IEC TS 63529

Edition 1.0 2026-04

TECHNICAL SPECIFICATION

DC side harmonics & filtering in HVDC transmission systems

ICS 29.200; 29.240.01

ISBN 978-2-8327-1168-2

IEC TS 63529:2026-04(en)

THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2026 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, …). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD 13
INTRODUCTION 15
0.1 Introduction 15
0.2 Continuing relevance 15
1 Scope 16
2 Normative references 16
3 Terms, definitions, symbols and abbreviated terms 16
3.1 General terms 17
3.2 Specific terms 18
3.3 Symbols 21
3.4 Abbreviated terms 21
4 Overview of this document 22
4.1 General 22
4.2 Experience 22
4.3 Literature 22
4.4 Harmonic generation 23
4.5 Modelling 23
4.6 Inductive coupling to telecommunication systems 23
4.7 Mitigation measures 23
4.8 Elimination or reduction of DC filters 24
4.9 DC side low-order resonance 24
4.10 Various other issues 24
4.11 Specification and design 24
4.12 Illustrative example 24
4.13 Reference material 24
5 DC side harmonic generation – LCC technology 25
5.1 General 25
5.2 DC side harmonic generation – basic concepts 25
5.2.1 Idealized assumptions 25
5.2.2 Influence of non-idealities 26
5.3 Stray capacitance and the three-pulse model 28
5.4 Influence of non-idealities 28
5.5 Harmonic cross-modulation from AC side 28
6 DC side harmonic generation – VSC technology 30
6.1 General 30
6.2 Harmonic generation from VSC using switch type valves 31
6.2.1 Overview 31
6.2.2 Two-level converter with carrier-based PWM 31
6.2.3 Two-level converter with optimized PWM (OPWM) 34
6.3 Harmonic generation from multilevel VSC 36
6.3.1 Overview 36
6.3.2 Harmonic generation from a CTL converter 37
6.3.3 Harmonic generation from MMC type converters 38
6.4 Harmonic cross-modulation from AC side 41
6.5 Influence of non-idealities 41
6.6 Ground mode harmonics 42

6.7 Converter impedance 43
6.7.1 Overview 43
6.7.2 Passive impedance 44
6.7.3 Active impedance 44
7 Modelling and analysis 45
7.1 General 45
7.2 Frequency domain, time domain and other techniques 45
7.3 HVDC converter modelling for LCC technology 46
7.4 HVDC converter modelling for VSC technology 47
7.5 DC line modelling 48
7.6 HVDC cable modelling 49
7.7 DC switchyard equipment modelling 49
7.8 Detuning due to frequency and component deviations 50
7.8.1 Overview 50
7.8.2 Individual consideration of filter component detuning and AC frequency variation 51
7.8.3 Equivalent frequency detuning 52
7.9 Harmonic current calculation 53
7.10 Frequency dependent modelling 54
7.11 Detailed aspects to be considered in studies for LCC 54
7.12 Transfer of disturbances between AC systems 55
8 Inductive coupling to telecommunication lines 56
8.1 General 56
8.2 Analytical method 57
8.3 Analysis of harmonic currents in the DC system 58
8.4 Mutual impedance between power lines and telephone lines 58
8.4.1 Overview 58
8.4.2 Calculations of mutual impedance 58
8.4.3 Variation of mutual impedance with frequency, resistivity and separation 63
8.4.4 Influence of earth resistivity 66
8.4.5 Crossings and angled exposures 67
8.5 Induced voltages on telephone lines 67
8.5.1 Overview 67
8.5.2 Longitudinal induced voltages 68
8.5.3 HVDC transmission line shield wires 68
8.5.4 Telephone circuit shielding factor (K_n) 69
8.5.5 Telephone circuit balance factor (B_n) 70
8.5.6 Psophometric weighting 70
8.5.7 Calculation of differential (metallic mode) weighted induced voltage 71
8.6 Equivalent disturbing current method (I_{eq}) 73
8.6.1 Methodology 73
8.6.2 Determination of H_n factor 74
8.6.3 Differences between a 50 Hz and a 60 Hz system 78
8.7 Modal analysis 78
8.7.1 General 78
8.7.2 Modal analysis of HVDC conductor currents 78
8.7.3 Modal analysis of mutual impedance 79
8.7.4 Modal analysis of coupling between HVDC and communication lines 81

8.8 Induced voltage in a test line 84
8.9 Electrode lines 84
8.10 Inductive coupling from HVDC underground cables 85
8.11 Frequency range 86
8.12 Digital telecommunications systems 87
8.13 Railway signal interference 87
9 Harmonic performance limits 88
9.1 General 88
9.2 Procedure to determine limits 89
9.3 Standard limits for induced noise 90
9.3.1 Overview 90
9.3.2 IEEE and Canadian standards 90
9.3.3 ITU-T standard 92
9.3.4 Comparison between standards 92
9.3.5 Allowance for other noise sources 92
9.4 Derivation of equivalent disturbing current (I_{eq}) limit 93
9.5 Rapid estimation of permissible disturbing current limit 94
9.5.1 Overview 94
9.5.2 Using IEEE recommendations 95
9.5.3 Using ITU-T recommendations 96
9.6 Considerations for definition of limits 97
9.6.1 Overview 97
9.6.2 Variation of performance limits along the transmission corridor 97
9.6.3 Variation of harmonic limits with time duration 99
9.6.4 Unbalanced bipolar operation 99
9.6.5 Consideration of pole mode contribution 100
9.6.6 Combination of harmonic current contributions from converter stations 100
9.7 Limits for induced voltage criterion 101
9.8 Experience from existing projects 101
9.9 Harmonic performance limits for HVDC cables 102
9.10 Harmonic rating limits for HVDC cables 104
9.11 Safety aspects 105
10 Harmonic performance verification and measurements 105
10.1 General 105
10.2 Compliance verification 106
10.3 Measurements on DC conductors 106
10.4 Measurements of external induction 108
10.4.1 Overview 108
10.4.2 Measurements to indirectly assess disturbing current 108
10.4.3 Verification by magnetic field measurements 110
10.4.4 Measurements to assess disturbance to an actual telephone line 111
10.5 Monitoring equipment and analytical software 112
10.6 Influence of mutual impedance and earth resistivity 112
10.7 Duration and analysis of measurements 114
11 Mitigation of adverse effects of DC side harmonics 114
11.1 General 114
11.2 Objectives of mitigation measures 115
11.3 Optimization of cost of mitigation measures 115

11.4 Mitigation measures in the HVDC system 115
11.4.1 Overview 115
11.4.2 Mitigation measures for LCC HVDC 116
11.4.3 Mitigation measures for VSC HVDC 117
11.5 Mitigation measures in telecommunication systems 118
12 DC filter design 118
12.1 General 118
12.2 DC filter fundamentals 119
12.3 Filtering mechanisms for LCCs 120
12.4 DC filter design process 123
12.5 Possible DC filter configurations 125
12.5.1 Single-tuned filters 125
12.5.2 Multiple-tuned filters 127
12.5.3 Damping resistors in shunt filters 133
12.6 Arrangement and switching of filter banks 135
12.6.1 Overview 135
12.6.2 Choice of switchable filter units 136
12.6.3 Capability and speed of switches 136
12.6.4 Switching of additional filters in monopolar mode 136
12.6.5 Use of out-of-service pole filters in monopolar mode 137
12.7 Neutral side smoothing reactors and impact on DC side harmonic flow 138
12.8 Pole to earth filters 139
12.9 Series filters 140
12.10 Active filters 141
12.11 Paralleling of DC lines and DC filters 142
12.12 Equipment rating for harmonic stresses 144
12.12.1 General 144
12.12.2 Calculation principles 144
12.12.3 Calculation considerations 145
12.12.4 Derivation of rating parameters 145
12.12.5 Outage contingencies 146
12.12.6 Short-time rating 147
12.12.7 Re-evaluation of critical cases 147
12.13 Rating for abnormal operation conditions 148
12.14 Transient rating 148
12.15 Protection aspects 151
12.16 Reliability and availability 152
12.16.1 Overview 152
12.16.2 Outage management 153
12.17 Audible noise 153
12.18 Losses 154
12.19 Mechanical and visual design 155
12.20 Economic aspects 157
12.20.1 General 157
12.20.2 Equipment costs 157
12.20.3 Other costs 158
12.21 Safety aspects related to harmonic currents 158
12.21.1 HVDC substations 158
12.21.2 HVDC transmission lines 158

12.22 Seismic requirements 159
13 Elimination or reduction of DC filters 160
13.1 General 160
13.2 Refurbishment of existing LCC HVDC schemes 161
13.3 Overhead line and cable transmissions 161
13.4 DC filters in a hybrid LCC-VSC system 162
13.4.1 General 162
13.4.2 Assessment of vulnerability of the VSC to DC side harmonic currents 163
13.4.3 With limitations due to telecommunication interference 163
13.4.4 No limitations due to telecommunication interference 163
13.5 Back-to-back systems 164
14 DC side low order resonance 164
14.1 General 164
14.2 Parameters affecting low-order resonance 165
14.2.1 Overhead line transmission 165
14.2.2 Cable transmissions 168
14.3 Low order harmonic voltage sources 170
14.4 Impact of high values of 2nd harmonic currents and voltages 171
14.5 Core saturation instability 173
14.6 Mitigation measures 174
14.7 Study and assessment 176
15 Coupling between DC line and parallel AC lines 177
15.1 General 177
15.2 Deleterious effects of fundamental frequency induction 178
15.3 Factors affecting significance 179
15.4 Study methods 181
15.5 Modes and impacts of induced currents 181
15.6 AC line configuration, loading and phase sequences 183
15.7 Effect of earth resistivity 184
15.8 Location along line route 185
15.9 Multiple AC line exposures 185
15.10 AC and DC lines sharing a tower 187
15.11 Transpositions 188
15.11.1 Overview 188
15.11.2 DC line transpositions 188
15.11.3 AC line transpositions 189
15.12 Cross modulation in LCC and VSC 190
15.13 Mitigation measures 190
15.13.1 General 190
15.13.2 Transposition of DC and/or AC lines 191
15.13.3 Fundamental frequency filters 191
15.13.4 Control actions 192
15.14 Interaction between nearby HVDC links 193
16 Harmonics in HVDC grids 193
16.1 General 193
16.2 Similarities with AC networks 194
16.3 Harmonic emissions in an HVDC grid 196
16.4 Network harmonic impedance of an HVDC grid 196

16.5 Harmonic distortion limits for HVDC grids 196
16.6 Allocation of headroom 197
16.7 Use of DC filters 198
16.8 DC side harmonic stability 198
17 Impact of geomagnetic storms 199
17.1 General 199
17.2 Impact on DC side harmonics 199
18 Guidelines for requirement specifications 200
18.1 General 200
18.2 Environmental licencing considerations 200
18.3 Vulnerable infrastructure 201
18.4 Circuit configurations and operating conditions 201
18.4.1 General 201
18.4.2 Circuit configurations 201
18.4.3 Operating modes 202
18.4.4 Special operating conditions 202
18.4.5 Range of operating parameters 202
18.4.6 Environmental parameters 203
18.5 Basic data to be considered for harmonic calculation 203
18.5.1 DC transmission line data 203
18.5.2 AC system data 203
18.5.3 Deviation of parameters and tolerances to be considered 204
18.5.4 DC filter outage and redundancy requirements 204
18.6 Methods for harmonic calculation 204
18.7 Performance requirements regarding telecommunication interference 205
18.8 Requirements regarding danger from induced voltages 205
18.9 Ripple voltage on cables and overhead lines 206
18.10 Other criteria for filter design 206
18.10.1 Additional requirements 206
18.10.2 Standards and test requirements 206
18.10.3 Filter component rating 206
18.10.4 Insulation levels 206
18.10.5 Availability, reliability and switching 206
18.10.6 Protection and safety 206
18.11 DC side harmonic field measurements 207
19 Equipment design and test requirements 207
19.1 General 207
19.2 General requirements 207
19.2.1 Structural 207
19.2.2 Failure rate 208
19.2.3 Quality assurance 208
19.2.4 Equipment test requirements 209
19.2.5 Technical information submitted by the contractor 209
19.2.6 Filter component ratings 210
19.3 Capacitors 210
19.3.1 Capacitors general 210
19.3.2 Capacitor design aspects 211
19.3.3 Capacitor electrical data 213
19.3.4 Capacitor tests 214

19.4 Reactors 215
19.4.1 Reactors general 215
19.4.2 Reactor design aspects 216
19.4.3 Reactor electrical data 217
19.4.4 Reactor tests 218
19.5 Resistors 218
19.5.1 Resistors general 218
19.5.2 Resistor design aspects 218
19.5.3 Resistor electrical data 219
19.5.4 Resistor tests 220
19.6 Arresters 222
19.6.1 Arresters general 222
19.6.2 Arrester design aspects 222
19.6.3 Arrester electrical data 223
19.6.4 Arrester tests 223
19.7 Current transformers 224
19.7.1 Current transformers general 224
19.7.2 Current transformer design aspects 224
19.7.3 Current transformer electrical data 224
19.7.4 Current transformer tests 225
19.8 Filter switching equipment 226
19.8.1 Filter switching equipment general 226
19.8.2 Filter switching equipment design aspects 226
19.8.3 Filter switching equipment electrical data 226
19.8.4 Filter switching equipment tests 227
Annex A (normative) Stray capacitances and the three pulse model 228
A.1 Overview 228
A.2 Calculation of three-pulse harmonic driving voltages 228
A.3 Phase angles of triplen order harmonic generation 232
A.4 Return path for ground mode currents 233
A.5 Triplen order harmonic current flow through stray capacitances 234
A.5.1 General 234
A.5.2 Odd order triplens 235
A.5.3 Even order triplens 238
A.5.4 Odd and even harmonic flow in bipolar mode 240
A.6 Complete harmonic current paths 241
A.7 Stray capacitive paths in converter transformer 244
A.8 Influence of non-idealities 247
Annex B (informative) Illustrative calculations 251
B.1 General 251
B.2 Data 251
B.3 Results 252
B.4 Mechanisms of harmonic current flow 252
B.4.1 Studies for current flow 252
B.4.2 Case A 252
B.4.3 Case B 252
B.4.4 Case C 252
B.4.5 Case D 253
B.4.6 Case E 253

B.5 Filter solutions for different target disturbance limits 253
B.5.1 Studies for filter solutions 253
B.5.2 Case F 253
B.5.3 Case G 253
B.5.4 Case H 254
B.5.5 Case I 254
B.5.6 Case J 254
B.5.7 Case K 254
B.5.8 Case L 254
B.6 General conclusions 254
B.7 Connection of filters from pole to earth 255
B.7.1 Case M 255
B.7.2 Case N 255
B.8 Smoothing reactor sizing 255
B.9 Electrode line harmonic disturbing current 255
B.10 Other operation modes 256
Bibliography 258

Figure 1 – DC-voltage for 12-pulse operation 26
Figure 2 – References and carrier for a two-level converter using PWM with pulse number 9 32
Figure 3 – Resulting modulation waveform for one phase of a two-level converter using PWM with pulse number 9 32
Figure 4 – AC current is directed through the positive path when the modulation signal is positive and the negative path when the signal is negative 33
Figure 5 – Source current from the converter on the DC side (before the pole capacitor) 33
Figure 6 – Current harmonic spectrum for a two-level converter with pulse number 39 34
Figure 7 – Current harmonic spectrum for a two-level converter with pulse number 39 (extended frequency range) 34
Figure 8 – Modulation waveform and fundamental voltage on AC side for OPWM 35
Figure 9 – DC side current waveform contribution from one phase 35
Figure 10 – DC current harmonic spectrum for a two-level converter with OPWM 36
Figure 11 – DC current harmonic spectrum for a two-level converter with OPWM (extended frequency range) 36
Figure 12 – Voltage source representation of the MMC or CTL ([28] [29]) 37
Figure 13 – Example of the DC voltage harmonic spectrum from a CTL converter 38
Figure 14 – Example of the DC voltage harmonic spectrum from a CTL converter (extended frequency range) 38
Figure 15 – Valve voltage generation [28] [29] 39
Figure 16 – Harmonic spectrum of the DC voltage U_{DC} 39
Figure 17 – Harmonic spectrum of the DC voltage U_{DC} (extended frequency range) 40
Figure 18 – Harmonic spectrum for one arm of the MMC converter (extended frequency range) 40
Figure 19 – Pole mode current paths for MMC symmetrical monopole 42
Figure 20 – Ground mode current paths for MMC symmetrical monopole 42
Figure 21 – Active and passive impedance elements 43

Figure 22 – Energy balancing 44
Figure 23 – Illustration of converter active impedance seen from the DC side 45
Figure 24 – Coupling between an HVDC overhead line and a parallel telecommunication line 56
Figure 25 – Complex earth return plane 61
Figure 26 – Absolute depth of earth return plane as a function of frequency and resistivity 61
Figure 27 – Complex earth return plane and image conductor 62
Figure 28 – Difference between Carson's and Dubanton's equations for 100 m separation and 1 000 Ω-m earth resistivity 63
Figure 29 – Real part of the mutual impedance for different separation distances (for 100 Ω-m) 64
Figure 30 – Imaginary part of the mutual impedance for different separation distances (for 100 Ω-m) 64
Figure 31 – Absolute value of the mutual impedance for different separation distances (for 100 Ω-m) 65
Figure 32 – Real part of the mutual impedance for different earth resistivities (for 100 m separation) 65
Figure 33 – Imaginary part of the mutual impedance for different earth resistivities (for 100 m separation) 66
Figure 34 – Absolute value of the mutual impedance for different earth resistivities (for 100 m separation) 66
Figure 35 – Comparison of C-message and ITU-T (formerly-CCITT) weighting curves 71
Figure 36 – Mutual impedances for varying separation at resistivity 100 Ω-m (linear frequency scale) 76
Figure 37 – Modal impedances as function of earth resistivity, for separation distance 100 m 80
Figure 38 – Modal impedances as function of separation for earth resistivity 100 Ω-m 80
Figure 39 – Example of HVDC cable route (red) and nearby telephone cable beside a road (blue) 86
Figure 40 – Relationship between induced voltage and telephone noise in dBrn 91
Figure 41 – Mutual impedance magnitude at 800 Hz versus separation distance 93
Figure 42 – Mutual impedance magnitude at 1 000 Hz vs. separation distance 94
Figure 43 – Permissible I_{eq} versus earth resistivity for varying separations (IEEE criteria) 95
Figure 44 – Permissible I_{eq} versus separation for varying earth resistivities (IEEE criteria) 96
Figure 45 – Permissible I_{eq} versus earth resistivity for varying separations (ITU-T criteria) 96
Figure 46 – Permissible I_{eq} versus separation for varying earth resistivities (ITU-T criteria) 97
Figure 47 – Variation along a DC line of total I_{eq} and harmonics emitted by one converter station 98
Figure 48 – Variation along a DC line of total I_{eq} and harmonics emitted by both converter stations 98
Figure 49 – Maximum exposure distances for two different VSC converter types 104
Figure 50 – Measurement of cable core current only 107

Figure 51 – Additive and subtractive connection of Rogowski coils 107
Figure 52 – Practical arrangements for test line measurements 108
Figure 53 – Alternative measurement locations to eliminate pole mode influence 109
Figure 54 – Convenient location of test vehicle 110
Figure 55 – Measurement of I_{eq} by magnetic loop antenna 111
Figure 56 – Possible test arrangement for telephone line partially parallel to DC cables 112
Figure 57 – Double test line method 113
Figure 58 – Overview of DC filtering configuration 120
Figure 59 – Additional line reactors 121
Figure 60 – Typical single-frequency filter configuration and sample impedance plot 125
Figure 61 – Single-frequency filter with bypass capacitor connection and sample impedance plot 126
Figure 62 – Typical double-tuned filter configuration and sample impedance plot 127
Figure 63 – Typical double-tuned filter configuration with bypass capacitor and sample impedance plot 130
Figure 64 – Typical triple-tuned filter configuration 131
Figure 65 – Impedance plot for a 12th/24th/36th triple tuned filter 131
Figure 66 – Double-tuned filters with optional resistor locations 133
Figure 67 – Double tuned filter impedance characteristic without resistors 133
Figure 68 – Impedance characteristic with R_2 = 300 Ω 134
Figure 69 – Impedance characteristic with R_1 = 500 Ω 134
Figure 70 – Impedance characteristic with R_{hp} = 500 Ω 135
Figure 71 – Common additional monopolar filter 137
Figure 72 – Smoothing reactance split between pole and neutral 139
Figure 73 – Impedance plot for one particular pole-earth filter 140
Figure 74 – Possible series “blocking” filter configurations 140
Figure 75 – Paralleling of converters and DC lines 143
Figure 76 – Equivalent circuit for transient analysis of earth faults on pole line 149
Figure 77 – Equivalent circuit for transient analysis of switching surges 150
Figure 78 – 800 kV DC filter HV capacitor 156
Figure 79 – Comparison of the design response spectra of different seismic codes 159
Figure 80 – Impedance of overhead DC line for different line lengths (remote end short-circuited) 165
Figure 81 – Circuit components affecting DC side resonance 166
Figure 82 – Influence of converter station components on 1 500 km DC side impedance 167
Figure 83 – Total impedance seen from inside the converter for an LCC HVDC cable system example 168
Figure 84 – Pole mode impedances of 300 km XLPE cable pair 169
Figure 85 – Pole mode impedances of 150 km XLPE cable pair 170
Figure 86 – Ground mode impedances of 300 km XLPE cable pair 170
Figure 87 – Direct current (in kA) response to AC 1-ph fault (time scale 10 ms/div) 173
Figure 88 – Additional line reactor 175
Figure 89 – Currents in DC line caused by inductive and capacitive coupling 178

Figure 90 – Half-cycle saturation due to DC offset 179
Figure 91 – Typical harmonic content of magnetizing current for half-cycle saturation..... 179
Figure 92 – Factors affecting fundamental frequency induction 180
Figure 93 – Induced modal voltages for different separations between AC and DC lines 182
Figure 94 – Alternative paths through symmetrical monopole for induced ground mode fundamental frequency current..... 183
Figure 95 – Induction in one DC conductor for close and distant AC-DC line separations 184
Figure 96 – Several parallel AC lines 185
Figure 97 – Second AC line acts partially as a load on the DC circuit..... 186
Figure 98 – Second AC line in same location acts as shield wires..... 187
Figure 99 – Capacitive coupling on a hybrid AC-DC transmission line..... 188
Figure 100 – Effect of transposing the DC line on induced fundamental frequency..... 189
Figure 101 – Effect of perfect AC line transposition on induced fundamental frequency in DC line..... 190
Figure 102 – Fundamental frequency blocking filters (with alternative resistor locations)..... 191
Figure 103 – Fundamental frequency blocking filter locations for a symmetrical monopole..... 192
Figure 104 – Example of a hypothetical HVDC grid [149] 193
Figure 105 – Concept of Planning Levels and Compatibility Levels ([108]) 195
Figure 106 – Planning level and headroom 195
Figure 107 – Geomagnetic induction in the DC circuit 199
Figure A.1 – Decomposition of 6-pulse waveform into three-pulse waveforms..... 229
Figure A.2 – Six-pulse converter modelled as series connection of two three-pulse converters..... 229
Figure A.3 – Twelve-pulse converter modelled as series connection of four three-pulse converters..... 230
Figure A.4 – 6^{th} harmonic driving voltage per three-pulse bridge 231
Figure A.5 – 12^{th} harmonic driving voltage per three-pulse bridge 231
Figure A.6 – Relative phase displacement of three-pulse sources (balanced bipolar operation) 233
Figure A.7 – Pole and neutral path equivalents for triplen harmonics 234
Figure A.8 – Odd triplen harmonic generation and current flow (part 1)..... 235
Figure A.9 – Odd order triplen harmonic generation and current flow (part 2)..... 237
Figure A.10 – Even order triplen harmonic generation and current flow..... 240
Figure A.11 – Triplen harmonic flow in bipolar mode..... 241
Figure A.12 – Harmonic current flow – monopolar operation (as generated by left-hand converter) 242
Figure A.13 – Harmonic current flow – bipolar operation (as generated by left-hand converter) 243
Figure A.14 – Example of converter transformer stray capacitance paths..... 245
Figure A.15 – Distributed element model of converter transformer winding 246
Figure A.16 – Characteristic harmonic voltage generation for a notional 800 kV converter at rated power 248
Figure A.17 – Harmonic voltage generation due to 1 % AC negative sequence voltage..... 248

Figure A.18 – Harmonic voltage generation due to voltage difference between Y and D windings 249
Figure A.19 – Harmonic voltage generation due to difference in reactance between Y and D windings 249
Figure A.20 – Harmonic voltage generation due to random variation in dx among phases 249
Figure A.21 – Harmonic voltage generation due to valve firing jitter 250
Figure A.22 – Harmonic voltage generation due to all sources simultaneously 250

Table 1 – Some of the more significant cross-modulation relationships 29
Table 2 – Earth penetration depth as a function of frequency and earth resistivity (Carson-Clem) 60
Table 3 – IEEE recommended noise and balance thresholds [87] 91
Table 4 – Recommended ITU-T limits for telephone noise 92
Table 5 – Comparison of seismic fortification goals and levels 160
Table 6 – Capacitor design parameters 213
Table 7 – Reactor design parameters 217
Table 8 – Resistor design parameters 219
Table 9 – Arrester design parameters 223
Table 10 – Current transformer design parameters 224
Table 11 – Filter switching equipment design parameters 227
Table B.1 – C-message weighted harmonic currents results for numerical example 257

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

DC side harmonics & filtering in HVDC transmission systems

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 63529 has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV. It is a Technical Specification.

CIGRE Technical Brochure 811 served as a basis for the elaboration of this document.

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

Draft	Report on voting
115/410/DTS	115/435/RVDTS

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 Technical Specification is English.

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/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,
– withdrawn, or
– revised.

INTRODUCTION

0.1 Introduction

This document is intended as guidelines to all aspects of DC side harmonic behaviour and filters for HVDC transmission systems. It is based on CIGRE Technical Brochure 811 [1][1] developed by CIGRE Working Group B4.68. CIGRE sought to bring together the experience, and consider the interests, of different sectors of the HVDC community to produce a Brochure [1] of interest to all parties concerned, including utilities, suppliers and consultants.

The objective of this document is to provide information to enable informed and intelligent decisions to be made by those concerned. Where there are different possible approaches to some aspect of design, the relative merits are discussed.

0.2 Continuing relevance

Two major technological changes have transformed the subject area of Technical Brochure 811 [1] since publication of the original CIGRE Technical Brochure 92 [2] on the same topic:

a) The replacement of analogue telephone systems by digital and optical and mobile (cell phone) technologies has reduced the relevance of inductive interference from HVDC lines, although there remain areas where local analogue telephone connections can still be affected.

b) The introduction of VSC HVDC converters with inherently lower harmonic generation, and often with underground cable transmission, has largely removed the need for DC side filters in HVDC projects using such technology.

The question might therefore be asked – if it is not useful to have DC filters in many future projects, is there a need for this document dealing with DC side harmonics and filtering? Strong justifications are given below.

c) National or international regulations governing electro-magnetic compatibility (EMC) often demand that no interference be caused to third parties, and this is an element to consider for third parties or regulators before an HVDC project can obtain planning permission or enter operation. Definitions of such interference include the frequency range addressed in this Technical Specification. Studies can be required to reduce the risk to all parties involved in an HVDC project, even if the conclusion is that no special mitigation measures are required.

d) There can be a telephone interference issue in regions where analogue technology is still used for the final connection from an exchange to the consumer’s premises, especially where telephone cables and HVDC cables are laid in, or alongside, the same road.

e) Some digital communication can be subject to interference or safety hazard from induction, even if not affected directly at audible frequencies.

f) Possible resonance of the DC transmission system at harmonic frequencies should always be considered and studied.

g) Coupling with parallel AC transmission lines in the same corridor, or even on the same tower, is becoming increasingly topical due to restrictions on the construction of new overhead lines.

h) The owners of older HVDC projects undergoing refurbishment might wish to consider whether their DC filters are still required, and this will necessitate studies.

i) As DC filters and DC side harmonic issues become less common, the expertise in this field will diminish, and therefore the comprehensive record of knowledge encapsulated in this document will be a valuable reference.

[1] Numbers in square brackets refer to the Bibliography.

1 Scope

This document is intended to inform and guide the harmonic design of the DC side of HVDC projects. It considers all aspects of AC current and voltage occurring on the DC circuit and also the interaction with adjacent systems.

The switching action in HVDC converters results in a wide spectrum of harmonics. These range from the fundamental frequency to the radio frequency range. Traditionally the specification of DC side harmonic performance has been limited to the frequency range of interest for induced audible noise on nearby telephone systems. Often a limit of 50^{th} harmonic has been applied, corresponding to 2 500 Hz or 3 000 Hz on 50 Hz and 60 Hz systems respectively. Occasionally the range has been extended to 5 000 Hz. This frequency range has corresponded to the spectrum of characteristic harmonic generation from thyristor line-commutated converters (LCC).

The introduction of HVDC voltage sourced converters (VSC) has meant that although the magnitude of DC side harmonic generation from these converters is generally lower, the generated spectrum of interest extends to higher frequencies.

The scope of this document therefore covers the frequency range up to approximately 5 000 Hz. Higher frequencies are mentioned only when relevant. The scope excludes the much higher frequency ranges appropriate to PLC communication and the radio interference spectra.

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 60633, *High-voltage direct current (HVDC) transmission - Vocabulary*

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

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in IEC 60633 and IEC 62747 and the following apply.

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

– IEC Electropedia: available at https://www.electropedia.org/
– ISO Online browsing platform: available at https://www.iso.org/obp