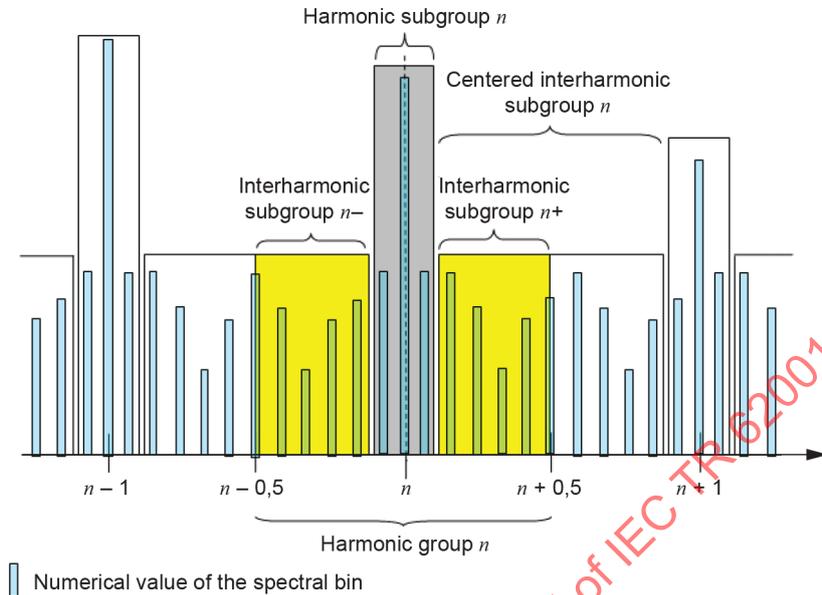
8.11.1 Suggested method

When studying or measuring interharmonics, the harmonic spectrum has to be considered as being continuous over all the frequency range. In order to facilitate numerical evaluation of such a continuous spectrum, discretization is necessary. The appropriate numerical methods are defined in IEC 61000-4-7 [3]. The frequency analysis should be performed with a resolution of 5 Hz. This analysis gives discrete numerical values at each 5 Hz spectral "bin".

In order to facilitate measurements and studies and to define limits, a grouping methodology of the spectral bins should be used. A suggested methodology is presented in Figure 41 and was shown to be effective in multiple projects of a Canadian utility. This methodology is inspired by the standard on the testing and measurement techniques of harmonics and interharmonics [3].

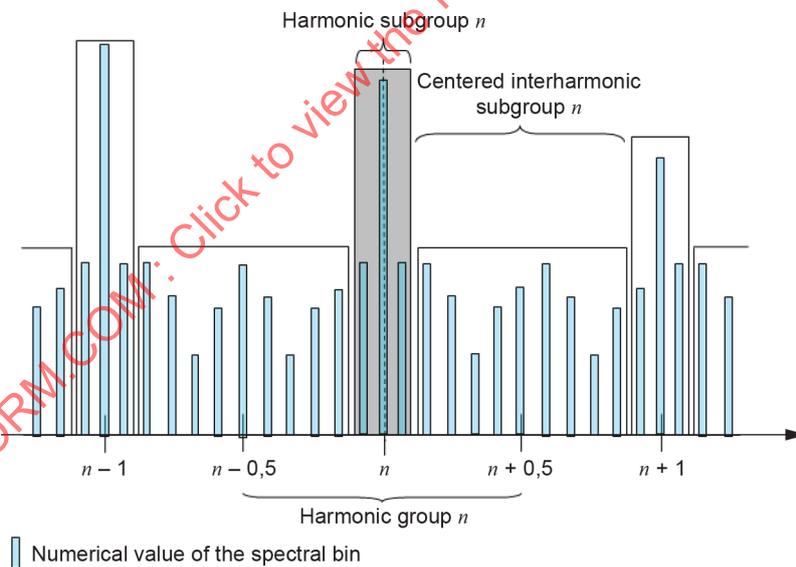
The main difference from [3] (illustrated in Figure 42) is the creation of interharmonic subgroups $n-$ and $n+$. This grouping methodology was developed to facilitate harmonic studies using common harmonic impedance loci (same impedance loci for harmonics and interharmonics) calculated from order " $n - 0,5$ " to " $n + 0,5$ ". Even if the same impedance loci are used, it is possible to have distinct limits and calculations for harmonics and interharmonics. By having more categories, this grouping methodology is also more flexible in the definition of limits by allowing the combination of multiple groups and subgroups.

The results from studies made according to this proposed methodology are still fully compliant with [3] measurements since the same subgroups still exist. However, the addition of subgroup $n-$ and $n+$ in a future revision of [3] is recommended as it would provide valuable information to facilitate studies without any added drawback.



IEC

Figure 41 – Proposed grouping methodology



IEC

Figure 42 – Comparison with grouping methodology of IEC 61000-4-7 [3]

Harmonic subgroup n : The harmonic subgroup n is made of harmonic n and of the two adjacent spectral bins. The RMS amplitude (I_n and V_n) of a harmonic subgroup is the square-root of the quadratic sum of the RMS amplitude value of the integer harmonic and the adjacent bins.

Interharmonic subgroups $n-$ and $n+$: The interharmonic subgroups are defined as the lower subgroup $n-$ and the upper subgroup $n+$. The subgroup $n-$ includes frequencies between the median frequency of two harmonics and the lower border of the harmonic subgroup n . Conversely, the subgroup $n+$ includes frequencies between the upper border of the harmonic subgroup n and the upper median frequency. Therefore, each spectral bin median frequency is

shared between two subgroups. The spectral bin amplitude of the median frequency allocated to each subgroup is equal to the amplitude divided by the square-root of 2. The RMS amplitude of an interharmonic subgroup (I_{n-} , I_{n+} , V_{n-} , V_{n+}) is the square root of the quadratic sum of the spectral lines included in the subgroup.

Centred interharmonic subgroup n : The centred interharmonic subgroup n includes the interharmonic subgroup $n+$ and the interharmonic subgroup $(n + 1)$, as shown in Figure 43. It includes all interharmonic components between two consecutive harmonic frequencies excluding those bins immediately adjacent to the integer harmonic. The RMS value of the amplitude of the centred interharmonic subgroup (I_{IH_n} and V_{IH_n}) is obtained using the following formulae:

$$V_{IH_n} = \sqrt{V_{n+}^2 + V_{(n+1)-}^2} \quad n = 1, 2, 3, 4 \dots 50 \quad (8)$$

$$I_{IH_n} = \sqrt{I_{n+}^2 + I_{(n+1)-}^2} \quad n = 1, 2, 3, 4 \dots 50 \quad (9)$$

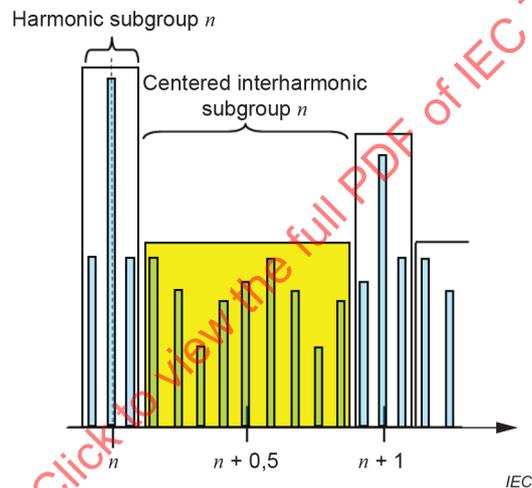


Figure 43 – Centred harmonic subgroup

Harmonic group n : The harmonic group n includes the harmonic subgroup n and both interharmonic subgroups $n-$ and $n+$, as shown in Figure 44. It corresponds to all the spectral bins associated with a given integer harmonic. The RMS amplitude value of the harmonic group (I_{H_n} and V_{H_n}) is obtained with the square root of the quadratic sum of the RMS amplitude of the three subgroups:

$$I_{H_n} = \sqrt{I_{n-}^2 + I_n^2 + I_{n+}^2} \quad n = 1, 2, 3, 4 \dots 50 \quad (10)$$

$$V_{H_n} = \sqrt{V_{n-}^2 + V_n^2 + V_{n+}^2} \quad n = 1, 2, 3, 4 \dots 50 \quad (11)$$

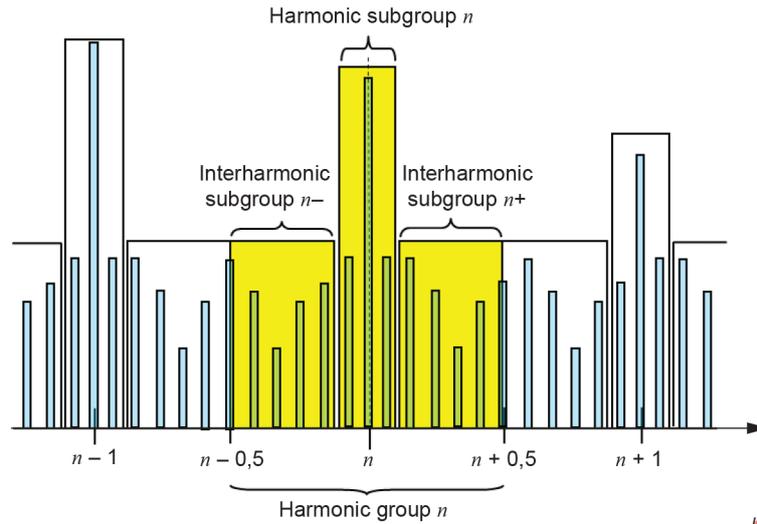


Figure 44 – Harmonic group

8.11.2 Power quality indices for interharmonic grouping

Using the proposed grouping methodology, it is now possible to calculate power quality factors and to compare with limits defined by the utility.

The individual harmonic distortion factor should be calculated using the harmonic group and compared with applicable limits for integer harmonics (a less conservative approach would be to use the harmonic subgroup instead):

- Individual harmonic distortion factor

$$DIH_n = \left(\frac{IH_n}{I_1} \right) \times 100 \% \tag{12}$$

$$DVH_n = \left(\frac{VH_n}{V_1} \right) \times 100 \% \tag{13}$$

The individual distortion factor of the centred interharmonic subgroup should be compared with applicable limits for interharmonics:

- Individual distortion factor of the centred interharmonic subgroup n

$$DIIH_n = \left(\frac{IIH_n}{I_1} \right) \times 100 \% \tag{14}$$

$$DVIIH_n = \left(\frac{VIIH_n}{V_1} \right) \times 100 \% \tag{15}$$

The global factors, such as the total harmonic distortion (THD) and the telephone influence factor (TIF), should be calculated using the harmonic group that take into consideration the effects of integer harmonics and interharmonics. As an example, the total harmonic distortion THD is calculated using Formula (16):

(16)

$$THD = \sqrt{\sum_{n=2}^{50} VH_n^2} \times \frac{100\%}{V_1}$$

where

VH_n is the phase-to-ground RMS magnitude value of harmonic group n at the bus,

V_1 is the phase-to-ground nominal voltage of the system.

8.11.3 Network impedance loci for interharmonic grouping

It is well known that utilities or TSOs should provide network harmonic impedance envelopes for the harmonic performance and rating assessments. CIGRE Technical Brochure 553 [9] and [13] provide many guidelines on the topic that are still valid in the context of a VSC.

However, it is necessary to modify some practices to take into account interharmonics. This document recommends in 8.11.3 a simple approach to achieve this goal without making major changes to current practices.

Since there is no standard or unique way to determine envelope characteristics, a method in compliance with [9] is described here.

For whatever band of harmonic orders is chosen for a particular envelope, some care is also needed to ensure that data relating to frequencies immediately above and below that band is also included in deriving the characteristics of the envelope. This is to take account of the effects of the variation of network frequency from the nominal value (both steady state and those applicable to short time rating), tolerances of the input data parameters, other uncertainties in data and assumptions, and also the fact that at higher order harmonics the modelling itself becomes increasingly less accurate.

To take into account these uncertainties, it is recommended to use a tolerance in percentage of the studied harmonic, rather than a fixed number of harmonic orders or hertz, so the impact increases proportionally with respect to harmonic order.

Figure 45 shows the range of frequencies at each individual harmonic order envelope as typically considered in an LCC project. Only low-order harmonics are shown but it should be noted that overlaps between harmonic orders will occur at higher frequencies. In fact, an envelope at a high order harmonic will include one or more adjacent order on each side. For example, a tolerance of $\pm 5\%$ at the 40th harmonic on a 50 Hz network equals ± 100 Hz or 2 harmonic orders.

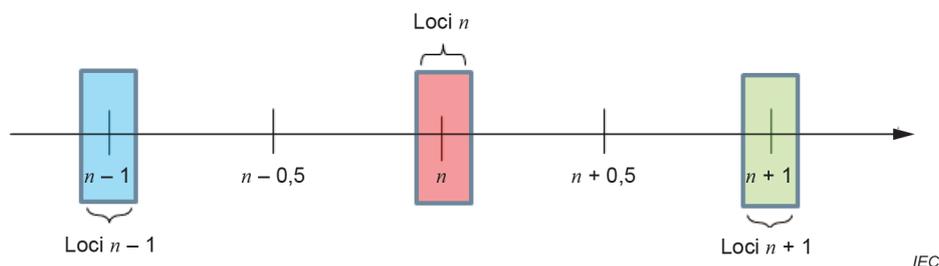


Figure 45 – Harmonic impedance frequency ranges for LCC

This method is not applicable to VSC since interharmonics should also be considered. For a study involving interharmonics, the network impedance should be calculated over the whole frequency range and not only at integer harmonics as illustrated in Figure 45.

In compliance with the proposed grouping methodology, the recommended approach is to scan the impedance of the network between two median frequencies and add a tolerance to allow for the inaccuracies (e.g. modeling, tap changer position, aging of components). For example, a frequency scan between 125 Hz and 175 Hz will be done for the third harmonic on a 50 Hz network and a 5 % tolerance will extend the range from 119 Hz to 184 Hz. Figure 46 illustrates the concept.

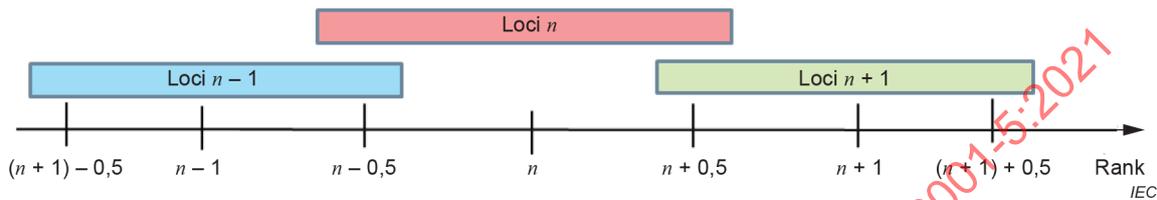


Figure 46 – Harmonic impedance frequency ranges for VSC with proposed methodology

Using a grouping methodology according to IEC 61000-4-7 [3] would lead a utility to evaluate specifically and separately envelopes for interharmonics and integer harmonics that would give, in theory, more precision in the assessment, but would also add more complexity (Figure 47). Softwares and tools that are being used by utilities and TSOs could also need modification to take into account these new envelopes.

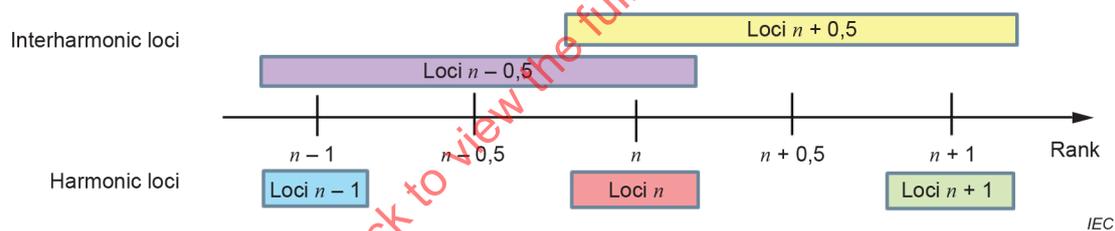


Figure 47 – Harmonic impedance frequency ranges for VSC with IEC 61000-4-7 grouping methodology

Taking into consideration the limitations and uncertainties involved in the calculation of harmonic envelopes, the suggested grouping methodology is an effective compromise between precision and complexity. The addition of subgroups $n-$ and $n+$ in a future revision of IEC 61000-4-7 [3] is recommended as it would provide valuable information to facilitate studies without any added drawback.

8.12 Assessment as a harmonic voltage or current source

IEEE Std 519 [7] assumes that all distorting devices are harmonic current sources, and IEC TR 61000-3-6 [5] also infers that the new connection is a source of harmonic current. This is a reasonably good assumption in most cases for line commutated converters, but may be a questionable assumption for VSC.

A VSC is most accurately represented as a voltage source behind an impedance, and thus the harmonic current is strongly a function of the harmonic impedance of the grid to which it is connected. The harmonic current output is therefore not something over which the VSC owner has direct control. To implement a harmonic current limit on its output therefore requires that the network harmonic impedance be known and used together with the VSC generated harmonic voltage source to calculate the harmonic current output. Typically, network impedance envelopes would be provided to facilitate the design process.

This is the converse of the normal procedure for LCCs, where the harmonic voltage distortion at the PCC is calculated from the LCC harmonic current source and the network and filter impedances. However, to calculate the harmonic current output from a complete LCC station, including filters, would also require knowledge of the network impedance.

In conclusion, there is little practical impact of whether the VSC is regarded as a harmonic current source or voltage source by the standards. In either case, it is necessary to take into account the network impedance when calculating the voltage or current distortion at the PCC.

It is recommended that future revisions of relevant standards and grid codes do not base their methodologies for setting limits or assessing compliance on an assumption that the connected installation will behave as either a current source or a voltage source.

8.13 Assessment of THD, TIF, THFF, IT

There are several harmonic voltage performance parameters which use an aggregate of individual harmonic values over the complete frequency range being considered. The aggregate may be defined as a linear sum or a quadratic (RMS) sum. The latter is normally used in the definition of the parameters total harmonic distortion (THD), and the telephone interference parameters TIF, THFF and IT-product.

The worst-case voltage distortion at each harmonic will occur in the case of the worst-case network impedance taken from a specified harmonic impedance envelope. It is unreasonable to consider that the worst-case network impedances can occur simultaneously for all harmonics, as the envelope will typically correspond to many different configurations and load states. To do so would result in a calculated value for these parameters far higher than could occur in practice. There is however no purely consistent way to calculate, when only a network envelope is specified rather than the separate consistent harmonic impedances for each configuration modelled. In LCC HVDC station design, it has been normal to assume a rather arbitrary criterion, typically expressed as:

"THD, TIF, THFF should be calculated with AC network impedance connected at the two harmonics which result in the highest value of that parameter and at all other harmonics the AC system harmonic impedance should be considered to be an open circuit" [11], [41].

This approach tended to give reasonable results for LCC, where usually only a few individual harmonics would have outstandingly significant values. For VSC however, especially for multi-level converters, there is typically a wide band of many low-magnitude harmonics and interharmonics. To select only two of these corresponding to the worst-case network would give unrealistically low values of the total parameter. Also, considering the network as open-circuit for other harmonics does not make sense when there are no AC filters – there would be no current flow at all in such a case and the full internal converter harmonic voltage would be seen at the PCC.

A different formulation of a similar principle would therefore be desirable in the case of VSC HVDC and it is recommended that future Technical Specifications for VSC projects should take this into account. However, this document does not make any specific recommendation for a methodology, as any such recommendation would be arbitrary, and as different approaches might apply to different technologies and projects.

Given the very low level of harmonic emission from modern VSCs, it is possibly unlikely that magnitudes of these aggregate parameters would in fact exceed the specified limits, even if the worst-case network impedance were to be considered for each harmonic. A reasonable approach may therefore be to make initial calculations considering simultaneous worst-case network impedances at every frequency, and only then, if the resulting total value of one of these parameters is problematic, should some methodology for calculating a more realistic value be jointly considered by the parties involved.

Similar considerations can be applied to the psophometric weighted harmonic current parameter I_T , with the difference that the worst-case values for harmonic current flow (rather than for harmonic voltage) are obtained for different network impedances [11], [41].

8.14 Measurement and verification of harmonic compliance

Measurements of harmonic distortion should be undertaken both before the tender phase of the HVDC station, and during its commissioning and trials. The following practices are not unique to VSCs. However, because of their importance and relevance to the topic of Clause 8, they are restated here.

Pre-tender, the objective is to measure background harmonic distortion which exists before the connection of the HVDC station. This background harmonic distortion is provided to HVDC suppliers together with the harmonic limits the station should respect.

During commissioning and trial operation, harmonic measurements are performed once the HVDC converter is built to check if its harmonic performance respects the specified limits.

IEC 61000-1-2 [4] and its reference give some recommendations on how to perform harmonic measurements. Further detailed information may be found in:

- IEC 61000-4-7 [3],
- IEC 61000-4-30 [42], and
- IEC TR 61869-103 [43].

The choice of voltage measuring transducer is of importance to guarantee the required accuracy for harmonic voltage measurements. Detailed information is provided in [9], [11] and [44].

For all equipment, low harmonic amplitudes are difficult to measure. Inaccuracy usually occurs for amplitudes below 0,2 % of the fundamental. Therefore, it may be difficult to verify low limits during the commissioning of the converter or later during its operation. This is especially true for even orders or those of multiples of three, which are almost non-existent in traditional power systems. In the case of VSC HVDC, the low magnitudes of interharmonic frequencies and higher order harmonics may be particularly difficult to measure and verify.

Regarding verification of harmonic compliance through measurement, it should be recognized that an installation could be correctly designed according to a customer's technical specification and yet result in measured harmonic distortion above the specified limits. In such cases, the following may be possible reasons.

- The actual network impedance at the time of measurement may fall outside the impedance loci provided by the customer for design purposes. This may be due to changes in the network itself that were not considered during the preparation of the network impedance data.
- Inaccuracies due to modelling tolerances in the preparation of these network impedance loci.
- The actual phasor addition of background harmonic voltages with those resulting from the new connection may be aggregated in a more linear relation than implied by the aggregation rule and exponent as used in the harmonic specification.
- The pre-existing harmonics at the time of compliance measurement may be different to those assumed for the harmonic performance assessment, which may have been taken at a previous time under different network conditions and loading.

These reasons apply equally to an LCC installation, but may be relatively more significant in the context of VSC because of the very low levels of distortion that may need to be verified.

8.15 Recommendations

The recommendations made throughout Clause 8 are summarized below.

Recommendations regarding the future revision of standards:

- **Even order harmonics:** Future revisions of the relevant standards should consider that unnecessarily low limits on even order harmonics, particularly at higher frequencies, may be a restricting factor for VSC technology. The rationale for such limits should be reconsidered, and if no deleterious impacts can be identified, then it is proposed that for the higher orders, typical of VSC, limits could be increased.
- **Higher frequency harmonics:** It is recommended that in setting limits for higher order harmonics, the present day VSC technology should not be unduly constrained due to an approach of limiting higher order harmonics as a precaution against unknown future issues.

There appear to be no known justifications for lower limits to be imposed for harmonics above the 50th order than those implemented at and around the 50th order.

If future standards extend the frequency range at which harmonic limits are mandatory, then for such limits to be meaningful, the techniques and data for accurate network representation at such frequencies will also have to improve, as well as means for accurate measurements of such frequencies at HV and EHV level.

- **Interharmonics:** Interharmonic limits should be set on a frequency-dependent basis according to Clause 10 of IEC 61000-3-6:2008 [5] and the statement "With respect to these effects, a conservative planning level for interharmonics can be set to 0,2 %" should be removed from that standard.

The addition of subgroups $n-$ and $n+$ in a future revision of IEC 61000-4-7 [3] is recommended as it would provide valuable information to facilitate studies without any added drawback.

The total harmonic distortion index should be modified to include interharmonics, or a separate index defined to limit the total amount of interharmonic distortion permitted.

- **Current source or voltage source:** It is recommended that future revisions of relevant standards and grid codes do not base their methodologies for setting limits or assessing compliance on an assumption that the connected installation will behave as either a current source or a voltage source.

Recommendations regarding practice by TSOs and other relevant bodies:

- **General:** It is recommended that, even if TSOs prefer to allocate a smaller proportion of the available headroom to a new VSC connection than would be the case for another non-linear installation of similar size, the limits chosen should take into account the feasible realistic performance of the VSC technology being considered.

When defining harmonic limits, a network operator should consider why a particular limit or a specific range of frequencies is specified, and ensure that the requirements are really pertinent to its network.

No assumption should be made regarding the nature of the installation as a current source or voltage source.

- **Even order harmonics:** Harmonic limits for even order harmonics should be set as high as possible within the boundaries of the relevant standards which have to be respected.
- **Higher order harmonics:** In setting limits for higher order harmonics (above h50), the present day VSC technology should not be unduly constrained due to an approach of limiting higher order harmonics as a precaution against unknown future issues.

It is suggested that, in order to allow at least a qualitative assessment of harmonic issues at higher frequencies, the HVDC supplier is asked to provide the emitted spectra over the full range of frequencies of significant magnitude, where this range will depend on the VSC technology being used.

- **Interharmonics:** The following recommendations are given to assist utilities when specifying interharmonic limits and to help achieving realistic design.
 - The existing international recommendations may be used as much as possible in specifying the limits, but interpreted and adapted according to the above discussion.
 - Any particularly stringent limits should have a motivation why such a level is desired. Discussion between the TSO and the HVDC supplier will facilitate appropriate decisions in early stages of the VSC design.
 - Allowance of some flexibility among individual interharmonic limits to permit exceptionally high values at some particular frequencies, perhaps at the expense of others.
 - Allowance of a flexible approach with regard to minor infringements of particular frequencies. It may be achieved through mutual customer-contractor discussions.

It is suggested that interharmonic limits should be set on a frequency-dependent basis according to Clause 10 of IEC 61000-3-6:2008 [5] and the statement in that document "With respect to these effects, a conservative planning level for interharmonics can be set to 0,2 %" should be disregarded.

The introduction of interharmonic subgroups $n-$ and $n+$ is suggested as it would provide valuable information to facilitate studies.

9 Harmonic mitigation techniques

9.1 General

The level of harmonic distortion caused by connection and operation of a VSC HVDC is generally very low, compared to an LCC HVDC of similar rating. Nevertheless, the converter station has to satisfy limits on permissible distortion imposed by the system operator, which may be low enough to require mitigation measures to be taken at the converter station. Clause 8 discusses the justification for such limits and appropriate levels.

Mitigation of any adverse harmonic impact of a VSC on the AC system to which it is connected may be achieved either by means of passive filters, or by active filtering or damping by the converter, or a mixture of techniques.

It should be made clear that the term "active filtering" as used here is achieved by introducing suitable signals into the controls of the VSC itself. It does not mean the introduction of separate "active filter" equipment, based on a passive branch in series with a power amplifier, similar to those installed on some LCC HVDC schemes in the 1990s but which were eventually discontinued for a number of practical reasons [45].

9.2 Passive filtering

Early generations of VSC HVDC schemes using switch-type valves were all equipped with passive AC filters [46], [47]. The filter bank sizes were very small (considered either in Mvar or % of converter power rating) compared to those required for a line commutated converter and were typically tuned to, or around, the switching frequency. Importantly, the filter remained connected throughout the converter power range.

More recent VSC schemes have been designed both with and without AC filters. Where such filters are installed, they are very small high pass filters with low q -factor (typically $q < 3$) in order to provide wide spectrum damping and reduce the risk of possible resonances which may become an issue in terms of harmonic stability. Typically, such filters are installed due to especially stringent design requirements with respect to limits and/or pre-conditions. Their purpose is to mitigate the intrinsic harmonic generation of the converter, or to reduce the amplification of pre-existing harmonics, or both.

Filtering at low harmonic orders ($h < 10$) would normally only be required if it were necessary to mitigate the amplification of pre-existing harmonic distortion from the supply network, rather than the inherent harmonic generation of the converter.

Optimum performance of AC filters is achieved by locating them at the point where harmonics are being evaluated, i.e. the network (primary) side of the converter transformer (see Figure 48) as in LCC schemes or most recent VSC schemes. Sometimes, there are practical limitations for the point of evaluation being inaccessible for installation of new filters and under such circumstances filters may be located at an accessible point closest to evaluation point, possibly at the cost of poorer harmonic performance at the actual point of evaluation.

Some early VSC HVDC schemes used filters located at the converter (secondary) side of the transformer, i.e. between the converter transformer and the VSC (see Figure 49) mainly to reduce harmonic stresses on converter transformer and to achieve a compact footprint. However, the optimum location for the filter is dependent upon the system design.

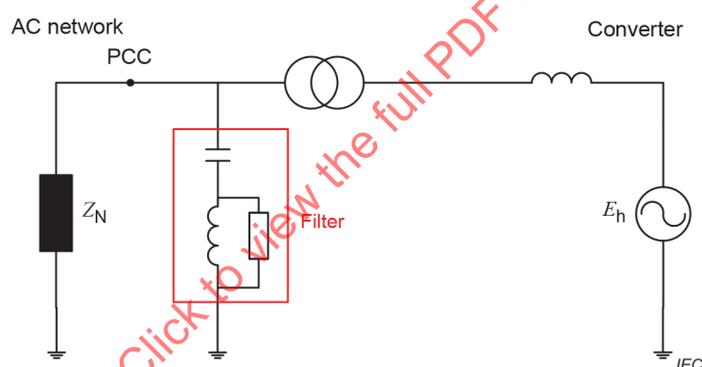


Figure 48 – AC filter located at primary (network) side of converter transformer

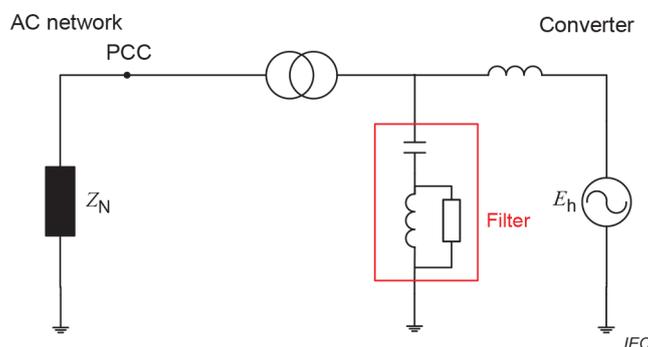


Figure 49 – AC filter located at the secondary (converter) side of converter transformer

The following can be disadvantages of passive filtering.

- Additional equipment which results in additional costs, lower reliability and greater space requirements.

- In the context of VSC HVDC installations, passive filters may need to be located within a screened building.

NOTE This could be because of pollution concerns, visual/architectural considerations, or to restrict the radiation of radio-frequency noise from the filter acting as an antenna for RF noise conducted from the converter, in locations where the limits on permitted RF noise are extremely low and conventional RF filtering is insufficiently effective.

Such an enclosure incurs added cost, and creates secondary issues such as heat dissipation from filter components and the possible fire-risk issues of locating oil-filled capacitors within a building.

- No flexibility in adjusting tuning frequencies or damping after purchase of components.
- The installation of passive filters creates new resonances in the grid. In case of a weakly damped grid with many converters, there is an increased risk of creating a resonance between one or more converters and the filters.

9.3 Active damping and active filtering by converter control

Besides the basic function of transmitting energy, the usefulness of a VSC can be supplemented by an active harmonic filtering or damping functionality, which is implemented in the higher level converter controls, or in the lower level control, depending on the phenomena [48]. For example in the case of weak grids with a high amount of cables, low order harmonic resonance with low damping may exist and active filtering or damping may be implemented to mitigate the resulting harmonic voltage at the PCC.

The two terms "active damping" and "active filtering" in the context of VSCs are often used interchangeably, and have overlapping meanings and implementation techniques. The broad distinctions between the terms may be thought of as follows. The term "active damping" is generally used to indicate a behaviour which is effective over a broad frequency range. The term "active filtering" is used for mitigation of specific harmonic frequencies or narrow frequency bands [49]. Both options have an upper frequency limit up to which they can be applied. This limit is dependent on the particular converter manufacturer and the technology used.

- Active damping can be envisaged as a "virtual resistor" providing additional network damping, which can be implemented in the upper level converter controls of a VSC. In Figure 3, it can be seen how the control of the HVDC converter works in regard to harmonics. By adapting the active converter impedance, the converter will create an opposing voltage to achieve the desired damping of the whole system (refer to Clause 6). The design and impedance value for this damping has to be calculated taking into account the current, the grid harmonic impedance and the level of the pre-existing harmonics. It is possible to use this method to mitigate distortion magnitudes at specific individual harmonics or over a broad frequency range.
- Active filtering can be envisaged in the same way as a conventional active filter, acting on pre-selected harmonics and creating a current or voltage in phase opposition to the existing distortion. Figure 3 shows the function of the controls and, in this case, instead of a broad frequency range as for active damping, just one or a few frequencies are included in the voltage signal. The maximum frequency for active damping and active filtering is restricted by the sampling rate of the control loop of the converter, including measurement, control and power hardware.

The negative impacts of either approach, for example higher converter losses or reduction of power transmission capability, have to be considered. In addition, control action to reduce one target harmonic may have the secondary effect of generating other harmonics, albeit of lower magnitudes. High level controls have a low bandwidth and cannot respond adequately to fast oscillations. Therefore, implementation of active techniques without fully considering the frequency response of the control system may risk interaction between the active function and grid resonances or other converter controls in the grid. To avoid such possible interactions, it should be investigated how the control behaves at grid resonances even in the higher frequency range. Active damping at one frequency range will tend to have a side-effect of reduced or even negative damping in another frequency range, as discussed in Clause 11. Additionally, the design of the active filtering and damping should be optimised to react appropriately, or not at

all, for transient events and not to act above a given frequency limit at which it may cease to contribute to damping and instead reinforce a resonance.

9.4 Optimization between passive and active mitigation

There is no general or favoured choice between passive and active mitigation techniques. Sometimes, a combination of the two may be the most robust solution. Active damping could, for example, add significant damping at lower frequencies while a small damped passive filter can be used to ensure positive output resistance to mitigate control interactions at higher frequencies.

Firstly, it is necessary to know and evaluate the harmonic environment in which the VSC station will operate, and the factors affecting the practicality and cost of mitigation measures. Some typical parameters are, for example, equipment cost, space and loss requirements, and the need for EMI shielding, which can all be monetized.

An optimised design for harmonic mitigation of a VSC HVDC scheme should consider the following factors.

- A low- q passive filter can provide damping over a wide range of frequencies with no upper limit (within the normal range of harmonic assessment).
- Passive filters require additional physical space, which can be especially costly if they have to be located indoors.
- The losses of a passive filter, even if it is small, may be significant mainly due to the pre-existing harmonics. If the filter is located indoors, this can be especially expensive as additional air-conditioning equipment may be required.
- Passive filters require additional auxiliary equipment (circuit breakers, current transformers, arresters) which all add to the capital cost, space requirements and maintenance costs.
- Active techniques have a limited upper frequency.
- Active techniques may increase the converter power losses.
- Active techniques may have an influence on the power transmission capability and dynamic performance of the converter. These factors should be considered in the overall design.
- Active techniques may create a risk of control interactions with other converters in the AC system. This needs to be recognized in the control design.

9.5 Specific mitigation issues and techniques

9.5.1 Unbalanced phase reactances or voltages

In harmonic studies for LCC HVDC, the unbalance between phase reactances due to converter transformer manufacturing tolerances has always been a significant factor in the generation of non-characteristic harmonics. Similarly, any unbalance of the network phase voltages (negative phase sequence) is responsible for the generation of a range of harmonic frequencies by LCCs. The relevance of these same factors for VSC harmonic generation is addressed below.

In a VSC installation employing controllable voltage source type valves (MMC, CTL), the converter valves are connected to the network by means of arm (or phase) reactors in each phase and, typically for high-power installations, three independent single-phase transformers, whose terminals are connected in the required star or delta configuration. The converter installation is sketched in Figure 50. Due to manufacturing tolerances, it is possible that the total phase reactance of reactors and transformers differs slightly between phases. As a consequence, the variations in those AC parameters controlled by the converter, and which are dependent on the phase reactance, can result in asymmetrical injections to the AC grid.

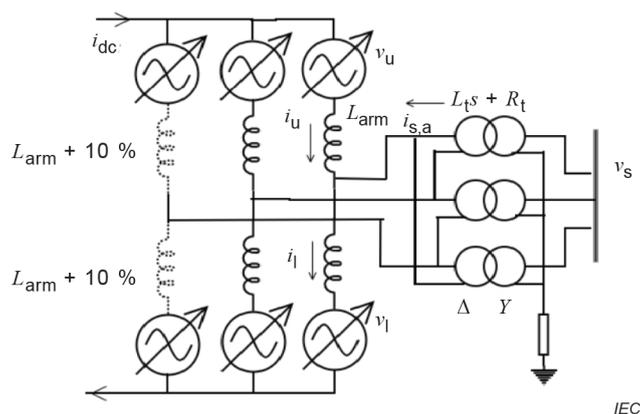


Figure 50 – Example of a converter station scheme with asymmetrical phase reactances

Unbalanced AC network phase voltages can appear due to various network conditions such as the connection of asymmetrical loads, long asymmetrical transmission lines, or unbalanced current injection from a given component.

The VSC synthesizes voltages at the converter terminals in order to define a power flow through the phase reactances. In common practice, these target voltages are achieved by controlling the phase currents, which follow a calculated current reference defined by the outer control loops. This scheme is sketched in Figure 51.

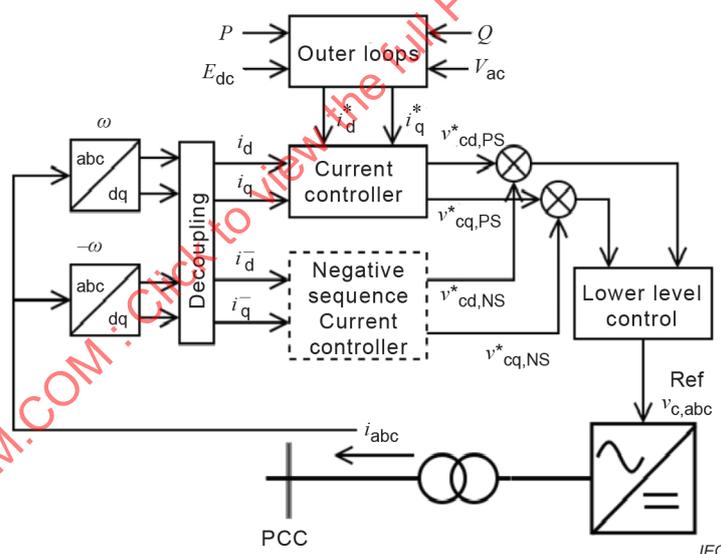


Figure 51 – Example of converter plant and control scheme

Commonly, the control is performed in dq domain. This means that the three-phase oscillating components of voltages and currents are transformed into DC components which follow a reference frame rotating at the grid frequency. In other words, the independent three-phase variables are converted into two components which represent a mean value for the three phases, related to the active and reactive components.

The control design of the dq components considers the phase reactance as the equivalent reactance in the dq domain and as consequence it considers the reactance of each phase as equal. This control scheme is depicted in Figure 52. Therefore, the resulting three-phase currents are controlled to the equivalent calculated values of i_d^{ref} and i_q^{ref} . This means that the three phase currents are controlled as if they were balanced and following a mean value of the three phases. As a consequence, in case of there being unbalanced phase reactances, the controlled output current per phase is unbalanced.

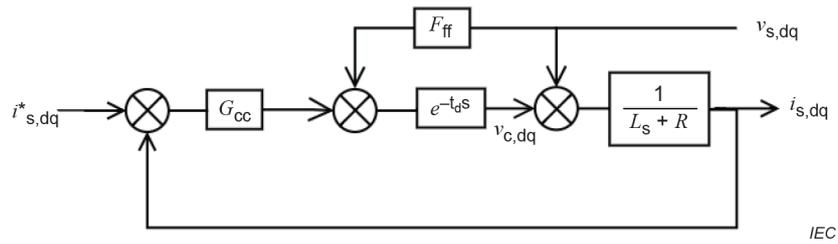
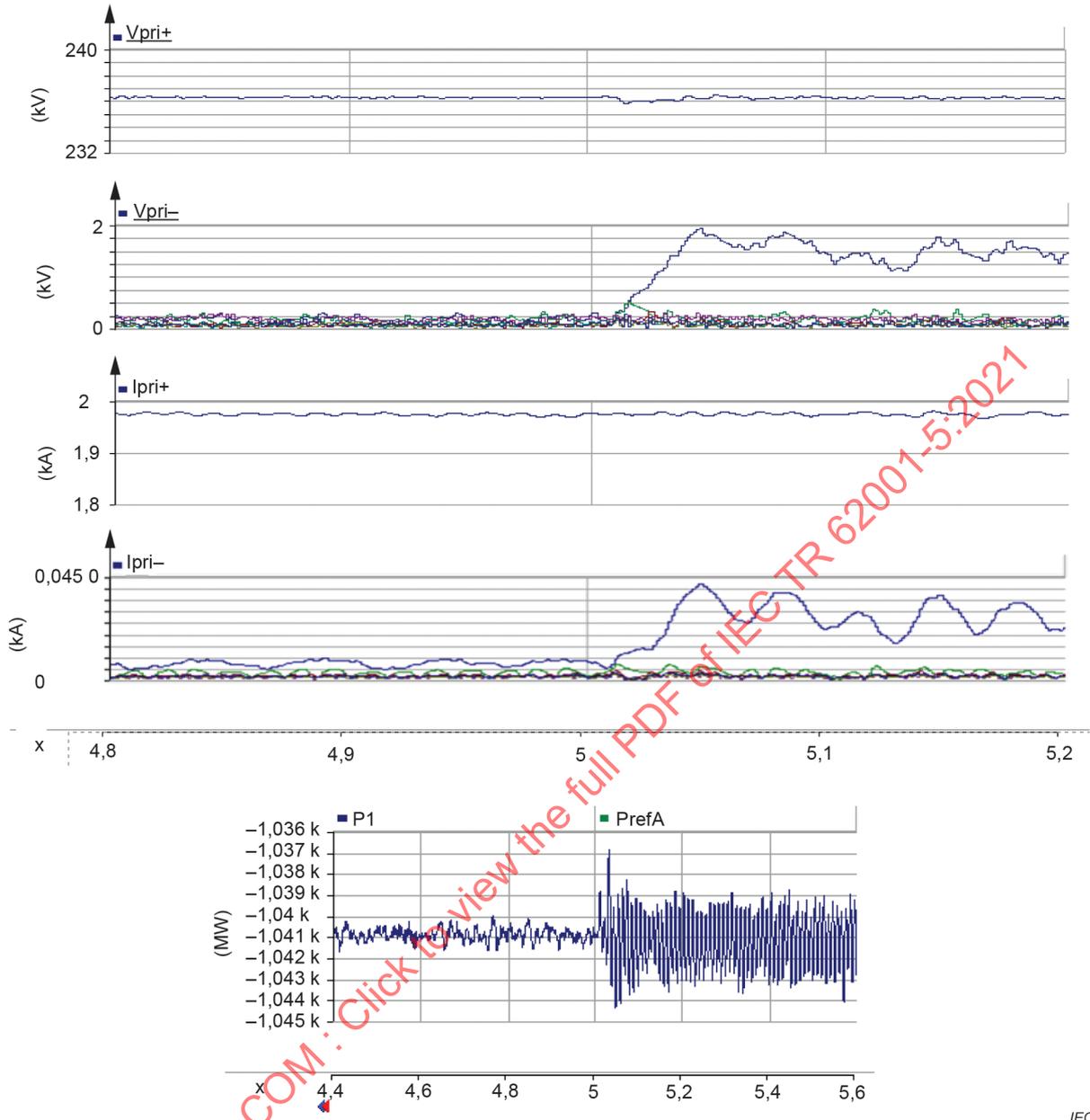


Figure 52 – Current control scheme

This is demonstrated by means of an EMT simulation whose results are shown in Figure 53 and Figure 54. During the simulation, the phase reactance in phase C is increased by 10 % at 5 s (this is higher than would occur in practice but is chosen for the simulation to demonstrate the impact clearly). Once the phase reactance in phase C is unbalanced, a negative sequence component appears in the primary voltage and current. The impact of this negative sequence component is visible as a second-harmonic oscillatory component in the active power.

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Figure 53 – Time-domain response of positive and negative sequence voltages and currents and active power when the converter does not compensate for effect of phase reactance unbalances

The implementation of such a control response can vary depending on the agreement between the customer and HVDC manufacturer regarding control of negative-sequence components. For example, the negative-sequence of the phase voltage, rather than current, could be also controlled to be zero. This strategy is preferable for fault-ride through during asymmetrical faults.

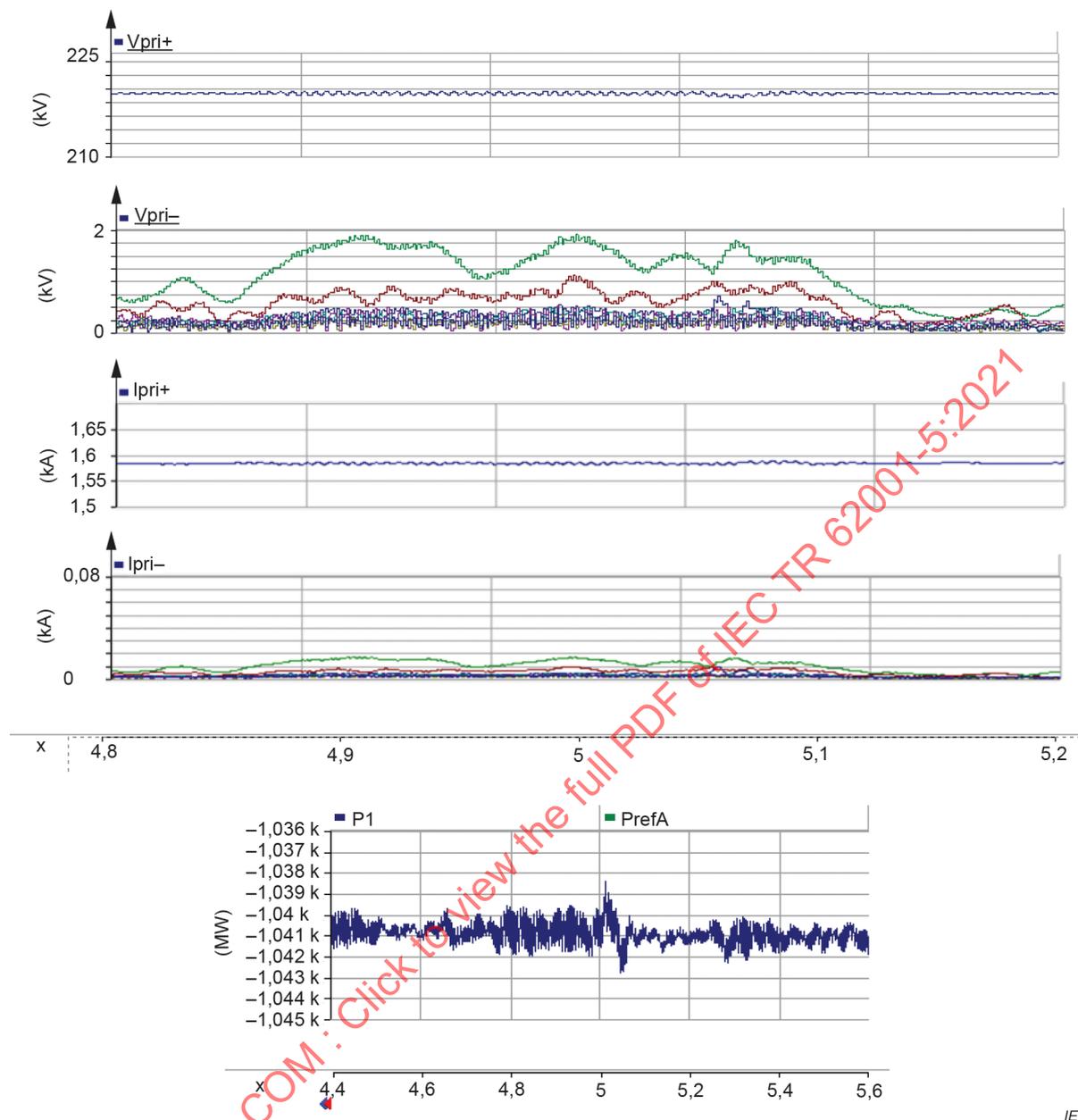


Figure 54 – Time-domain response of positive and negative sequence voltages and currents and the active power when the converter controls phase currents to be balanced

To sum up, voltages and currents can be fully controlled, as long as converter limits are not reached, and asymmetries in currents and voltages can be removed. These asymmetries can be caused by steady-state voltage asymmetries, asymmetrical faults or asymmetries in the phase reactances. In general, this is not a problem but the HVDC supplier and customer need to agree on the chosen control of the negative sequence applicable for the different circumstances responsible for the asymmetries.

9.5.2 Power oscillations due to AC supply voltage unbalance

It is desirable that the converter should avoid the propagation of power oscillations resulting from unbalanced voltage conditions in one of the AC systems.

To conclude, MMCs have the capability to control the power injected through each phase. The behaviour is completely determined by the developed controls and how the energy is stored in each of the six converter arms. These capabilities are generally limited to the operational voltage and current limits in converter arms.

The performance of the converter response and output powers may be specified with regard to the following points.

- Requirements about how AC oscillations are propagated through the converter and to both AC and DC systems.
- Requirements about how the energy needs to be stored in each of the arms in order to withstand imbalances. This might require oversizing the submodule (SM) capacitances or number of submodules.
- Requirements about how synthesized voltages and output currents respond to imbalances in the AC system, that is, how positive and negative sequences in voltages and currents are controlled in case of imbalances or asymmetrical faults. Preferably, this desired response should be specified for transient and steady-state periods.

9.5.3 Harmonic cross-modulation between AC and DC sides

Harmonic cross-modulation between AC and DC sides of the converter is a common issue in the design of LCC HVDC links [52].

The voltage source converter has been commonly considered as a "firewall" against the spreading and propagation of disturbances, including harmonics, between the AC networks connected by a VSC HVDC link. However, a cross-modulation effect can occur in VSC HVDC systems and harmonics at one side can be cross-modulated to the other side if there is no mitigation technique applied [53] [54] [55].

The synthesized voltage at the AC side is obtained from a control signal, hence harmonic distortions on one side of the converter should not be transferred to the other side if the modulation and control of the voltage is able to adequately mitigate them. The effectiveness of control mitigation is greater in MMC HVDC converters because the AC voltage is synthesized from the DC voltage at the converter capacitors and not from the DC voltage at the link. There may however be a remnant, reduced harmonic cross-modulation.

The harmonic transfer between both sides is not the typical open-loop concept where the injected harmonics from some source are transferred along the circuit being only influenced by the circuit elements. On the contrary, the study becomes a closed-loop issue where the controlled outputs, voltages at the capacitors, are influenced by the distortions transferred through the control by means of feedback or feed-forwards signals. Figure 56 sketches this behaviour and how different distortions can influence the controlled output and thus be transferred through the converter.

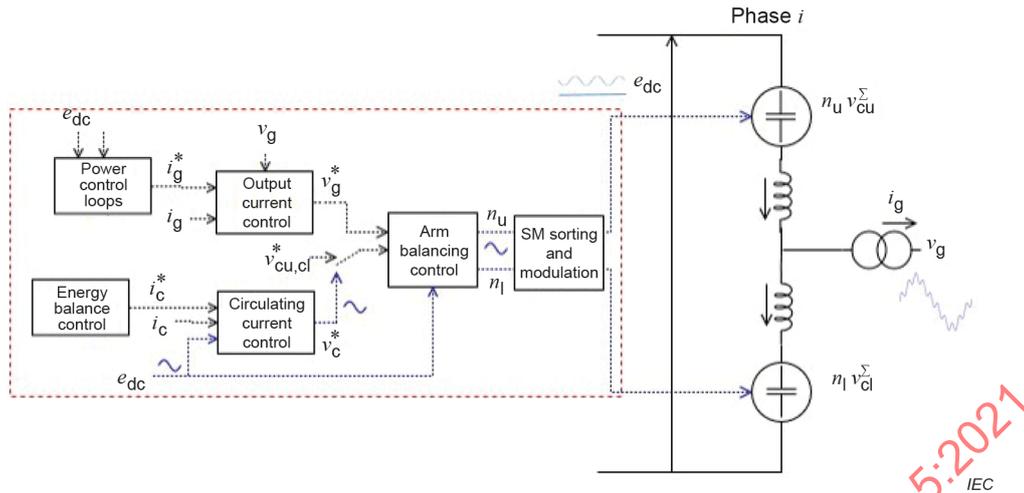


Figure 56 – Influence of distortions at the AC and DC side voltages and the propagation through the control

Disturbances are transferred to the output by means of the input signals and their propagation through the control. The way in which a harmonic is transferred to the other side of the converter is influenced by different filtering and estimation techniques or by the use of different reference frames, such as $dq0$, to perform the control. The harmonic transfer can be mitigated if the control is able to compensate the distortion.

A full description of different techniques for mitigation and the influence of different control levels on the harmonic transfer is beyond the scope of this document. However, as an example, Figure 57 and Figure 58 show the time-domain response of AC and DC voltage respectively for two variants of control. During the first period, the insertion indices are simply calculated by $(v_c^* \pm v_s^*)/e_{dc}$. As a consequence, the existing harmonic at the DC side (Figure 57) is also coupled to the AC side (Figure 58) because of the use of the DC voltage in the denominator. At 4 s on the time axis, the calculation of the insertion indices is modified and DC distortion does not influence in the AC grid side voltages.

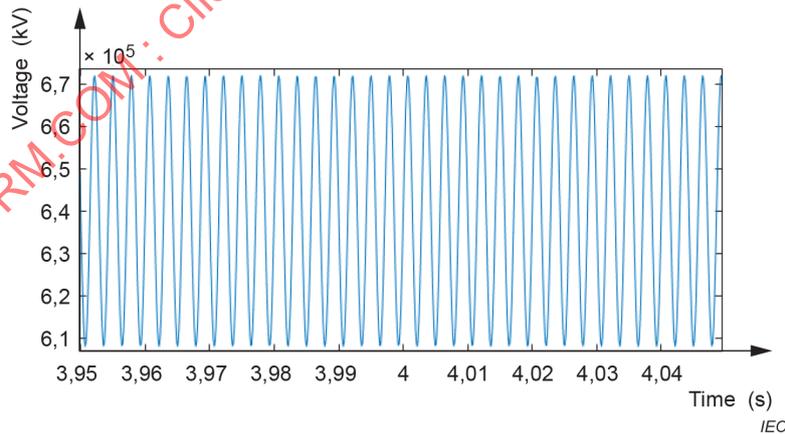


Figure 57 – 6th harmonic content in DC side voltage of MMC

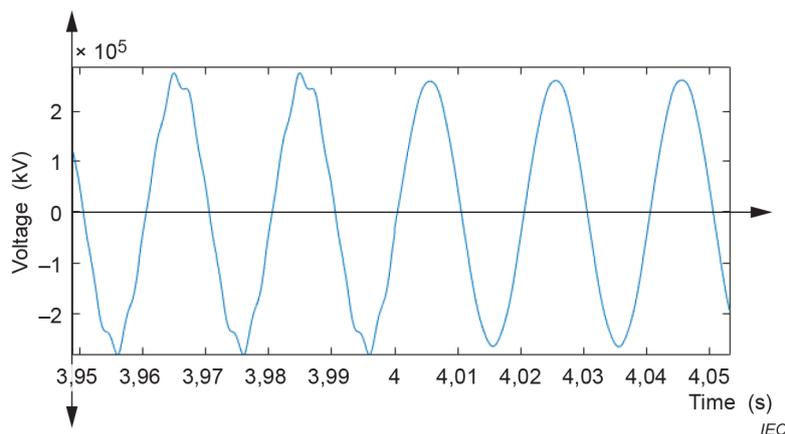


Figure 58 – Resulting AC side voltage with modification of control at $t = 4$ s

The extent of cross-modulation is therefore determined by the manner in which internal controls and measurements can reject and filter out the existing harmonics at the PCC. The required behaviour and studies should be decided on a project-specific basis. Cases where the voltage distortion at the PCC is significant could result in the specification of a control feature to either filter out the existing harmonics at the output or provide active damping to compensate the harmonics.

Consequently, the issue of cross-modulation of harmonics is not considered as significant a problem as in LCC HVDC systems and it can be shown that the impact is generally low.

9.5.4 Cross-modulation of DC side fundamental frequency current

This is a specific case of the cross-modulation phenomenon discussed above.

If an HVDC transmission line runs parallel to or nearby an AC transmission line, for sufficient distance and with sufficiently small separation, then a significant fundamental frequency AC current may be induced in the DC circuit [56] to [60].

The cross-modulation action of an LCC converts this DC side fundamental current into direct current (and second harmonic) in the converter transformer windings. This direct current tends to drive the core into saturation, which is evidently undesirable and can cause overheating, gassing and trip, as well as production of additional AC side harmonics.

For LCC technology, such fundamental current can be a serious issue and may require mitigation measures such as series filters (blocking filters) in the DC circuit, tuned to the fundamental frequency. As this has been such a significant issue for many LCC projects, the question of whether it is also relevant to VSC transmissions should be posed and investigated.

There are several essential aspects to consider in the case of a VSC HVDC.

If the action of higher level controls is ignored, then there would be some degree of cross-modulation. It is possible to derive an analytical expression for the cross-modulation of fundamental frequency DC side current to direct current in the transformer windings, for a VSC converter under such assumptions. In principle, it can be stated that the ratio of transformer DC to induced fundamental current is lower for a VSC than for an equivalent LCC. The magnitudes of the currents in the three phase windings will be dependent on the phase relationship between the induced fundamental frequency current and the AC side phase voltage. The current in the three phases will vectorially sum to zero.

However, higher level controls, such as current control or circulating current control, will have an inherent impact both on the level of fundamental current and on the cross-modulation effect, even if they are not designed to perform a specific mitigating function.

If specific mitigation measures are required, then control functions may be used. Such functionality would depend on the specific design of the VSC controls, but in principle it is more feasible for VSC than for LCC due to the possible use of its inherent energy storage to partially decouple the AC and DC sides, and to its enhanced controllability.

Most early VSC HVDC projects were cable transmissions, where such induction is limited by the close spacing of DC cable pairs and to a lesser extent due to the partial electromagnetic shielding provided by the cable sheaths. Also, the cables in the existing VSC HVDC projects have not been routed closely parallel to AC cables. Increasingly, however, VSC will also be used for overhead line transmissions and may share rights-of-way in close proximity to AC lines. In the case of hybrid transmission routes in particular, with AC and DC lines possibly on the same towers, the induction of fundamental frequency may be of such magnitude that some mitigation may be required, despite the weaker cross-modulation effect of VSCs. Detailed investigations and simulations are advisable in all such cases.

10 Modelling

10.1 Provision of models

Transmission system operators may have an interest in modelling the harmonic characteristics of a HVDC VSC as part of their overall system planning and analysis. There may therefore be contractual requirements that the HVDC supplier should provide such a model. Ideally, this would also include harmonic generation spectra, allowing TSOs to make an assessment of harmonic levels throughout the AC network. This model should preferably also be open to use by a third party, such as a contractor for a future VSC in the proximity.

An elaborate model made in order to take the impact of control into account, typically implemented in time-domain, is something which HVDC suppliers will have for each VSC design, but would be reluctant to share with a third party, as it could embody intellectual property. In any case, such an elaborate model may not be justified for the TSO's purposes. There may be particular concerns that have to be addressed by the HVDC supplier during design work, for example cross modulation of harmonics (AC-DC-AC), particular low order harmonic resonances etc., which need to be included in the supplier's model, but access for a third party to such a detailed and specific model may not be permissible.

For most practical purposes, a simpler Thevenin or circuit equivalent will suffice. In order to emulate the impact of control, this equivalent may have to be an approximation, as the converter impedance may not be purely passive for the complete harmonic range. Any such simplified model should be validated against measurements on an operational HVDC project, or, if these are impractical, against an elaborate model, typically in time domain with relevant parts of the control included.

Both the emissions and the output impedance of the HVDC converter model are dependent on the operating point. Therefore, for defining the harmonic emissions, there should be provided tables of values applicable for different operating points and control modes of the converter. Similarly, the impact of the grid impedance can vary and influence the output impedance of the HVDC converter model. Because of this fact, different operating points of the grid impedance may have to be considered in the model if a significant impact is observed.

10.2 Time and frequency domain

When dealing with resonances and harmonic stability, studies are usually done in the frequency domain, considering a window from fundamental frequency to an appropriate upper frequency for the phenomenon studied. For each frequency of study (defined by the chosen frequency step appropriate to the phenomenon being investigated), a steady-state is computed with the available models and from the defined harmonic (or interharmonic) sources. Running the simulations in the frequency domain is convenient since computation times are short and numerous scenarios can therefore be considered.

Alternatively, simulations can also be executed in the time domain, computing the response of the system over time in response to an excitation. For harmonics and resonance studies, a steady state solution is required. Due to the simulation time required to reach steady state, time domain simulations may not be the most appropriate methods for studying harmonics, but they can be advantageously used to derive the steady state frequency response of the converter model, as will be shown in 10.5. Because all control details (i.e. control response and cross modulation effects) and HV equipment are included in the model, the main drawback of time domain simulation is the computation time performance. The time consumption depends on the time step of the simulations, which needs to be appropriate for the phenomenon studied and the required accuracy. One approach to reduce the computation time is to perform such studies using real time simulators connected to actual replica control hardware.

To study harmonics and resonances, appropriate electromagnetic grid as well as HVDC converter models are required. Subclause 10.8 summarizes techniques to properly model the grid and describe the frequency dependency of equipment. Grid modelling for harmonic studies is extensively described in [9], [12] and [61]. A frequency dependent network equivalent can also be used to effectively reduce computation time [14].

The problem often encountered in harmonic and resonance studies is that the required detailed converter model is generally developed to be used in time domain whereas the norm is rather to do the simulations in frequency domain. As a compromise, control systems are usually removed for convenience from the converter model to be used in the frequency domain which may lead to serious shortcomings, as illustrated in 6.3.

Referring back, the circuit of Figure 2 is easy to simulate in the frequency domain and 10.5 describes how it can be built from the detailed converter model usually used in time-domain approaches. Figure 2 a) illustrates the required model while Figure 2 b) is a more convenient reduction for simulation. Indeed, Figure 2 a) is partly based on control system models which can only run in the time-domain. Figure 2 b) is based on an equivalent Thevenin source. $V_{\text{Fundamental}}$ is the 50 Hz or 60 Hz converter source (equal to V_{PEH}) whereas $V_{\text{Harmonics}}$ represents the non-ideal behaviour of the converter, i.e. the harmonic voltage injected by the switching of power electronic devices (equal to V_{synth}). The device Z represents the frequency response of the converter impedance and takes into account the linearized control. Consequently, it includes the exact resonances of the HVDC system.

10.3 Modelling of the converter control for harmonic and resonance studies

As was shown in 6.3, it is necessary to take into account the control system of HVDC converter when performing harmonic and resonance studies since the control system will modify the equivalent impedance of the converter.

One of the solutions proposed to reconcile converter models running in the time domain and harmonic studies preferably done in the frequency domain is to bring the converter models into the frequency domain.

To represent a converter and its controllers for steady-state analysis in the frequency domain, it is necessary to extract the linear part (or transfer function) of the system [62]. There are two main general approaches to compute the equivalent frequency impedance of the converter from a detailed converter model:

- analytical approach – by linearizing the converter model by means of small signal or transfer functions of the control system (10.4.2);
- numerical approach – by simulating the detailed converter model in EMT tools (10.5).

These techniques have to be employed for every operating point of the converter which needs to be studied. In the succeeding Subclauses 10.4 and 10.5, a generic VSC-MMC station is considered in order to describe the two approaches. As a consequence, the following figures are only valid for a generic VSC-MMC station, although a similar approach can be applied to any type of VSC from any manufacturer.

10.4 Converter linearization by analytical approach

10.4.1 General

To develop an analytical model of the harmonic impedance, linearization based on an average model (AVM) of a VSC-MMC station [63] is considered. Several linearized models can be developed for the MMC that take in account internal variables as in [64] and [65]. This document describes the classical and simple method commonly used for VSC technology. The AVM model referred to as the MMC "Model 4" in [66] (or as "Type 6" in [16]) is used here for illustration and is shown in Figure 59. This small-signal model includes the equivalent capacitor C_{dc} of the MMC. The terms L_{arm} and R_{arm} (the latter not shown) refer to the inductance and resistance of each arm.

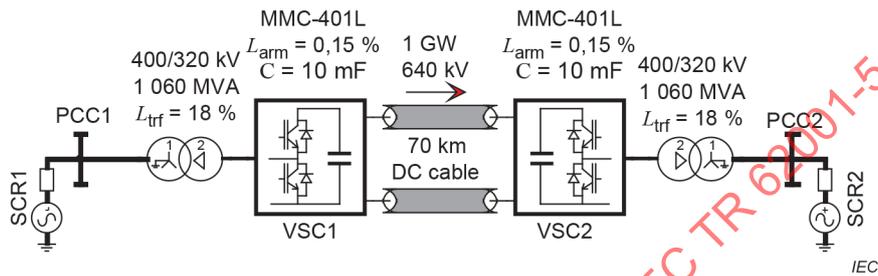


Figure 59 – VSC HVDC transmission system

10.4.2 VSC-MMC linearized model

The small-signal model can be found from Figure 60 by first deriving the equation in the dq reference frame and secondly in the real-imaginary reference frame [66].

The circulating currents as well as the capacitor voltage balancing of submodules (SMs) are neglected [67] [68]. Only the inner current loops (i -control) and the outer control are modeled. Furthermore, linearization of the model around a steady-state set point allows consideration of only the linear part of the controller.

The process that leads to the complete small-signal station model illustrated in Figure 60 is described in details in [63] and its references ([64], [65] and [68]).

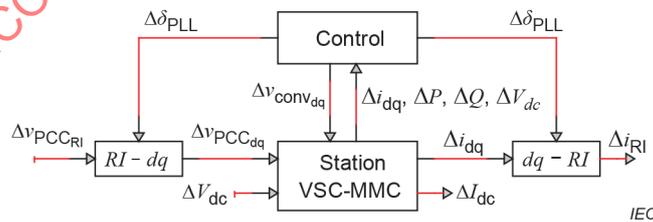


Figure 60 – VSC station model using the small-signal approach

10.4.3 Input impedance

The small signal model presented above is based on a linear model (or transfer function). Therefore, the frequency response of the converter station, from the AC side, can be deduced and the Thévenin impedance computed analytically:

$$\begin{bmatrix} \Delta v_{PCC_d} \\ \Delta v_{PCC_q} \end{bmatrix} = \begin{bmatrix} Z_{dd}(S) & Z_{dq}(S) \\ Z_{qd}(S) & Z_{qq}(S) \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} \tag{17}$$

where

$Z_{dd}(s)$ and $Z_{qq}(s)$ are the impedances in the d and q reference frame respectively;

$Z_{dq}(s)$ and $Z_{qd}(s)$ are the cross-coupling terms in previous equation but are negligible when the converter is not operated on a weak grid ($SCR < 2$) [69].

10.4.4 Advantages of analytical method

The analytical approach allows the use of numerous classical tools for modal analysis such as eigenvalues, Nyquist diagram, and participation factor method [70].

It also gives access to all parameters of the control system of the converter. Their effect on the equivalent converter impedance can be studied independently in detail.

10.4.5 Drawbacks of analytical method

Detailed knowledge of the control system is required for application of this method. All relevant control loops, filters and delays should be accurately included in the control model for the frequency range to be studied.

Since VSC-MMC technology includes a large amount of variables, the complexity of deriving an accurate linearized model is considerable. As the control system becomes complex, the technique may become too difficult to use.

Because of these two drawbacks, the analytical approach is likely suitable only for HVDC manufacturers.

The alternative method based on a numerical approach to determine the equivalent frequency impedance of the converter is presented in 10.5.

10.5 Deriving the converter impedance by numerical approach

10.5.1 Methodology

The numerical approach is based on EMT models. As a consequence, the MMC AVM model used previously with the analytical approach is not sufficiently detailed for this application.

Several models for EMT studies were proposed in [66]. "Model 1" is the most detailed model. It considers a detailed representation of power switches with ideal IGBTs, non-linear diodes and snubber circuits. However, such a model is complex and requires a very long computation time. Moreover, manufacturers usually do not provide such models but prefer working with "Model 2" or "Model 3" models. "Model 2" model simplifies power switches by ON/OFF resistors in each submodule. While providing good accuracy regarding harmonic studies, "Model 3" model allows greatly reducing computation time by assuming that the capacitor (C_i) voltages of each cell per arm are equal. In this case, N submodules of each arm are reduced to an equivalent one with a capacitor $C_{tot} = C_i/N$ (since C_i are constant for $i = 1..n$). This is shown in Figure 61 [66].

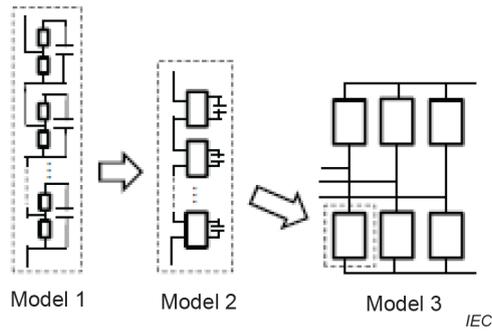


Figure 61 – Model evolution in decreasing complexity

"Model 3" model is based on arm switching functions. It can therefore represent the harmonic behaviour of the VSC HVDC as well as any second harmonic circulating current inside the converter. Figure 62 represents the "Model 3" model [66].

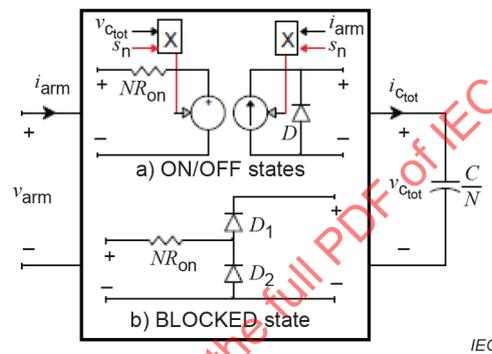


Figure 62 – Switching function model of MMC arm

In terms of control, the outer control loop (P , Q and V_{ac} control loop) is necessary to control voltage and current sources. The energy control loop which ensures the balance between the capacitor voltage of each arm can also be included in the model.

These "Model 3" or "Model 2" models are convenient for EMT models to perform harmonics and resonance studies but they are simulated in the time domain.

A numerical approach allows bringing together the models and the study. It is introduced in [71], [72]. The conversion scheme is illustrated by Figure 63.



Figure 63 – Time domain to frequency domain stratagem

Small harmonic currents are injected at the point of common coupling, as shown in Figure 64.

NOTE A voltage injection method can also be used [62]; however, it is usually less common practice.

As the injected harmonic currents are only of a few amps, i.e. very low compared to fundamental frequency current, the controller and protection system will not be disturbed and will operate normally. The effect of the control system on the converter impedance will not change the setpoint.

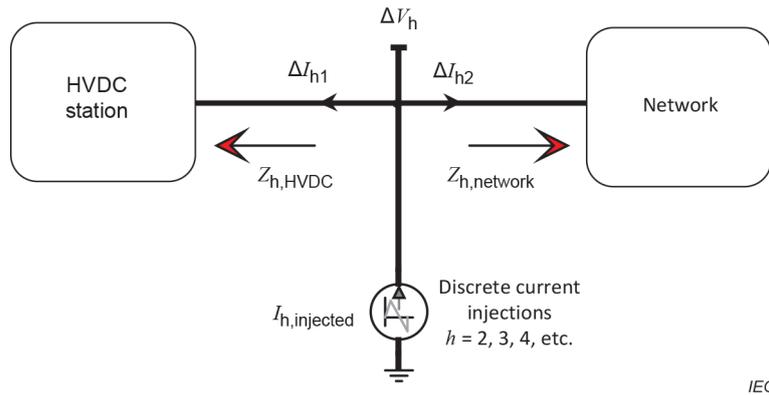


Figure 64 – Example of a circuit to linearize a network and a VSC including controllers

$I_{h,injected}$, the injected harmonic currents, is split into ΔI_{h1} and ΔI_{h2} – Formula (18). The induced harmonic voltages are observed at the PCC as a consequence of the injected harmonics $I_{h,injected}$. By applying Ohm's law, the harmonic impedance of the HVDC station $Z_{h,HVDC}$ is simply calculated from Formula (19).

$$I_{h,injected} = \Delta I_{h1} + \Delta I_{h2} \quad (18)$$

$$Z_{h,HVDC} = \frac{\Delta V_h}{\Delta I_{h2}} \quad (19)$$

By modifying the current source injected $I_{h,injected}$, it is possible to identify the separated harmonic current source of the converter represented in Figure 64. This procedure is explained in detail in [18].

Harmonic voltages and currents have to be measured when steady-state conditions are reached during the time-domain solution to obtain correct results. If this operation is repeated for each harmonic, the frequency equivalent impedance of the converter can be derived. This technique has to be repeated for every converter operating point which needs to be studied. As a minimum, the whole range of active and reactive powers operating points should be covered. Ultimately, a combination of operating points including various unbalance and background harmonic conditions should be studied.

When injecting a current at the k^{th} harmonic order, attention should be paid to the modification of the converter harmonic emission at the orders $k - 1$ and $k + 1$. This modulation is however of lesser significance.

This numerical approach allows a compromise between VSC converter models, which are usually built in time-domain and harmonic studies, which are commonly performed in frequency domain.

10.5.2 Advantages of numerical method

This technique gives a solution to the drawbacks of the analytical linearization approach. A detail control system can be represented in the converter model without affecting the complexity of the technique. This approach is more accurate and can take into account the non-linearity of the control system.

Moreover, this technique allows the use of black box devices which protect the intellectual property of HVDC manufacturers while sharing the functionality of their control models. The

numerical approach is therefore suitable for the converter station owners, the HVDC manufacturers and third parties.

10.5.3 Drawbacks of numerical method

Computing the equivalent impedance of the converter is done in two steps.

- 1) At first, to initialize the simulation, the converter station needs to be started and the desired operating point needs to be reached.
- 2) Then, the methodology described in 10.5.1 is applied and the converter impedance is derived.

For step 1), simulation time will depend on the tools and HVDC EMT model used: generally speaking, the EMT model can take several hundreds of milli-seconds to several seconds to reach steady state operation. Depending on the EMT tool that is used, a snapshot option can be used to start the simulation at steady state, which will greatly reduce the computation time of the initialisation. On the other hand, if real-time simulation including real cubicles is used, the time to reach steady state is close to the real field time, that is some tens of seconds to few minutes of simulation time.

For step 2), several frequency scan methods can be applied. Generally speaking, some seconds of simulation time is needed to estimate the frequency response of the converter station. For offline EMT tools, this simulation time can take some minutes of computation time depending on the complexity of the HVDC model. If real time simulation is used and is available, the computation time will be equal to the simulation time, therefore only some seconds will be necessary.

Accuracy of the impedances determined by time-domain EMT simulation can decrease with increased simulation time-step duration, particularly with simulation tools that do not interpolate or subdivide time steps for discrete switching events that do not coincide with discrete time steps. Decreased time step durations, however, increase the computational burden, requiring either longer computational time to complete the simulations or dedication of increased computational processing capability. Therefore, there is an inherent tradeoff between accuracy, time to perform the analysis, and computational resources.

10.6 Choice between analytical and numerical methods

Both an analytical approach and a numerical method have been described to derive the equivalent impedance of a converter.

The numerical method has no limitation in its type of user – anyone who has a converter model can use this method. It is particularly appropriate for academics, consultants and system operators who usually do not have access to the details of the control system of the converter. With a black-box model provided by a manufacturer, i.e. not accessible, the equivalent impedance of the converter can still be derived for harmonic and resonance studies. Moreover, the numerical method is less complex to use because it does not require an understanding of precisely how the converter operates.

Manufacturers can use the numerical method but also have the option of the analytical approach, because they have full access to their control system details. For specific purposes, the analytical approach can be advantageous to identify precisely the impact of each control parameter.

10.7 Model validation

In terms of model validation, several approaches are possible.

- In comparison with measurements: if harmonic measurements are available with different grid and converter configurations, they can be used as reference for the simulation results of the VSC converter model.

- In comparison with off-line simulation results obtained from a more complex model: when measurements are not available, the simulation results of a more detailed model than the one to be validated can be taken as a reference. The structure of the model should be closer to reality (as is "Model 1" model in [63]) to allow validating less complex model ("Model 2" or "Model 3" in [63] for instance).
- In comparison with real-time simulation results: measurements on the real system are sometimes difficult to schedule or to realize. Nowadays, HVDC manufacturers have (and TSOs may have) access to a real-time simulation laboratory where the replicas of the control system of a VSC converter can be studied. The converter high voltage components are still necessary to be modelled in the real-time simulation tool but the comparison between on-line and off-line tends to be more accurate than a comparison between exclusively off-line models.

10.8 Network impedance modelling

Just as the converter needs to be properly modelled for harmonic and resonance studies, the network impedance also has to be adequately modelled. Subclause 10.8 provide information on what should be considered when performing the network impedance modelling.

One of the most critical parameters for any filter performance evaluation is the harmonic network impedance that the design and performance verification should assume.

If the assumptions for network impedance are too optimistic, the outcome may be that specified harmonic performance limits may not be satisfied when the scheme is put into service. Alternatively, if the assumptions are too pessimistic, then unjustified equipment (filters) may be required.

NOTE The term "optimistic" implies a network or network impedance envelope which has a low probability of resonating with the converter station, and/or a high degree of damping, and therefore will result in low harmonic distortion. The term "pessimistic" implies the opposite.

It is therefore important that the implications of an unrealistic representation of the network impedance are understood, and efforts made to ensure that the specified representation is as realistic as possible.

The subject of network impedance envelopes is treated extensively in [41], [10] to [13], [9], [61] and the representation of individual components of the power system at harmonic frequencies is the subject of [14]. Rather than repeat any of that material, this document only focusses on some aspects which may require particular attention in the context of VSC HVDC.

Relevant frequency range: With the switching frequency of PWM converters at more than 1 kHz, and the effective switching frequency of modular multi-level converters at even higher frequencies, properly designed VSC HVDC systems inject very little harmonic energy in the low-order range. On the other hand, harmonics even up to the 200th order may need to be evaluated to obtain compliance with some customer and interconnection requirements. It is extremely difficult or even impossible to create an accurate model of an extensive AC network at such high frequencies. Therefore, as frequency rises, it should be accepted that the accuracy of the network impedance calculation diminishes, and conservatively specified generalized envelopes may have to be adopted.

Extent of model: In general, the required model extent decreases with increasing harmonic order. Therefore, the size of the network model for VSC HVDC harmonic studies may not need to be as extensive as would normally be required for an LCC HVDC system harmonic study. However, every component in the proximity of the VSC converter will affect the resistive characteristic of the network impedance. Modelling the resistance of such components should be a point of attention.

Loads: The frequent practice of modelling loads as series or parallel resistance and inductance networks, based solely on matching the fundamental frequency active and reactive power flow, and connected directly to transmission buses without consideration of the intervening transformer inductances, produces substantially inaccurate modelling at the higher-harmonic components relevant to VSC HVDC performance. Load models should account for the inductances of these transformation stages, and the shunt capacitance of MV lines, cables and capacitor banks.

Transmission lines: At the higher harmonic orders of relevance to VSC HVDC harmonic performance evaluation, the assumption of balanced (perfectly transposed) transmission lines is of questionable accuracy. Due to the fact that most lines have lengths that are multiples of these wavelengths, cross-coupling of the sequence components can be very strong even where line phase imbalance is small. The damping of higher-order harmonic propagation in the positive sequence can be predominantly due to coupling of the positive sequence to the zero sequence, more so than the damping of the positive sequence parameters themselves. Therefore, the use of single-phase models for higher frequencies results in an under-estimation of damping. An alternative method may be to use such single-phase models but for higher frequencies include adjusted impedances based on a 3-phase detailed model of adjacent lines, cables and transformers.

Transformers: Saturation and core loss effects are of negligible importance at the frequencies of interest for VSC HVDC harmonic analysis. Frequency-dependent damping of the series (terminal-to-terminal) impedance of transformers can be of great importance when transformer impedance is a substantial factor. Power transformers tend to achieve their greatest impedance angle at a few hundred hertz or less, and thus a series resistance-inductance representation is completely inadequate. At the higher harmonic orders of interest for VSC HVDC, winding capacitance (both inter-turn, inter-layer, and winding to core and tank capacitances) can be of significance. Cross-coupling of sequence components should also be considered, as described above for transmission lines.

Cables: Cable modelling is discussed in depth in [14] including aspects which apply especially to the higher frequencies of interest in the context of VSC. The advantages and shortcomings of different modelling techniques are considered, with extensive references.

Wind and photo-voltaic generation: Unlike general power grids, such generation plants or parks are limited in scope. While they may be represented in the conventional manner as network impedance envelopes as seen from the HVDC bus, it can be advisable to model them in detail. The typically high cable content can result in localized resonances, and interactions with the converter controls at harmonic frequencies can result in so-called harmonic instability (Clause 11). The connected generation park should consider the above-mentioned representation of lines and transformers. Additional components, such as possible shunt capacitor installations, also need to be included. Finally, the generator installations, either the generator itself or the conversion system, also have an influence in the network impedance. These are sometimes not properly represented in studies due to lack of proprietary information, but should be if an accurate network representation is to be obtained.

The complete wind energy conversion system (wind turbine, converter and filter/reactor) is represented as a harmonic current source according to IEC 61400-21-1 [15]. Consequently, some tools also follow this approach. However, their harmonic injection and influence on the network impedance differ from conventional non-linear loads. Nowadays, the two main technologies are Type-III, a DFIG, and Type-IV [73], [74], a synchronous machine connected through an AC/DC/AC converter. The most accurate representation of the DFIG is the parallel impedance between the equivalent impedance of the induction machine and the small transformer feeding the converter connected to the rotor. In this case, the behaviour is mainly inductive. Regarding Type-IV, its configuration is very similar to the VSC. Consequently, the most accurate representation would be the terminal impedance representing the reactor (usually configured as an LCL filter or a derivation thereof) and control dynamics as explained in 10.3. If the latter information is not available, the impedance should represent at least the connection reactor or filter, but significant aspects of the behaviour might be omitted.

Photo-voltaic generation plants have a similar configuration to that of a Type-IV wind turbine. Therefore, the most accurate representation relies on considering the interconnection filter and reactor plus the influence of control dynamics from the converter.

HVDC converters and FACTS in the proximity: The presence of other controlled conversion devices electrically close to the VSC HVDC should be treated with particular care. In the case of another VSC, the most accurate representation would be by the use of the equivalent impedance as explained in Clause 6. In case this information is not available, the terminal impedance at the point of connection should represent the passive components up to the valves, i.e., transformer and phase reactors, plus a shunt filter if present.

An LCC HVDC converter may have a very wide range of harmonic impedances, depending on which of possibly many AC filters or shunt banks are connected at different load levels, and on the harmonic impedance of the converter itself. Similarly, SVCs and other FACTS devices may have different modes with distinctly different harmonic impedances.

Insofar as any such devices may be represented by a passive harmonic impedance, they may be included within the overall network harmonic impedance envelope. However, if there is a possibility of harmonic interaction involving the control systems, then such devices should be fully modelled independently of the remaining network envelope, and the possible interactions studied.

11 Harmonic stability

11.1 General

In a conventional power system stability study, the electromagnetic characteristics of the circuit are not relevant, because all active controls and dynamics occur at low frequencies. However, voltage source converters utilize dynamics and control loops extending over a wide range of frequencies and up to considerably higher frequencies than conventional installations such as synchronous machines or line commutated converters. A VSC appears as an active component and its dynamics interact with the electromagnetic nature of the network, and may be affected by resonances. The result of this interaction is a new type of stability problem in power systems, which has become known as "harmonic stability". Although the suitability of the term may be questioned, it is used in the present document. An overview of dynamic interactions of different natures over a wide frequency range is shown in Figure 65. To correctly assess the interaction of VSCs with the surrounding network, the electromagnetic behaviour of both the converter and the interconnected power system equipment up to several kilohertz should be adequately modelled.

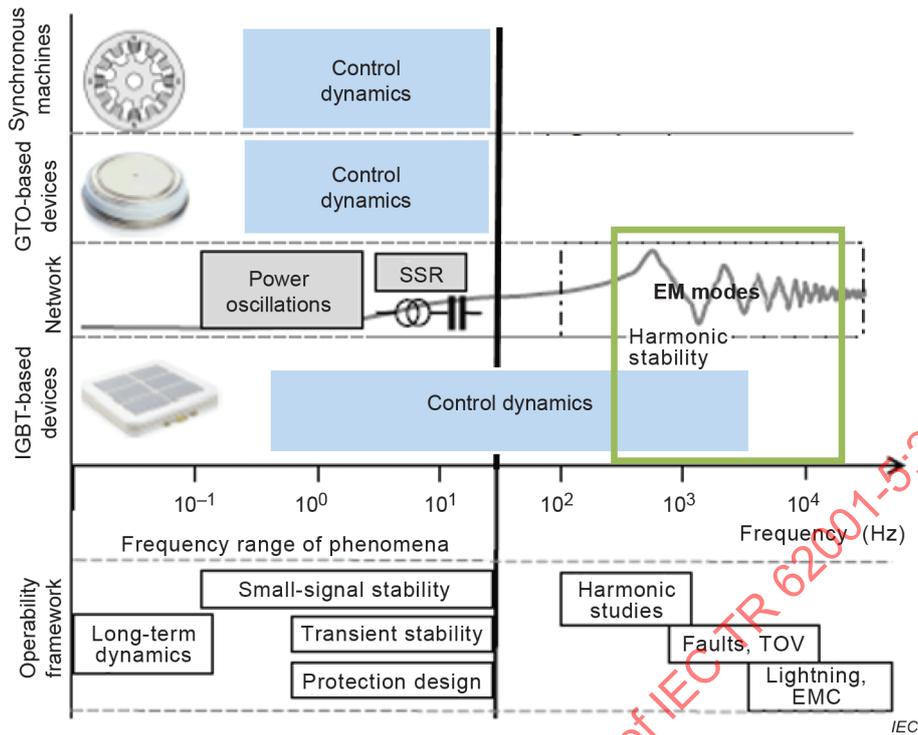


Figure 65 – Dynamic interactions between components and study framework

The harmonic stability problem may result in a sustained oscillation or in an instability with a high-frequency component of increasing magnitude. The instability frequency does not necessarily coincide with any integer harmonic (thereby emphasizing the imperfection of the term "harmonic instability"). This behaviour may lead to shutdown due to control or protective actions of the converter station or, in the worst case, to the damage of some network components.

At the high-voltage transmission level, such instability has also been observed in some VSC installations. In the future, this problem is likely to become more significant because of

- a) the probable massive penetration of power electronics based equipment,
- b) the phase-out of conventional generation, and
- c) the extended tendency of obtaining more efficient assets and transmission equipment.

All of this tend to increase the amount of high-frequency electronic controllers and reduce the amount of damping in the system.

Operators and HVDC vendors are currently challenged to come up with the most suitable solutions to avoid problems related to such harmonic instability. There are still multiple relevant questions that need to be answered for a better understanding of the problem, definition of best practices to mitigate it, and development of solutions.

11.2 Literature review

This harmonic instability issue has provoked a lot of interest in both industry and academia. The first documented problem was experienced in the 1990s in traction networks [75]. Subsequently, some installations of IGBT-based converters resulted in the appearance of large magnitude harmonics which were initially unexpected [76]. Those problems have led to the drafting of standards and requirements dealing with harmonic instability and proposed methods of analysis.

The same problem was observed in the use of VSCs interfaced by means of an LCL passive filter required to decrease the harmonic distortion of the output current. The interaction of this resonant filter with the control may result in oscillatory behaviour because the converter controls the output current through the LCL filter, which itself has a particular resonance. Further details regarding the problem and analysis may be found in [77]-[79], regarding the control and mitigation of the interaction in [80]-[82], and regarding the impact of other connected installation in the vicinity or variation of short-circuit impedance on the experienced instability in [83] and [84].

Further interest has more recently developed because of the installation of offshore power plants. These entail networks with multiple installations of power electronics and the presence of multiple resonances extending over a wide range of frequencies. Further details about the analysis methodologies in such networks may be found in [85]-[88].

Finally, harmonic instability has also been observed and analyzed in onshore high voltage networks. Where there is very low damping in such networks, they may be sensitive to harmonic instability [18] and [89]. Refer also to the work of the CIGRE WG C4.49 [90].

11.3 Definitions

As the topic of harmonic instability is relatively new, it is important to be clear in the definition of the terminology used in the subsequent discussion.

A "natural frequency" is the frequency of a wave component present in a network voltage or current oscillation after the network is subjected to a disturbance, excluding the frequencies of components in the exciting signals. When focusing on passive electromagnetic phenomena, i.e., neglecting the effect of controls and other phenomena in the power system, the natural frequency corresponds to the oscillation of energy between electric and magnetic fields of system components due to a disturbance which leads to a temporary energy imbalance. The energy oscillates between the fields until the oscillatory behaviour is damped due to power dissipation.

"Resonance" occurs at any of the system's natural frequencies. This results in periodic components with amplified magnitude of voltages and currents and appears as a peak value in the circuit impedance.

"Negative resistance" is a property of some electrical circuits and devices in which an increase in voltage across the terminals of the circuit or device results in a decrease in the in-phase component of current through it. It may also be envisaged as the characteristic of an active component when it responds to current flow not by creating a potential drop in opposition to the current flow and thereby dissipating energy, as with a normal resistance, but instead responding by creating an e.m.f. which reinforces the current flow and injects energy into the circuit. This behaviour results in the decrease of system damping within a given range of frequencies. The component behaves as an active source. A negative-resistive behaviour in a component is not in itself a detrimental aspect, but, in the event that system natural frequencies appear in the same frequency range, the resulting interaction between system natural frequencies and the negative-resistive behaviour needs to be addressed.

"Harmonic instability" is the condition in which a natural frequency of the network is excited because a given or several installations are adversely controlling the energy in the system, leading to oscillations with non-decreasing amplitude at that frequency. This is observable from the small-signal behaviour at the controlled component terminals in the form of a "negative resistance". The surplus of energy flowing into the circuit is transferred as an oscillation of the energy stored between the electric and magnetic fields.

11.4 Theory

11.4.1 General

Harmonic instability is explained in 11.4 by dividing it into the different phenomena involved which include network resonances, the impact of control dynamics, and the interaction between network and converter dynamics.

In 11.4, network resonances, the dynamic response, and the oscillatory behaviour resulting from a disturbance are introduced first with the help of a simple circuit in which converter dynamics are not considered. Next, the impact of converter dynamics on the damping provided and the source of the problem of instability are explained using the equivalent converter impedance. Finally, the resulting network dynamics arising from the interaction between both systems are evaluated with frequency-domain techniques.

11.4.2 Passive harmonic resonance

Two different related phenomena are considered – namely the steady-state behaviour and the dynamic response.

Consider a simple RLC circuit such as in Figure 66 which, if subjected to a periodic input corresponding to the resonance frequency given by $1/(2\pi\sqrt{LC})$, would produce amplified steady-state voltages and currents at that frequency.

Figure 66 shows the circuit, driven in steady state at a lower frequency (for example the network fundamental frequency) with constant magnitude V , and its response to a voltage step. This disturbance results in the excitation of the circuit natural frequency. In this circuit, the time-domain behaviour corresponds to an oscillatory mode at the same frequency $1/(2\pi\sqrt{LC})$ with a magnitude decaying due to the losses in resistance R , superimposed on the lower frequency of the driving source. Physically, the oscillation is due to a continuous exchange of electric and magnetic energy stored by the respective capacitive and inductive components.

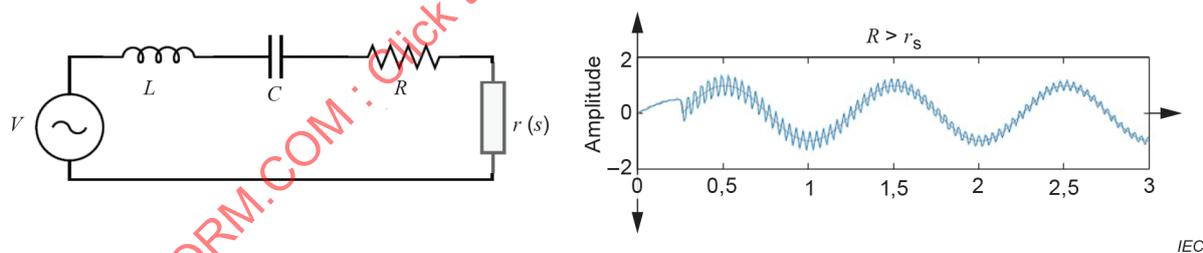


Figure 66 – RLC circuit and time-domain response to a step disturbance

The electric power grid consists of multiple items of equipment which may be considered as various RLC components which interconnection results in different network resonances. These passive resonances are natural and need not be problematic; however, they could jeopardize the network when

- there is a periodic input – e.g. generation of harmonics – in the system that coincides with a natural frequency and thus excites a resonance, possibly resulting in high values of voltage and current at that frequency, and
- the switching of an element causes a step-change in the network which results in high-frequency oscillations possibly leading to overvoltages. This problem is widely known in operations involving the switching of capacitor banks.

The CIGRE Technical Brochure 569 [91] provides detailed information about these phenomena.

The connection of a converter station to the network as depicted in Figure 67 also results in natural frequencies or resonances different to the ones existing prior to connection. This can be observed by plotting the respective equivalent impedances of the converter station Z_{conv} and the passive network Z_{h} as shown in Figure 67.

NOTE In this initial example, the converter impedance is represented simply by its passive impedance – mainly that of the transformer and phase reactors.

The new resonances are determined by the points where the magnitudes of both equivalent impedances intersect and their peak value is determined by the phase difference. Phase differences closer to 180° result in resonances with higher magnitude. This is shown in Figure 68 where the frequency behaviour of the equivalent converter station impedance, the network impedance, and the total equivalent impedance Z_{eq} as seen from the PCC are plotted. Elevated values of current and voltage may be expected if the circuit is excited at the frequency of one of the impedance peaks, such as at 1 340 Hz.

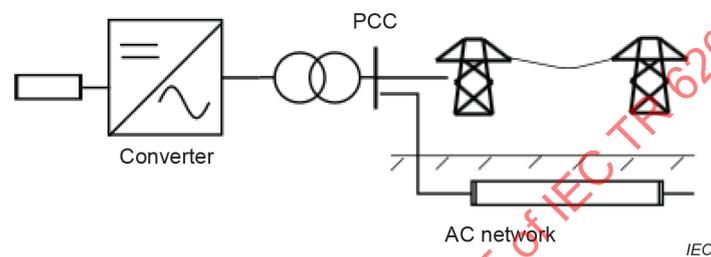


Figure 67 – Connection of the converter station to a passive network

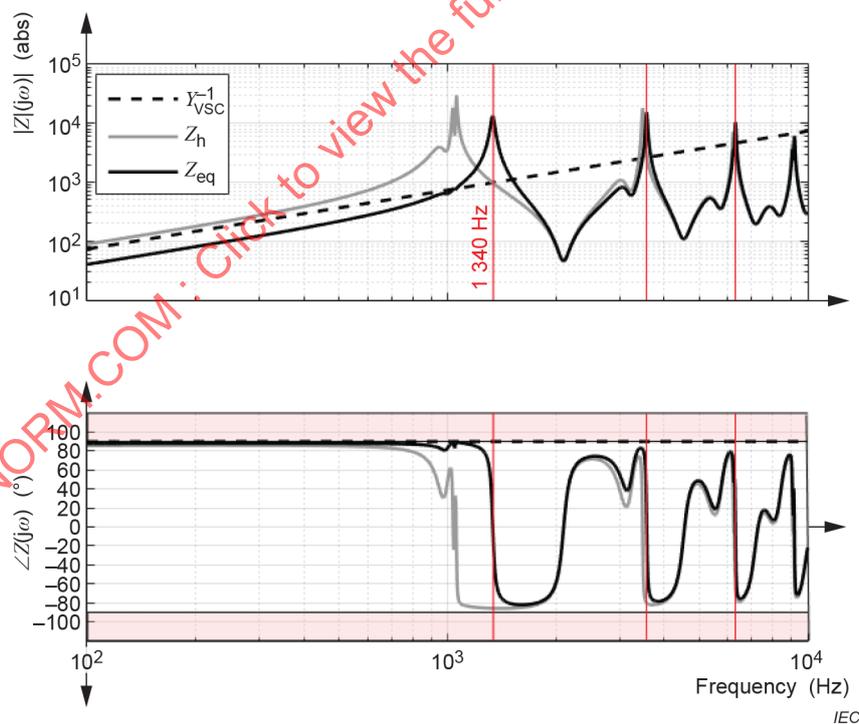


Figure 68 – Bode plot of the converter, network and equivalent impedances

For this analysis of passive impedance only, useful tools include frequency sweeps of the parallel equivalent impedance between the converter and the AC network at the point of common coupling, and steady-state simulations to calculate the resulting harmonic amplitudes (see 10.5).

Treating a VSC as a passive impedance may be an acceptable simplification in some circumstances; however, it risks obscuring possible important aspects of interaction with the network which can only be adequately analyzed by considering the active behaviour of the converter.

11.4.3 Active behaviour of converters

As discussed in Clause 6, converter and control-specific dynamics have an impact on the overall equivalent impedance of the converter station. This total equivalent impedance should therefore not only represent the passive behaviour of converter components but also all dynamics seen from the point of common coupling (PCC). This active impedance is influenced by different controllers and dynamics such as delays or measurement filters.

Specifically, the control strategy used to obtain the modulation outputs has a significant influence. There are two main strategies employed:

- a) a cascaded control with outer loops and the current control loop;
- b) a direct controller without the middle step of the current controller.

Generally, the first option is used for converters connected to the grid (or grid-following) and the second strategy for islanded systems (or grid-forming).

11.4.4 Active impedance of a VSC with a generic current control

The example in Figure 69 demonstrates a VSC with a simple and generic current control as available in the literature. In reality, other features and controls will also have an impact on the equivalent impedance.

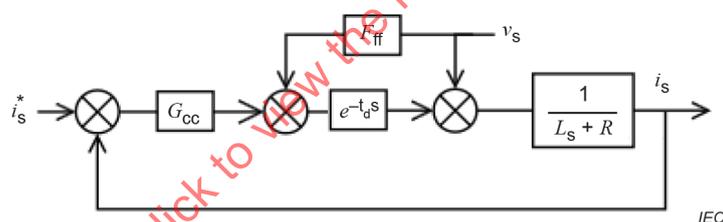


Figure 69 – Dynamic scheme of the current controller and phase reactor

The passive elements of the VSC are shown as an equivalent impedance Z_{conv} , representing the leakage impedance of the transformer and the phase reactor in L and the equivalent losses in R . The control is defined by a feedback loop controlling the current at the PCC to follow a reference current which is in turn determined by the loops defining the power exchange. The transfer function of the current controller is denoted by G_{cc} . This loop also has the voltage at the PCC as a feed-forward term through the filter F_{ff} . A dead-time $e^{-t_d s}$ is represented in order to consider the time delay between the calculations and the synthesization at the valves. This control is very generic and it is the most common approach for VSC control.

Substituting the terms in Formula (7) by the terms in Figure 69, the VSC harmonic impedance is mathematically represented as:

$$Z_{conv} = \frac{C_V(f) + Z_T(f) + Z_R(f)}{1 - C_V(f)} = \frac{e^{-t_d s} G_{CC} + Ls + R}{1 - e^{-t_d s} F_{ff}} \quad (20)$$

Figure 70 shows the Bode plots of the converter station active and passive impedances. One can observe the significant influence of control dynamics with frequency.

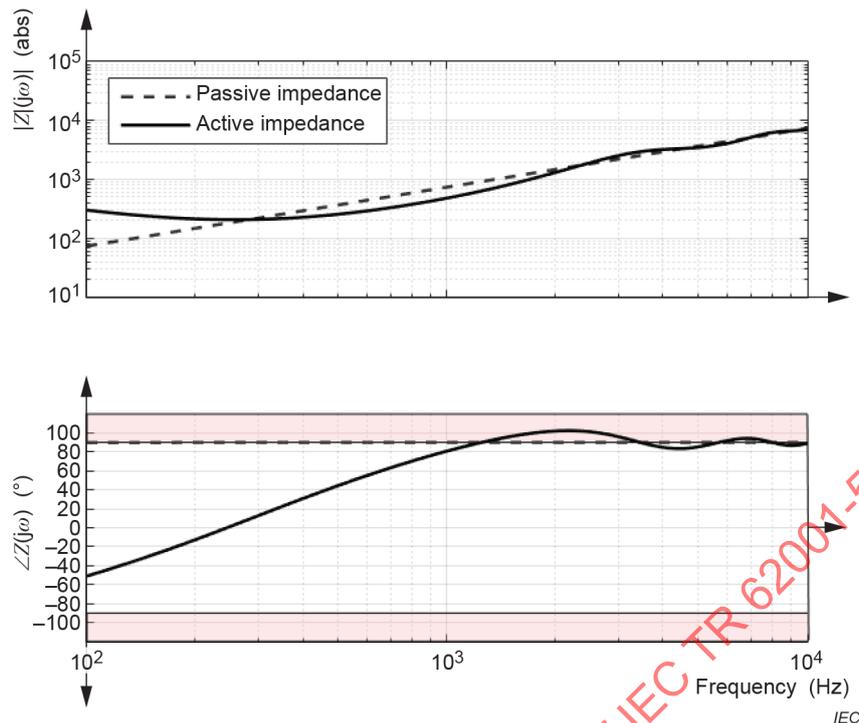


Figure 70 – Bode plot of the converter passive and active impedance

In this example, two different behaviours are observed along the frequency range. Between 100 Hz and 1 000 Hz, the phase angle of the active impedance results in increasing damping in comparison with the purely inductive behaviour of the passive impedance. This result is expected from the impact of the current control loop, which has the objective of controlling the current flowing through the reactor, with a constant proportional characteristic. Therefore, in case of existing resonances within this range, the converter response leads to a beneficial effect because it will damp the electromagnetic natural frequencies and mitigate the resulting network resonances.

Above 1 kHz, the behaviour differs significantly. The phase angle falls outside the passive boundaries ($-90^\circ < \theta < +90^\circ$) for certain frequency ranges as highlighted in red. These regions correspond to an equivalent negative resistive behaviour, or active conductance, of the converter. The consequence of this response is a decrease of the system damping within these frequency ranges.

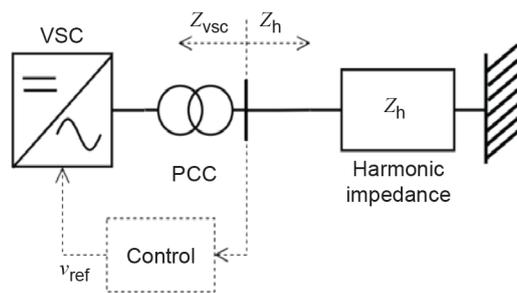
11.4.5 Harmonic instability

When the converter is connected to the electrical grid, the overall network resonances vary because of (i) the connection of the converter passive components and (ii) the impact of the converter's active behaviour. The result of the interaction between the network resonances and the active behaviour of the converter is the scope of the harmonic stability study.

The interaction is characterised by the natural frequencies of the network and the damping provided by the network and the converter. Electromagnetic natural frequencies appearing within a region in which the converter presents negative resistance behaviour may result in an instability if the network itself does not provide enough damping to compensate.

Besides the extreme case of instability, resonances coinciding with this region may also result in sustained oscillations for several seconds with corresponding over-voltages and other adverse effects.

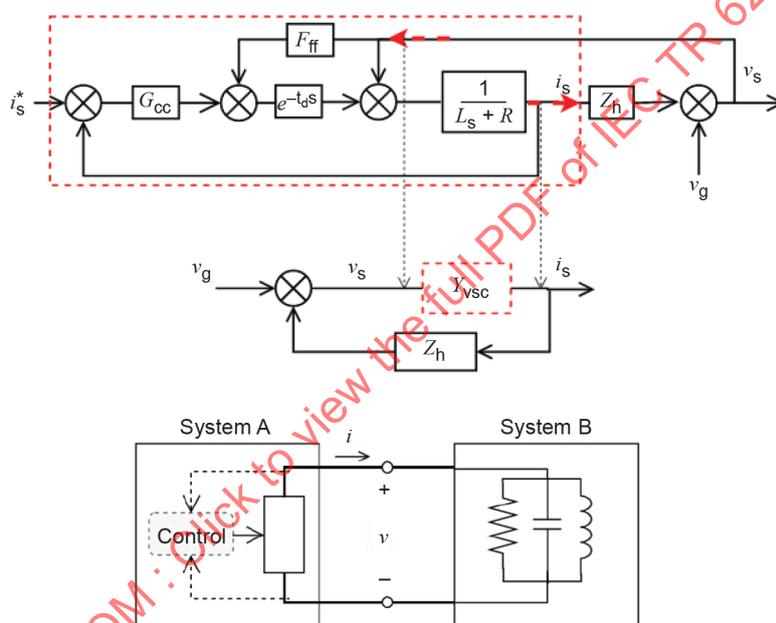
A generic example composed of a system with a VSC and a network with a given frequency-dependent behaviour is shown in Figure 71.



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Figure 71 – Example of a network composed of a VSC and a frequency-dependent AC system for the study of control interactions

The control dynamics together with interaction with the network (represented by the Thévenin impedance Z_h) are shown in Figure 72 where the terms have the same meaning as in Figure 69. The reduction of the complete VSC to an equivalent admittance is also illustrated.



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Figure 72 – Dynamic interaction between the active VSC impedance and the network passive impedance

The resulting resonances are represented in Figure 73, which may be contrasted to Figure 68 where only the passive impedance of the converter was represented. The interconnection of the VSC to the network results in new resonant points determined by the frequencies at which the impedance curves cross. The amplification factor is dependent on the angle difference. The closer to 180° the angle difference, the more amplified the resonance. Focusing on the VSC impedance curve, the angle shows some regions larger than 90° between 1 kHz and 3 kHz for this specific case. In these regions, the apparent negative resistance of the VSC active impedance will tend to exacerbate the resonance.

At 1 420 Hz, a resonant point of the equivalent parallel impedance Z_{eq} as seen from the PCC coincides with a negative resistance region of the converter.

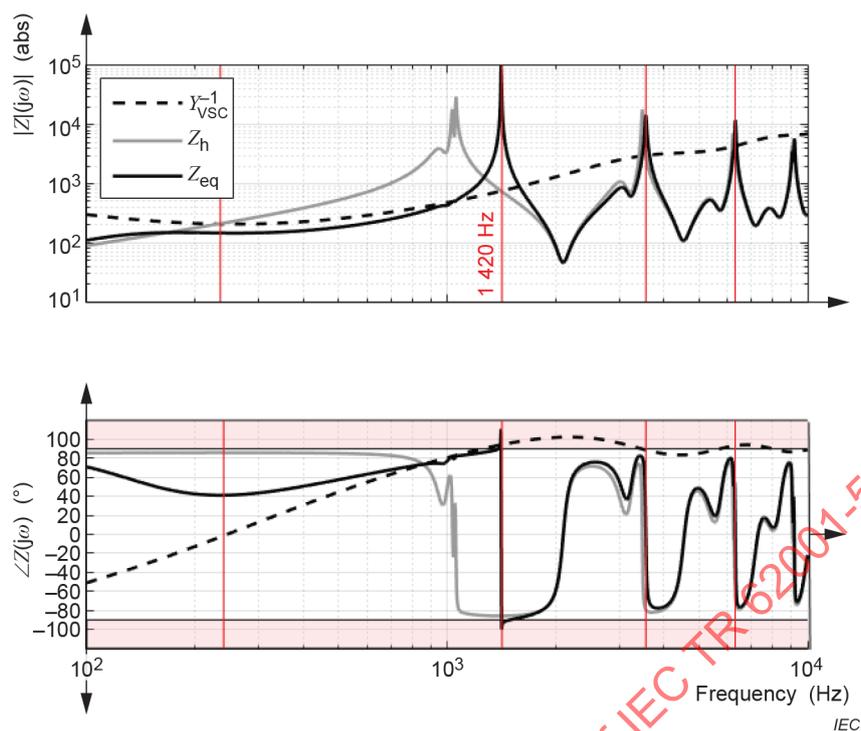
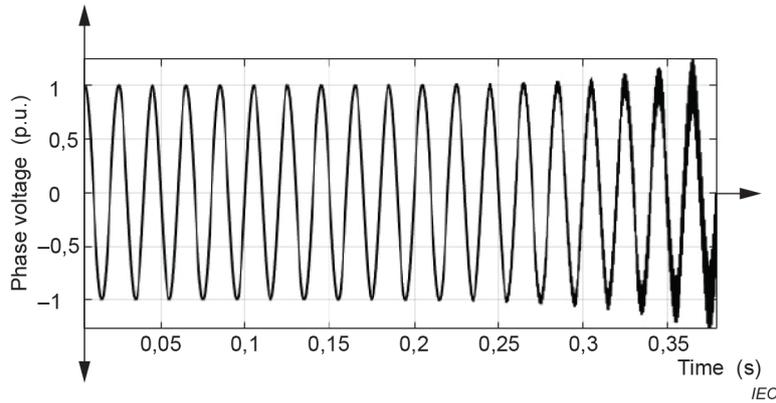
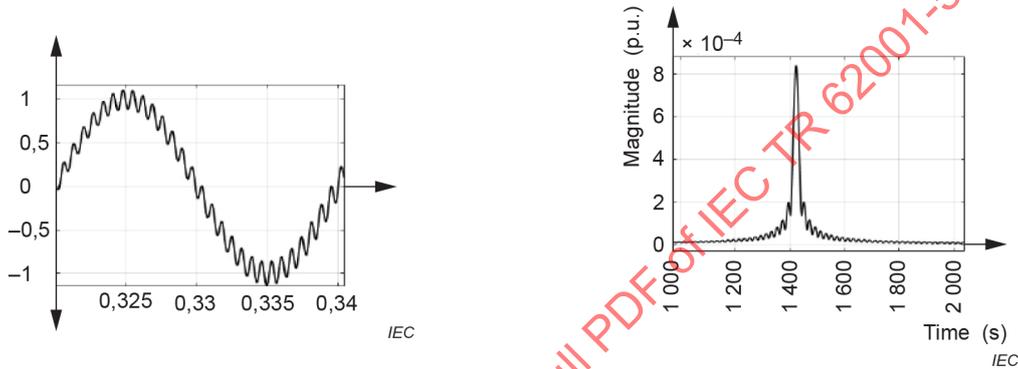


Figure 73 – Bode plot of the VSC and network impedance, including active converter effects

In an EMT simulation study of this system, the interaction is observed in the time-domain response of the PCC voltage as shown in Figure 74 a), b) and c). An initial small perturbation excites the natural frequency at 1 420 Hz, and the distortion increases as the converter effectively feeds energy into the system at that frequency. If the simulation were continued, the instability would increase until in reality some protection would act to trip the converter or other system component.



(a) Time-domain response of the phase voltage at the PCC



(b) Phase voltage during one period

(c) FFT applied within the window $t = 0:0,25$

Figure 74 – Results of EMT simulation study of the investigated system

11.5 Analysis methods

11.5.1 General

Harmonic stability can be studied by means of different methods, as typically done for all dynamic phenomena. Currently, there is no single universally accepted practice for harmonic stability analysis, rather a number of approaches demonstrated by academia and industry. Subclause 11.5 presents an overview of some of these methods. It is important to note that the analysis methods described are, with the exception of EMT simulation, to be considered as small disturbance methods based on implicit or explicit linearization. Whereas passive components can be considered approximately linear in most cases, converter control systems may contain rather strong non-linearities, which makes it imperative to perform analysis for various operating points and switching states of the grid.

11.5.2 Network impedance scans

Network impedance scanning is the most basic form of analysis technique that can be used to predict harmonic problems in power networks. Impedance scanning and subsequent analysis is an important tool in characterizing oscillations, and the way they propagate in the network and amplify or attenuate in the process. Resonance analysis is conveniently done using so-called impedance scans, even in complex networks (the approach is explained in 10.5). An impedance scan returns the input impedance seen from a general location and is defined as

$$Z(s) = \frac{\Delta V(s)}{\Delta I(s)} \tag{21}$$