

# TECHNICAL REPORT



High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters –  
Part 3: Modelling  
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## CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references.....	10
3 Harmonic interaction across converters.....	10
3.1 General.....	10
3.2 Practical experience of problems.....	11
3.3 Indicators of where harmonic interaction is significant.....	13
3.4 Interaction phenomena.....	14
3.5 Impact on AC filter design.....	15
3.5.1 General.....	15
3.5.2 AC side third harmonic.....	15
3.5.3 Direct current on the AC side.....	16
3.5.4 Characteristic harmonics.....	16
3.6 General overview of modelling techniques.....	16
3.6.1 General.....	16
3.6.2 Time domain AC-DC-AC interaction model.....	18
3.6.3 Frequency domain AC-DC-AC interaction model.....	19
3.6.4 Frequency domain AC-DC interaction model.....	19
3.6.5 Frequency domain current source model.....	19
3.7 Interaction modelling.....	20
3.7.1 General.....	20
3.7.2 Coupling between networks.....	20
3.7.3 Driving forces.....	21
3.7.4 System harmonic impedances.....	22
3.8 Study methods.....	22
3.8.1 Frequency domain.....	22
3.8.2 Time domain.....	22
3.9 Composite resonance.....	23
3.10 Core saturation instability.....	23
3.11 Particular considerations for back-to-back converters.....	23
3.12 Issues to be considered in the design process.....	24
3.12.1 General.....	24
3.12.2 Fundamental frequency and load issues.....	24
3.12.3 Negative phase sequence.....	25
3.12.4 Pre-existing harmonic distortion.....	26
3.12.5 AC network impedance.....	27
3.12.6 Converter control system.....	28
3.12.7 Combination with "classic" harmonic generation.....	29
3.12.8 Relative magnitude of pairs of low-order harmonics.....	29
3.12.9 Superposition of contributions.....	30
3.13 Parallel AC lines and converter transformer saturation.....	30
3.14 Possible countermeasures.....	32
3.14.1 AC (and/or DC) filters.....	32
3.14.2 DC control design.....	32
3.14.3 Operating restrictions and design protections.....	33

3.15	Recommendations for technical specifications .....	33
3.15.1	General .....	33
3.15.2	Specified design data .....	33
3.15.3	Requirements regarding calculation techniques .....	34
4	AC network impedance modelling .....	35
4.1	General.....	35
4.2	Implications of inaccurate definition of network impedance.....	36
4.3	Considerations for network modelling .....	37
4.3.1	General .....	37
4.3.2	Project life expectancy and robustness of data .....	37
4.3.3	Network operating conditions .....	37
4.3.4	Network impedances for performance and rating calculations.....	38
4.3.5	Modelling of network components.....	39
4.3.6	Representation of loads at harmonic frequencies .....	40
4.4	Network harmonic impedance envelopes .....	40
4.5	Methods of determining envelope characteristics .....	43
4.5.1	General .....	43
4.5.2	Low order harmonics.....	43
4.5.3	Mid-range and higher order harmonics .....	44
4.5.4	Balancing of risk and benefit .....	45
4.5.5	Consideration of tolerances on harmonic bands .....	46
4.5.6	Two separate envelopes for one harmonic band .....	48
4.5.7	Critical envelope parameters.....	49
4.5.8	Impedance envelopes for performance and rating conditions.....	49
4.6	Examples of the impact of different network impedance representations .....	50
4.6.1	Effect of network envelope parameters on resultant distortion .....	50
4.6.2	Effect of network minimum resistance on filter rating.....	53
4.7	Interharmonic impedance assessment .....	54
4.8	Measurement of network harmonic impedance.....	56
4.9	Conclusions .....	57
5	Pre-existing harmonics .....	57
5.1	General.....	57
5.2	Modelling and measurement of pre-existing harmonic levels .....	58
5.3	Harmonic performance evaluation, methods and discussion .....	60
5.3.1	General .....	60
5.3.2	"Incremental" harmonic performance evaluation.....	60
5.3.3	"Aggregate" harmonic performance evaluation.....	61
5.3.4	Both "incremental" and "aggregate" performance evaluation .....	62
5.3.5	"Incremental" and "maximum magnification factor" harmonic performance evaluation.....	63
5.4	Calculation of total harmonic performance indices.....	63
5.5	Harmonic rating evaluation .....	64
5.6	Difficulties with the voltage source/worst network model for rating.....	65
5.6.1	Background .....	65
5.6.2	Illustration of the voltage source/worst network method.....	66
5.7	Further possible calculation procedures for rating evaluation.....	68
5.7.1	Using measured levels of pre-existing distortion .....	68
5.7.2	Applying compatibility level voltage source at the filter busbar.....	70

5.7.3	Limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR) .....	72
5.7.4	Limiting total source distortion to the defined THD .....	73
5.7.5	Limiting harmonic order of pre-existing distortion .....	75
5.8	Conclusions .....	75
Annex A (informative) Location of worst-case network impedance .....		76
Annex B (informative) Accuracy of network component modelling at harmonic frequencies .....		79
B.1	General .....	79
B.2	Loads .....	79
B.3	Transformers .....	82
B.3.1	Transformer reactance .....	82
B.3.2	Transformer resistance .....	82
B.4	Transmission lines .....	85
B.5	Synchronous machines .....	87
B.6	Modelling of resistance in harmonic analysis software .....	88
Annex C (informative) Further guidance for the measurement of harmonic voltage distortion .....		91
Annex D (informative) Project experience of pre-existing harmonic issues .....		93
D.1	General .....	93
D.2	Third harmonic overload of filters in a back-to-back system .....	93
D.3	Third and fifth harmonic overload of filters in a line transmission .....	94
D.4	Overload of a DC side 6 <sup>th</sup> harmonic filter .....	94
Annex E (informative) Worked examples showing impact of pre-existing distortion .....		96
E.1	General .....	96
E.2	Pre-existing distortions .....	97
E.2.1	Example 1 – Illustration of magnification .....	97
E.2.2	Impact of network impedance parameters .....	101
Annex F (informative) Comparison of calculation methods .....		103
F.1	General .....	103
F.2	Reference case – Converter generated harmonics only .....	106
F.3	Method 1 – Source voltages behind impedance sector .....	106
F.4	Method 2 – Source voltages at filter bus (see 5.7.2) .....	106
F.5	Method 3 – Limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR) (see 5.7.3) .....	107
F.6	Method 4 – Limiting total source distortion to the THD level (see 5.7.4) .....	107
F.7	Method 5 – Pre-existing harmonics considered only up to the 10 <sup>th</sup> , with 10 % margin on converter generation for remainder (see 5.7.5) .....	110
Bibliography .....		111
Figure 1 – Key elements of a complete AC-DC-AC harmonic interaction model .....		17
Figure 2 – Equivalent circuit for evaluation of harmonic interaction with DC side interaction frequency greater than AC side fundamental frequency .....		21
Figure 3 – DC side 6 <sup>th</sup> harmonic voltage due to AC side 5 <sup>th</sup> harmonic (fixed angle) and 7 <sup>th</sup> harmonic (varying angle) .....		27
Figure 4 – Simple circuit used to represent AC network impedance at 5 <sup>th</sup> and 7 <sup>th</sup> harmonics .....		28
Figure 5 – Example of a single impedance locus for harmonic orders 2 to 49 .....		41

Figure 6 – Example of simple circle envelope encompassing all scatter points for harmonic orders 2 to 49 .....	42
Figure 7 – Example of an impedance envelope for 7 <sup>th</sup> to 13 <sup>th</sup> harmonic with associated scatter plots .....	44
Figure 8 – Example of an impedance envelope for 13 <sup>th</sup> to 19 <sup>th</sup> harmonic with associated scatter plots .....	45
Figure 9 – Example of an impedance envelope for 19 <sup>th</sup> to 25 <sup>th</sup> harmonic with associated scatter plots .....	45
Figure 10 – Example of the need to extend the band of harmonics to allow for resonance effects .....	47
Figure 11 – Application of tolerance range in percentage of the harmonic number .....	48
Figure 12 – Application of tolerance range in percentage of the harmonic number, zoomed to show 11 <sup>th</sup> and 13 <sup>th</sup> harmonics .....	48
Figure 13 – Example showing two impedance envelopes for a particular band.....	49
Figure 14 – Example of impedance envelopes under "performance" and "rating" conditions for harmonic orders 4 <sup>th</sup> to 7 <sup>th</sup> .....	50
Figure 15 – Example of impedance envelopes "performance" and "rating" conditions for harmonic orders 25 <sup>th</sup> to 31 <sup>st</sup> .....	50
Figure 16 – Discrete envelopes for different groups of harmonics.....	51
Figure 17 – Example showing a distributed generation causing about 15 % attenuation of ripple control signal at the PCC.....	55
Figure 18 – Generic circuit model for calculation of harmonic performance or rating .....	59
Figure 19 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system .....	60
Figure 20 – Circuit model for calculation of incremental performance .....	61
Figure 21 – Equivalent circuit of a network for the $h$ <sup>th</sup> harmonic .....	66
Figure 22 – Typical voltage magnification factor .....	67
Figure 23 – Pre-existing distortion set to measured levels (plus margin).....	68
Figure 24 – Pre-existing distortion applied directly at the filter bus .....	70
Figure 25 – Harmonic voltage stress on a shunt capacitor with IEC planning levels applied .....	72
Figure A.1 – Equivalent circuit model for demonstration of worst-case resonance between AC filters and the network .....	76
Figure A.2 – Diagram indicating vectors $Z_F$ , $Z_N$ and $Z_H$ .....	77
Figure B.1 – Typical equivalent load network.....	80
Figure B.2 – Relative error of equivalent load loss resistance $R_n$ of using [28] compared with Electra 167 [27] model.....	83
Figure B.3 – Effect of temperature on transformer load loss .....	84
Figure B.4 – Ratio between harmonic and fundamental frequency resistance as calculated for balanced mode components and calculated from averages of reduced $Z$ matrix resistance values .....	86
Figure B.5 – Ratio between harmonic and fundamental frequency resistance as calculated for balanced mode components and calculated from averages of reduced $Z$ matrix resistance values, for varying earth resistivity .....	87
Figure B.6 – Comparison of synchronous machine reactance between [4-1] recommendation and test measurements for a salient pole hydro generator of 370 MVA .....	87
Figure B.7 – Comparison of synchronous machine resistance between [17] recommendation and test measurements for a salient pole hydro generator of 370 MVA .....	88
Figure B.8 – Comparison of different approximations for resistance variations.....	89

Figure B.9 – Network impedance for Araraquara substation .....	90
Figure E.1 – Harmonic models for converter and for pre-existing distortion .....	97
Figure E.2 – Geometrical visualisation of selecting worst-case impedance for converter harmonics.....	97
Figure E.3 – Simple filter scheme to illustrate magnification.....	98
Figure E.4 – Plots illustrating magnification of various pre-existing harmonics.....	101
Figure F.1 – Network impedance sector used in example.....	103
Figure F.2 – Assumed filter scheme for examples of different methods of calculation .....	104
Figure F.3 – IEC planning levels used for source voltages in the study.....	105
Table 1 – Dominant frequencies in AC–DC harmonic interaction .....	15
Table 2 – Comparison of calculated harmonic voltage distortion between two methods of representing network harmonic impedance .....	52
Table 3 – Comparison of calculated harmonic voltage distortion considering the variation of network impedance angle.....	53
Table 4 – Comparison of calculated filter harmonic current considering the variation of network minimum resistance and filter detuning.....	54
Table 5 – Amplification factor $\tan \phi$ at different network impedance angles.....	66
Table 6 – Variation of calculated filter harmonic current as a function of detuning .....	71
Table B.1 – Constants for resistance adjustment – five parameter equations.....	89
Table E.1 – Parameters of elements of a simplified filter scheme shown in Figure E.3.....	98
Table E.2 – Voltage and current distortion for $Z_{\min} = 1 \Omega$ and varying $\phi$ .....	101
Table E.3 – Voltage and current distortion for $\phi = \pm 85^\circ$ and varying $Z_{\min}$ .....	102
Table F.1 – Table F.1 – Parameters of components of filters shown in Figure F.2.....	104
Table F.2 – Component rating calculated using different calculation methods.....	106
Table F.3 – Rating calculations using Method 3 – for BP1113 C1.....	107
Table F.4 – Rating calculations using Method 3 – for HP24 R1 .....	109
Table F.5 – Rating calculations using Method 4 – for BP1113 C1.....	110

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**HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –  
GUIDANCE TO THE SPECIFICATION AND  
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IEC TR 62001-3, which is a Technical Report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This first edition of IEC TR 62001-3, together with IEC TR 62001-1, IEC TR 62001-2 and IEC TR 62001-4, cancels and replaces IEC TR 62001 published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TR 62001:

- a) expanded and supplemented Clause 6;
- b) new Clause 4;
- c) new Clause 5;
- d) new annexes on the location of worst case network impedance;
- e) accuracy of network component modelling at harmonic frequencies;
- f) further guidance for the measurement of harmonic voltage distortion;
- g) project experience of pre-existing harmonic issues;
- h) worked examples showing impact of pre-existing distortion;
- i) comparison of calculation methods.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
22F/411/DTR	22F/415/RVC

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

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

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 ([standards.iteh.ai](http://standards.iteh.ai)).

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## INTRODUCTION

The IEC TR 62001 series is structured in four parts:

### Part 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.

### Part 2 – Performance

This part deals with current-based interference criteria, design issues and special applications, field measurements and verification.

### Part 3 – Modelling

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

### Part 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.

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

## Part 3: Modelling

### 1 Scope

This part of IEC TR 62001, which is a Technical Report, provides guidance on the harmonic interaction across converters, pre-existing harmonics, AC network impedance modelling and simulation of AC filter performance.

The scope of this document covers AC side filtering for the frequency range of interest in terms of harmonic distortion and audible frequency disturbances. It excludes filters designed to be effective in the PLC and radio interference spectra.

This document concerns the "conventional" AC filter technology and line-commutated high-voltage direct current (HVDC) converters.

### 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 61000-3-6:2008, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-30, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*

### 3 Harmonic interaction across converters

#### 3.1 General

In order to facilitate the analysis of harmonic generation by an HVDC converter, simplifying assumptions are often made. Typically, the HVDC converter is regarded as a generator of harmonic currents, with an infinite internal impedance. Such an assumption is reasonably valid for practical purposes for most harmonics, and is the basis of the calculation methods described in IEC TR 62001-1.

The customer should be aware, however, that such a simplified approach has limitations, and can lead to incorrect analysis and design in some circumstances. In practice, the converter is a link between the AC and DC side harmonic systems, and the AC side harmonic currents may be strongly influenced by the harmonic impedance and harmonic current flows on the DC side.

This is particularly true for low-order harmonics, and it is strongly recommended that the analysis of third harmonic distortion and filtering requirements should take into account the AC/DC side harmonic interaction. At the 11<sup>th</sup> and 13<sup>th</sup> harmonics, the interaction effect can

also be significant. At higher frequencies, although interactions occur, their practical impact on filter design and harmonic performance will normally be negligible.

Subclauses 3.2 to 3.15 give an overview of the interaction phenomena, focusing on practical implications for AC filter design. The technical specification should make it clear that such phenomena have to be taken into account, and the customer should be able to address the subject in his evaluation of the bidders' designs.

The terms "harmonic interaction" and "cross-modulation" are used synonymously in this report. "Cross-modulation" is to be understood here as the process of harmonic transfer across one converter, not, as it is sometimes used in a more specific sense, as the transfer of harmonics from one AC system to another via the intervening HVDC link.

CIGRE Technical Brochure 143 [1]<sup>1</sup> discusses in detail the technical aspects related to the subject. This is a comprehensive review of the subject and included valuable references to other publications. However, it concentrates on the theoretical aspects of calculation procedures. CIGRE Technical Brochure 533 [2] contains more guidance on the practical requirements for specifying and evaluating the treatment of cross-modulation during a tender and subsequent design process and some aspects not included or only briefly covered in [1]. Some of the fundamental conclusions of [1] [2] and other referenced books and papers have been summarised in this document.

Harmonic interaction across the converters can be a cause of problems, some examples of which are illustrated in 3.2. Proper consideration of cross-modulation during the design process can be of benefit not only in avoiding such future problems in operation, but also in possibly simplifying designs. There are examples of where 3<sup>rd</sup> harmonic filtering would have been necessary when using a simplified classic calculation with a stiff current source, but shown to be unnecessary when a full interaction model was applied, taking into account the impedances on both sides of the converter. It should therefore not always be assumed that consideration of cross-modulation will introduce problems or make the design more difficult – it may actually resolve some difficult issues.

This document does not recommend prescribing calculation procedures and conditions in the customer's technical specification. In practice, issues involving harmonic interaction have been treated in very different ways and using different study methods by various HVDC contractors in the past. However, customers need comparable bids and want to be in control of the risks associated with this phenomenon. Clause 3 will therefore pinpoint the important assumptions that need to be defined in a technical specification and it will recommend that contractors should justify their chosen calculation procedure and verify its accuracy.

### 3.2 Practical experience of problems

There has been considerable experience from operational HVDC schemes of adverse harmonic interactions between AC and DC sides of the converter. Several experiences are described in detail in [1]. A brief summary of some illustrative issues is given below.

One of the earliest incidents of reported interaction is related to the Kingsnorth HVDC link [3]. The particular combination of DC reactors and DC cable capacitance of the Willesden pole resulted in a series resonance condition at the fundamental frequency in the DC circuit. A small 2<sup>nd</sup> harmonic present on the AC side therefore resulted in high fundamental current on the DC side, which in turn gave cause to unequal firing pulse spacing. This resulted in a further contribution to the fundamental frequency voltage on the DC side and created small direct currents in the converter transformers, which tended to saturate the transformer cores, generating further 2<sup>nd</sup> harmonic distortions on the AC side. An additional flux control loop in the HVDC control system solved the problem. This was one of the earliest examples of what

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<sup>1</sup> Numbers in square brackets refer to the Bibliography.

is known as "core saturation instability" which has subsequently been observed on several HVDC schemes.

At the Chateauguay back-to-back converter station, a similar phenomenon occurred. A 2<sup>nd</sup> harmonic resonance condition was observed at the AC side of the converter [4]. The initially small pre-existing voltage distortion at the 2<sup>nd</sup> harmonic was transferred to the DC side of the converter. The resulting fundamental current on the DC side transferred back to the AC side as a 2<sup>nd</sup> harmonic current. Due to a parallel resonance of the AC network impedance at the 2<sup>nd</sup> harmonic, this converter current gave rise to a corresponding voltage distortion, and the loop was closed. The problem was solved by introducing an auxiliary direct current controller which created an external damping for the fundamental frequency component of the direct current. Shunt filters tuned to the 2<sup>nd</sup> harmonic have also been installed on the AC side.

During commissioning of the Gezhouba-Shanghai HVDC transmission, non-characteristic DC harmonic currents of orders 2, 6 and 18 were observed which caused an unduly large equivalent disturbing current. It was found that pre-existing voltage distortions of order 3, 5 and 7 on both AC sides caused a number of non-characteristic voltage distortions on the DC side. These met with near-resonant conditions at these frequencies on the DC side resulting in the observed current distortions. The implementation of additional resistive damping in the DC filters, as well as changes to the neutral capacitor, solved the problem.

For the same scheme, it was also reported that the 11<sup>th</sup> harmonic AC side converter current was significantly higher, and the 13<sup>th</sup> harmonic significantly lower, when a 12<sup>th</sup> harmonic current of not negligible value flows in the DC circuit. Possibly, this is the case for most HVDC schemes, but is rarely mentioned.

In the design of the Quebec-New England multiterminal scheme, a 60 Hz component in the DC circuit caused by induction from nearby AC lines was anticipated due to the planned DC line route. This induced fundamental frequency current would cross the converter and generate direct current in the transformer winding, which could lead to core saturation. The design of the scheme therefore included a series blocking filter tuned to the fundamental frequency inserted in the DC neutral of each converter.

A second issue in the same project was related to the Radisson converter station [5]. The station is located in an area of the far north of Canada where geomagnetic activity is strong and the ground resistivity is high. This combination can create high direct currents in transformer neutrals during geomagnetic storms. During such an event, 5<sup>th</sup> and 7<sup>th</sup> harmonic distortion on the AC side due to transformer saturation produced excessive 6<sup>th</sup> harmonic on the DC side resulting in the failure of a DC filter arrester. It was found that the converter impedance as seen from the AC side, which was heavily determined by 6<sup>th</sup> harmonic impedance of the DC side, shifted the resonance frequency between the AC network and the complete converter station from below 3<sup>rd</sup> (i.e. not considering converter impedance) to around 5<sup>th</sup> harmonic. The problem was mitigated by introducing a 5<sup>th</sup> harmonic re-tuning circuit to two existing 36/48<sup>th</sup> harmonic AC filters. This re-tuning circuit consists of a filter reactor in parallel with a resistor, installed at the neutral side of the filter. This circuit, normally short-circuited by a bypassing switch, is activated when high 5<sup>th</sup> or 7<sup>th</sup> harmonic distortion is detected, resulting in a re-tuning of the filter to 5<sup>th</sup> harmonic.

At the Sandy Pond inverter station of the same scheme, increasing levels of pre-existing 5<sup>th</sup> harmonic in the AC network resulted in overload of the DC side 6<sup>th</sup> harmonic filter, due to cross-modulation. The problem was resolved by converting the existing shunt capacitors to 5<sup>th</sup> harmonic filters.

The Blackwater back-to-back HVDC Intertie also suffered from a 2<sup>nd</sup> harmonic instability related to transformer core saturation. A solution was reported which involved modulation of the converter firing angles.

At the Kristiansand converter station on the Norwegian side of the Skagerrak, HVDC Transmission scheme transformer core instabilities and occasional significant harmonic

distortions in the low order range have been observed, which led to tripping of AC lines and transformers. Theoretical investigations [6] indicated that the energization of a 400kV shunt reactor in the Tjele converter station in Denmark can cause saturation of the local transformers. The resulting AC side 2<sup>nd</sup> harmonic voltage distortions cause a significant fundamental current in the DC circuit which is transferred to the Kristiansand converter station in Norway. The Kristiansand converters transform this fundamental current into a DC current on their AC side resulting in unsymmetrical transformer saturation. The zero sequence currents thus generated on the network side can reach values which are able to trigger AC line protection. The effectiveness of a 50 Hz damping control similar to the one developed for the Chateaugay project was proven for the Skagerrak scheme.

A second effect, occasionally observed at Kristiansand, was transformer tripping due to current overload. It was found that high negative phase sequence components of the fundamental frequency voltages in Norway, caused by heavy load flow over not fully transposed AC lines, cause third harmonic current generation by the converters on the AC side, and this feeds into an AC network which can experience occasional resonance at third harmonic. As these network resonances can not be avoided, detuning of the impedance by temporary filter tripping, triggered by a protection related to high harmonic currents, was defined as a general counter measure.

The Sasaram 500MW back-to-back HVDC station interconnects two asynchronous AC systems. During initial commissioning testing, on some occasions the unbalance in one of the AC systems exceeded the specified level of 1 % NPS voltage. This resulted in 2<sup>nd</sup> harmonic generation on the DC side and consequent 3<sup>rd</sup> harmonic current generation into the AC system. This resulted in thermal overload of the resistors in the installed 3<sup>rd</sup> harmonic C-type filters. The problem did not persist, but illustrated the sensitivity of some station equipment to AC-DC harmonic interactions.

During design studies of a large undersea HVDC interconnection in Japan, a vulnerability to core saturation instability was observed. The DC cable system exhibited series resonance near the fundamental frequency, and the AC systems had an impedance resonance near the second harmonic. The AC systems were not particularly weak. For purposes of compaction, the shunt capacitor banks were implemented using dead-tank construction at medium voltage, with transformers connecting these banks to the EHV level. The transformer-capacitor combination yielded a series resonance near the third harmonic, introducing the impedance resonance with the grid at a lower frequency near second harmonic. Small signal analysis techniques, described in [7], were used to screen system conditions for this core saturation instability phenomenon. A modification of the capacitor bank design was implemented, which has avoided this issue during operation.

### 3.3 Indicators of where harmonic interaction is significant

The practical implications of AC-DC harmonic interaction are mainly related to low order harmonics. Although the theory of cross-modulation is equally valid at all frequencies, the increasing inductive impedance of the converter transformers and DC side smoothing reactors with rising frequency tend to limit higher order DC side harmonic currents and, consequently, their transferred impact on the AC sides is correspondingly smaller.

Harmonic interaction has to be considered for both harmonic performance and filter rating type calculations as well as its impact on protections and the overall dynamic behaviour of the converter station and its controls.

HVDC systems connected to AC nodes with low short circuit ratios, i.e. implying high network impedance at low order harmonic frequencies, and/or nodes which tend to experience significant negative phase sequence components of the fundamental voltage, are more likely to be at risk of harmonic interaction problems.

For back-to-back schemes, interaction should always be investigated, as their DC circuit may not provide effective smoothing or damping of harmonics and as they may interconnect systems with asynchronous or even different nominal frequencies.