

1124™

IEEE Guide for Analysis and Definition of DC Side Harmonic Performance of HVDC Transmission Systems

IEEE Power Engineering Society

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**Transmission & Distribution Committee
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IEEE Power Engineering Society**

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Abstract: Guidelines are provided for evaluating and mitigating harmonic induction effects from high-voltage direct-current (HVDC) lines on the adjacent telephone communication lines. Specifically, this guide presents methodology and approach for a) Determining the number of wireline communication circuits that will be affected by unacceptable interference and cost-effective remedial measures; and b) Computing interference levels that would result with various practical dc filter/smoothing reactor designs and the costs of these filters.

Keywords: equivalent disturbing current, filters, harmonic currents, harmonic voltages, HVDC transmission systems, induction, inductive coordination, interference, mitigation methods, mutual impedance, noise, telephone circuits

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Introduction

(This introduction is not part of IEEE Std 1124-2003, IEEE Guide for the Analysis and Definition of DC-Side Harmonic Performance of HVDC Transmission Systems.)

The purpose of this document is to provide guidelines for evaluating and mitigating harmonic induction effects from high-voltage direct-current (HVDC) lines on the adjacent telephone communication lines. Specifically, this guide presents methodology and approach for

- a) Determining the number of wireline communication circuits that will be affected by unacceptable interference and cost-effective remedial measures.
- b) Computing interference levels that would result with various practical dc filter/smoothing reactor designs and the costs of these filters.

Participants

At the time this guide was completed, the IEEE Working Group on HVDC Harmonics, which was sponsored by the DC and FACTS Subcommittee of the Transmission & Distribution Committee of the IEEE Power Engineering Society, had the following membership:

F. S. Prabhakara, *Chair*

Keith A. Adams	Robert H. Lasseter	Carlos A. O. Peixoto
Michael H. Baker	T. (Ting) H. Lee	Kellie J. Peterson
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R. S. (Bob) Burton	H. Peter Lips	John Reeve
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Jeffrey A. Donahue	Karl N. Mortensen	Rao S. Thallam
David P. Hartmann	David J. Melvold	John J. Vithayathil
Ali F. Imece	Stan Overby	Dennis A. Woodford
Suresh C. Kapoor	Neil A. Patterson	Gene Wolf
P. C. S. Krishnayya		C. T. Wu

The following members of the balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Vernon L. Chartier	Jurgen O. C. Kansog	Orville J. Plum
James F. Christensen	P. Sarma Maruvada	F. S. Prabhakara
Frank A. Denbrock	Stig L. Nilsson	John G. Reckleff
George Gela	Carlos A. O. Peixoto	Mark S. Simon
Adel E. Hammad	Robert C. Peters	John J. Vithayathil

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*Member Emeritus

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Alan Cookson, *NIST Representative*

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IEEE Guide for the Analysis and Definition of DC-Side Harmonic Performance of HVDC Transmission Systems

1. Overview

During operation of dc valves, significant amounts of harmonic currents and voltages are produced. These harmonics can cause various problems, so filters are usually installed on both ac and dc sides of the converters in order to reduce the harmonics emanating from the converter stations to acceptable levels.

Inductive coordination involves the study of interference on wireline communication circuits caused by the harmonics carried on the ac and dc transmission lines, plus identification and implementation of remedial measures necessary to avoid unacceptable interference.

Harmonics propagating on ac transmission lines connected to the converter station are controlled by the ac filters. Due to the complex and changing nature of the connected ac systems, detailed inductive coordination studies on the ac system are not usually undertaken. The accepted procedure (Dickmader and Peterson [B4])¹ used on recent dc transmission projects has been to specify ac filter performance in terms of values of individual harmonic distortion, total harmonic distortion, and a composite “telephone influence factor” (based on weighted harmonic voltage). The limiting value specified for these factors are normally based on previous satisfactory experience on similar projects.

Interference from harmonics propagating on two-terminal dc transmission lines can be more accurately predicted because the routing of the dc line and nearby communication circuits is generally known, and it is possible to determine the harmonic currents on the dc line. Thus, it is possible to carry out detailed inductive coordination studies for dc-side harmonics on two-terminal dc systems.

Calculation of harmonic current profiled on dc transmission lines for multiterminal dc systems is more complicated and the complexity increases rapidly with the number of terminals involved. Inductive coordination studies for these dc transmission lines are still worthwhile; however, statistical methods and/or approximation are necessary in order to keep the number of computation cases for harmonic current profiles on the dc transmission line to a reasonable level of effort.

¹The numbers in square brackets correspond to those of the bibliography in Annex A.

1.1 Scope

This guide contains information and recommendations pertaining to the analysis and specification of the performance on the dc side of a high-voltage direct-current converter station concerning the electrical noise at harmonic frequencies up to 5 kHz generated by converter stations in a dc transmission system. This guide also contains information and suggestions pertaining to measurement of dc filter performance and noise level induced in wireline communications circuits from harmonic currents on dc transmission lines.

1.2 Purpose

Inductive coordination studies for dc transmission lines have two basic aspects:

- a) Determination of the number of wireline communication circuits that will suffer unacceptable interference and the costs that would be involved in remedial measures applied to the affected wireline communication circuits.
- b) Computation of interference levels that would result with various practical dc filter/smoothing reactor designs and the costs of these filters.

The optimum solution can be obtained by a cost/performance study. A substantial part of the work involves identifying all wireline communication circuits in the vicinity of planned dc transmission lines and calculating probable levels of induced interference for each circuit. These calculations are tedious and time-consuming, even using available computer programs, due to the detailed calculations involved and determining the exact parameters of each exposure. This can be further complicated by changes to the dc transmission line route (due to factors involved in finalizing the dc line right-of-way), which changes the wireline communication circuit exposures to be analyzed; changes in dc filter designs producing changes in harmonic current profiles on the dc transmission lines; difficulties in reaching agreement between power and telephone companies on limits of allowable induced interference; and short dc project construction schedules.

Reaching an optimum solution can be a lengthy, iterative process. Each dc project is unique, so that a solution used previously on a similar dc transmission project is not necessarily the optimum solution for the dc project under study. However, by using a simple, systematic approach to the problem and by selecting boundaries to the variation of each relevant operating parameter, the required studies can be started early in the project and a satisfactory conclusion reached relatively quickly.

One approach (Patterson and Fletcher [B18]) involves de-coupling the calculation of dc filter characteristics and harmonic current profiles on the dc transmission line (the power system analysis) from the calculation of coupling factors at harmonic frequencies between the dc transmission line and each adjacent wireline communications circuit due to harmonic currents on the dc transmission line (the communications system analysis).

2. References

When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 1137TM-1991 (Reaff 1998), IEEE Guide for the Implementation of Inductive Coordination Mitigation Techniques and Applications.^{2,3}

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3. Explanation of terms

3.1 DC harmonics

This term refers to the ac *harmonic content* of the dc voltage or current of an HVDC system, as defined in *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B8]. In an ideal bridge converter, the dc voltage harmonics have frequencies of only even multiples of the fundamental frequency at characteristic frequencies; however, in practice other even and odd multiples of fundamental frequency (at noncharacteristic frequencies) can also appear due to system imbalances and stray capacitances.

3.2 Ideal converter

An ideal converter is considered to be a converter that has balanced sinusoidal voltage, circuit impedances, firing angle, and no stray capacitance, and smooth dc current for purposes of commutation, etc.

3.3 Harmonic order

The order of a harmonic of the dc voltage/current is the ratio of its frequency to the fundamental frequency on the ac side of the converter.

3.4 Characteristic/noncharacteristic harmonics

In an ideal converter, the characteristic harmonics are those harmonics that are based on theoretical waveforms of dc voltage of a converter and can be expressed in terms of the pulse number of the converter; for example, for a six-pulse converter, the harmonic order can be expressed as $6n$, where n is an integer and, in general, the expression would be pn , where p is the pulse number. All other harmonics not defined by such an expression are traditionally termed as *noncharacteristic harmonics*. Noncharacteristic harmonics usually are relatively small. However, for a practical converter, such a definition is not applicable, and a more precise approach is to express harmonics in terms of triplen and nontriplen harmonics (see 3.5).

3.5 Triplen harmonics

Triplen harmonics are those harmonics that are multiples of the third harmonic; for example, 3, 6, 9, 12, 15, . . . and can be classified as either *odd* or *even*. The *even* triplen harmonics, which are multiples of the converter pulse number (for example, 12, 24, . . . for a twelve-pulse converter), are the same as characteristic harmonics of an ideal converter and flow through the poles of the converter (pole mode in a balanced system). However, due to imbalances in the poles, a residual even triplen harmonic current may flow through a ground return path. Other triplen harmonics (odd and even) are zero sequence type and flow either through the ground mat or the neutral ground (refer to 5.6).

Non-triplen harmonics are those harmonics that are neither multiples of the third harmonic nor the converter pulse number and can appear due to system or converter imbalances.

3.6 Equivalent disturbing current (I_{eq})

Equivalent disturbing current (I_{eq}) is used to denote a single harmonic current at a reference frequency (usually 1000 Hz for the 60 Hz system) that would produce the same interference in a telephone line as produced by all individual harmonics. The equivalent disturbing current takes into account the C

message weighting factor (C_n) and a frequency dependence factor (H_n) for mutual coupling to the telephone line.

3.7 Harmonic performance

The term *harmonic performance* refers to the performance of the harmonic filtering system on the dc side in mitigating the flow of harmonic currents into the dc line. The harmonic performance may be expressed in terms of the equivalent disturbing current (usually in mA) or the induced voltage in a telephone line (usually in mV/km), or in terms of the individual or total harmonic current levels. The latter method of specifying is not very commonly used in the U.S. and Canada. The specified performance becomes the basis for the design of the dc harmonic filtering system.

The harmonic performance is often specified separately for bipolar and monopolar modes of operation, since the monopolar operation is usually for only short duration and a relatively lower performance can be tolerated.

3.8 DC harmonic filtering system

The elements that help in filtering the dc harmonics are a) dc line filters, neutral capacitors or filters; b) the smoothing reactor; and c) a series reactor on the line side of the filter, if used. These elements help to reduce the harmonic flow into the dc line by carefully designing their interaction with the line (e.g., resonance). The harmonic filters, if provided, may be single-tuned, multiple-tuned, high-pass filters, or active filters.

3.9 Induced noise/interference

The term *induced noise* refers to the voltage induced in a communication circuit due to the harmonics present in the dc line. Generally, the induced noise calculations are based on the electromagnetic coupling and the effect of the electrostatic coupling is neglected unless both circuits are very close and the communication circuit is composed of unshielded conductors. The terms *induced noise* and *interference* are often used in a synonymous manner and include the quality of the communication circuit and signal.

3.10 Inductive coordination

The term *inductive coordination* refers to the general study of coordination between the power and communication circuits to mitigate the effects of interference, including the remedial measures on both circuits. The design of the filtering system on the dc side of an HVDC system would be a part of the overall inductive coordination study.

3.11 Ground resistivity

Since the magnetic coupling between the power and communication circuit is usually dominated by the zero-sequence component (see 3.15) rather than the positive-sequence component (by an order of magnitude or more), the resistivity of the ground circuit is a key factor in influencing the mutual impedance. The resistivity of the ground is dependent on the nature of the soil, ranging from 0.1 ohm-meters ($\Omega\cdot\text{m}$) for swampy soil to 30 000 $\Omega\cdot\text{m}$ or more for solid rock. A typical value of 100 $\Omega\cdot\text{m}$ is frequently used for the ground resistivity. The resistivity is derived from the expression $R = \rho L/A$ and denotes the resistance of a body of one meter cube. Note that the resistivity is not entirely uniform for the mass of the ground; however, a constant value is generally used.

3.12 System imbalances

System imbalances between phases on the ac side have a very significant effect on harmonic generation on the dc side. The imbalances can be in the system or commutating impedance looking from the converter, or in the system phasor voltages, or in the stray capacitances of the converter and transformer, etc. The imbalances resulting from the converter control firing angle can also be a cause of the noncharacteristic harmonics.

3.13 Bipolar mode of operation

The bipolar mode of operation is the normal mode of operation with both positive and negative poles in service. Ideally, both poles should carry the same harmonic currents, but in real life this is not so, and the difference between the two poles must flow either through ground or a metallic conductor, if provided.

3.14 Monopolar mode of operation

In the monopolar mode of operation, the return current path is either through the ground, sea (water) or through a metallic conductor. A bipolar HVDC system may be operated as a monopolar system, when one pole is out of service.

3.15 Sequence components

In the bipolar mode of operation, the currents in the two poles are not necessarily equal in magnitude and phase, and thus for purposes of analysis they can be analyzed into two components: a positive sequence component, where the pole currents are equal in magnitude but opposite in direction, and a zero-sequence component, where the pole currents are equal in magnitude but in the same direction and return through the ground. This is similar to the sequence components used in a three-phase ac system.

3.16 C message weighting

For the purpose of assessing the effects on a telecommunications circuit of voice frequency interference from nearby electric power facilities, the C message weighting is customarily applied. Weightings are assigned to individual harmonics of 60 Hz such that an interfering voltage on the telecommunications circuit, when multiplied by its appropriate C message weighting factor, will characterize its interfering effect on the user of a 500-type telephone set. In the construction of a noise measuring set, the C message weighting is implemented through a filter with an appropriate loss-frequency characteristic. The highest weighting, 1.0, is assigned to 1020 and 1080 Hz. The pass-band between 6 dB down points is from about 540 Hz to about 3300 Hz. The 60 Hz weighting is -55 dB. Therefore, any induced noise at 60 Hz is negligible.

3.17 Circuit noise (noise-metallic)

The C message weighted voltage, which appears between the two wires of a telephone voice-frequency line (transverse voltage), is the source of the noise that appears in the telephone receiver connected to the line. The unit of measurement for circuit noise is dBrnC (decibels above reference noise, with C message weighting). The 0 dBrnC corresponds to 1 picowatt (pW) of energy dissipated in a 600 Ω

termination. The corresponding voltage across the $600\ \Omega$ termination is $24.5\ \mu\text{V}$. A 1000 Hz tone of 0 dBm (reference to 1 mW of power in a $600\ \Omega$ termination) has an interfering effect of 90 dBnC. The telephone industry would like the total circuit noise caused by all sources on any voice frequency circuit to not exceed 20 dBnC at a customer's network interface.

3.18 Longitudinal noise

The C message weighted voltage, which appears between the ends of a telephone pair (common-mode voltage) because of interference from nearby power facilities, is usually referred to as *longitudinal noise*, because the voltage is induced into the circuit conductors longitudinally. Longitudinal noise is closely related to two other terms in telephone utility parlance.

3.19 Noise-to-ground

If the two conductors of a telephone pair are connected to ground at one end, the longitudinal noise appears at the other end as a voltage to ground. When measured with a noise measuring set (NMS) that samples only 1% of the average voltage to ground, and reads in dBnC, this reading is customarily referred to as *noise-to-ground*.

3.20 Power influence (PI)

If the necessary 40 dB correction is then added to the noise-to-ground reading, the resultant figure is called *power influence* or *PI*. If the NMS automatically applies the 40 dB correction, then the set reads PI directly. The telephone industry would like the PI to not exceed 80 dBnC at the customer network interface. This is predicated upon an assumed *balance* of the facility of 60 dB (see 3.21).

3.21 Longitudinal balance

The numeric difference between PI and circuit noise is called the *longitudinal balance of the telephone circuit*. Only *balance* will be subsequently used in this guide to mean *longitudinal balance*. Balance is affected adversely by any condition that results in unequal voltage drops in any section of the two-conductor line. Such *imbalances* may be caused by a high-resistance joint (series unbalance), by a leakage to ground (shunt unbalance), or by unequal induced voltages in the two conductors (direct metallic induction). The telephone industry would like to maintain its circuits to have a balance higher than 60 dB. Unfortunately, at frequencies above 1000 Hz, the balance tends to drop off to lower values. Telephone cable balance, excluding terminating equipment, is typically measured in the field using instruments with C message weighting and 50–55 dB balance is not uncommon.

4. General methodology

The recommended methodology for analysis and specification of harmonic performance on the dc side of HVDC converter stations consists of the following stages. Each stage may consist of several studies and some studies may have to be repeated until the final parameters of the HVDC system are selected.

- Pre-specification studies (initial communication studies, etc.)
- Power system studies (dc harmonic analysis)

- Communication and coordination studies
- Commissioning studies (performance measurements)
- In-service studies

These stages are discussed below and shown in a block diagram in Figure 1 along with contract procedural stages.

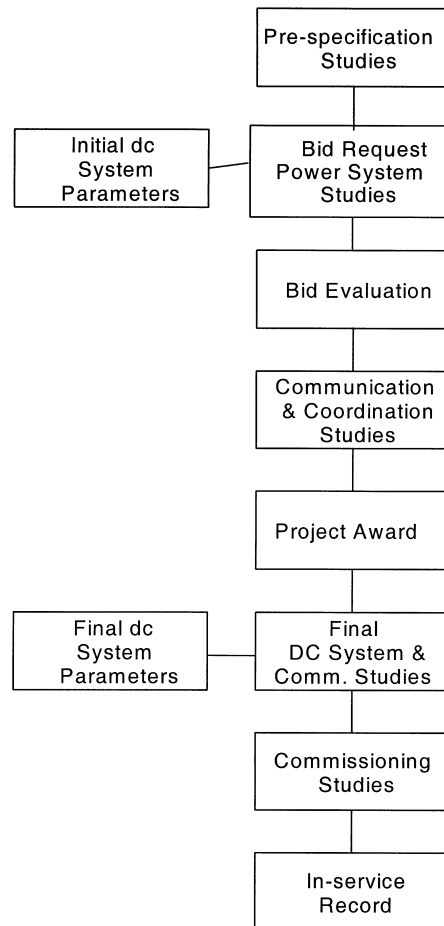


Figure 1—Methodology for HVDC inductive coordination study

4.1 Pre-specification studies

For proper design of dc harmonic filters, it is essential that the electric utility company work with the telephone company to collect physical data and establish ground rules for inductive coordination that would help select realistic harmonic performance criteria. This stage may be termed as the *pre-specification stage*, prior to power system studies and prior to writing the full specifications of the harmonic filters by the utility company (possibly in consultation with HVDC manufacturers).

In the pre-specification stage, it is not necessary to go into the aspects of dc filter design, rather all the factors that help determine the performance criteria and influence system design and equipment reliability should be considered and incorporated into the specifications.

Initially, the power utility company must establish the routing of the dc line and determine which telephone wire lines in the vicinity may be affected. The latter will depend on a number of factors, for example, physical separation, angle of crossing (if any), shielding of telephone wires, circuit balance, and ground resistivity. A joint task force with the telephone company would be most desirable in this respect. The data on ground resistivity should be obtained for all different types of soil, particularly in areas with high rock content and consequently high soil resistivity values.

Once the physical data is obtained and the number of exposed telephone lines is determined, the next step is to determine the anticipated induced noise in the telephone lines from the dc line. A mutually agreed figure for the permissible noise between the electric utility and the communication utility should be arrived at in terms of the induced metallic voltage (dBrnC). However, for specifications of the dc harmonic filters, the design criterion should be expressed, preferably, in terms of equivalent disturbing current. See 6.5.2 for acceptable noise levels in communication circuits. There are a number of possible courses open to the electric utilities for specifying the dc harmonic filter performance criteria and this guide does not attempt to define these courses. However, this can be done first in a preliminary form with the calculation of mutual coupling impedances, based on the geometry of the power and communication lines, and estimates of the equivalent harmonic currents (I_{eq}).

A mutually agreed figure for the permissible noise should be arrived at, preferably expressed in terms of equivalent disturbing current, which is convenient for the HVDC system engineers. The concept of equivalent disturbing current is discussed in detail in Clause 7 and historical dc filter design criteria in Clause 10. Clause 7 describes equations for I_{eq} and the use of coupling factor (H_n). This factor combines shielding factor (K_n) and circuit balance factor (B_n), both being frequency dependent. Any assumptions made with regard to this factor should be clearly defined in the specifications. Other options for defining the limit in terms of dBrnC or mV/km are open, but these expressions would require a greater coordination effort between the power system engineers and communications engineers. In selecting the limit, full advantage should be taken of any known performance data or experience on similar dc projects. Differences in dc system rating or ground resistivity can be accounted for.

Owing to a significant cost involved in the design and hardware of dc harmonic filtering, the utility may decide to proceed with one limit or more than one limit on the induced noise for bidding purposes and decide on the final choice later. Another option open to the utility is to request incremental costs for filters and smoothing reactors over the base design. However, if more than one limit or interference level or incremental cost for filters are included in the specifications, then sufficient time must be allowed for the manufacturer to come up with meaningful options.

Based on preliminary noise criteria, families of curves can be developed by relating the number of communication circuits requiring mitigation to the value of I_{eq} . Further, a cost of mitigation for different I_{eq} levels can be estimated. Note that very often physical changes in the location of the dc line and/or the telephone line and other mitigation techniques may be less expensive than installation of high-cost real-estate occupying filters.

Specifications: The technical specifications for the dc harmonic filtering equipment basically fall into two parts: 1) system considerations including performance criteria; and 2) component selection. The first part is discussed in Clause 8. The second part is primarily the manufacturer's responsibility; however, the electric utility is to define its practices and applicable national standards.

The specifications should clearly define the spare requirement, such as on-line or off-line spare filter banks or filter components, smoothing reactor, and neutral grounding components.

The specifications should define all operating configurations, e.g., bipolar/monopolar operation, six-pulse/twelve-pulse operation, metallic/ground return, reduced voltage operation, etc. Generally speaking, one performance criteria is set for normal operating conditions. These levels must have been determined prior to specification writing in consultation with the telephone utility company.

4.2 Power system studies

The power system studies concentrate on the harmonic voltage generation from the HVDC converters and the harmonic current flow in the dc lines. These studies are usually performed by the HVDC equipment manufacturer. The modeling techniques for these studies are discussed in Clause 6. This subclause, however, outlines the methodology for such a study and the final expression of harmonics in terms of the equivalent disturbing current. The study will consist of the following steps, which may have to be done in an iterative manner to reach the final design:

a) *Determine ac system, converter, and dc line parameters*

The following ac system parameters should be specified by the electric utility: 1) steady state negative sequence voltage, 2) ac system frequency deviations, both in steady-state and transient, 3) ac system positive sequence voltage variations range, and 4) ambient temperature ranges. Harmonic content in the ac system voltage may be included, if found significant.

The transformer and converter parameters can be determined only after other system studies are completed, usually by the HVDC equipment manufacturer. The electric utility may, however, have earlier performed preliminary studies to select the equipment ratings.

b) *Select dc smoothing reactors and dc filters*

A preliminary value of the smoothing reactor and the total capacitance of the filters has to be selected for initial studies that can verify resonance, minimum dc current operation, etc. A final selection can only be made after the performance level has been calculated (see Step f). Note that these selections are usually made by the manufacturer during the system design and are not pre-specified by the utility.

c) *Determine harmonic driving voltages*

The study should include both triplen and nontriplen harmonic voltages. This step can be completed only after transformer and converter parameters are known (see Clause 5).

d) *Calculate harmonic current flow in the dc lines*

This is to be calculated for both rectifier- and inverter-ends for different operating configurations on the dc side (e.g., bipolar, monopolar metallic, etc.).

e) *Calculate equivalent disturbing current (I_{eq})*

The I_{eq} is to be calculated for all conductors. For example, at the terminal end there may be a neutral conductor and an electrode line conductor, in addition to the pole conductors. Since the harmonic currents will vary along the transmission line due to the traveling wave effect, it is necessary to calculate I_{eq} at discrete points along the lines (e.g., every 20–30 km). A plot of such a profile will be desirable.

f) *Compare the profile to the target values of I_{eq} (specified limits)*

If the I_{eq} limit is exceeded, reconsider the filter selection (for the given total filter capacitance) and recalculate from Step d), otherwise reconsider the smoothing reactor size and total filter capacitance and recalculate from Step b).

g) *Bid evaluation*

The manufacturer's bid is to be evaluated for its technical content, including system/design studies, equipment specifications, options, or alternatives. The manufacturer's proposal would provide all basic system parameters and transformer impedance and control firing, etc. These should be evaluated if they have materially changed from the pre-specification communication studies. With the updated data and known harmonics or equivalent disturbing current in the dc line, the performance criteria should be re-evaluated.

4.3 Communication and coordination studies

The detailed results from the power system studies can be used with the communication circuit data collected during pre-specification to review the communication interference and more accurately predict the communication circuits that will require mitigation.

4.3.1 Communication studies

The purpose of this study would be to update the data and assumptions made in the pre-specification studies. The analysis can also be made in greater detail for configurations, etc.

- a) Review the communication circuits that require mitigation and possible mitigation techniques.
- b) Confirm ground resistivity data for the geological profile along the dc route. This may include measurement of earth resistivity.
- c) The calculated frequency spectrum of dc harmonic currents from the design studies can be used to validate the I_{eq} assumptions pertaining to frequency dependence (coupling factor H_n) and pole mode coupling.
- d) Calculate the mutual impedance at the equivalent disturbing current frequency (normally 1000 Hz) for each circuit, if any changes have been made since the pre-specification studies.
- e) Calculate revised induced noise levels for each circuit, considering specific equivalent disturbance current levels from the profiles calculated in power system analysis.
- f) Typical versus worst case interference can be investigated.

4.3.2 Coordination study

Once the power system analysis and the communication system analysis studies are completed, the results of both can be analyzed and discussed. The coordination study will consist of the following steps:

- a) Calculate a revised statistical graph and list of circuits showing calculated induced noise versus agreed limits.
- b) Determine the extent and severity of induced noise interference.
- c) Determine costs of remedial measures for communication circuits.
- d) Determine the best cost/performance ratio for the combination of dc filtering equipment and remedial measures to wireline circuits that will result in a satisfactory induced noise.
- e) Specify the performance requirements of dc filtering in terms of the final optimized equivalent disturbing current value. This would be used by the manufacturer for the requisition design. Depending upon the changes made in the requisition design over the proposal design, it may be necessary to recalculate the induced noise from the actual I_{eq} levels or this step may be deferred until after the commissioning stage.

4.3.3 Project award

Project award is, of course, made on the basis of a complete project of which the dc-side filtering equipment is only a part. At this point, negotiations should be made with the supplier if any system parameters or operating conditions have changed that require redesign or change in rating of the dc filter equipment.

4.3.4 Final dc system studies

Once the supplier has received the project award, the final study should update the proposal system study (see 4.2) with final transformer and converter parameters. Harmonic generation and line constants, etc., which may not have been fully modeled before, should be recalculated as accurately as possible. The final study should examine various operating cases and determine the worst operating scenario. The study should compare the performance with and without dc filters for normal operating configuration.

4.4 Commissioning studies

The harmonic performance may be verified by field measurement on projects where telephone interference is particularly critical. The method of measurement must be specified along with the assumptions that must be made in the calculations of performance from the measured data. Test configuration and system conditions must also be specified. A level of tolerance in the acceptance of design calculations must also be specified (for example, within 10% of the design limit). This, of course, assumes that the measurement error is small relative to the agreed design tolerance.

Comparison between the measured data and the design data may be a difficult task since the former would be for a typical situation whereas the latter is more likely to be for the worst case scenario. This may be further complicated by the fact that the design calculations are often based on RMS summations of the contributions from various terminals (unless otherwise decided), whereas in a real system the contributions would add vectorially. The experience on field measurements so far indicates that it has not been possible to verify magnitudes of calculated single harmonics (usually maximized) due to practical differences and continual system changes at both ends and also drifts between them in phase angle and frequency. It is therefore recommended that based on several measurements an average approach be adopted.

The measurement of I_{eq} is best done by directly measuring the current in the pole conductors. Direct-current transformers (DCCT) are not adequate for this type of measurement; therefore special equipment must be installed, e.g., a Rogowski coil or resistive shunt. Other possible approaches, e.g., measuring the induced voltage on a probe-wire, are discussed in Clause 10. Whatever method is used, it must be agreed between the utility and the manufacturer. Note that the measurements of harmonic currents in the pole conductor are normally made at the terminals and therefore the measured performance is valid only at the terminal and does not reflect the same performance at some other point on the dc line.

If possible, simultaneous measurements on the telephone lines will be extremely beneficial. This will serve as a direct correlation between the dc operating configuration and power level and the induced noise level.

4.5 In-service studies

Once the dc project is commissioned, the relationship between the measured I_{eq} performance and the measured communication interference will be known. Therefore, periodic checking of either the interference on selected communications pairs or harmonic currents in the dc pole conductors can be made to verify that the harmonic performance has not degraded. Periodic measurements of the filter component parameters or filter tuning (in de-energized state) are also recommended.

5. DC harmonics

5.1 Introduction

The purposes of Clause 5 are threefold: first, to orient the reader to the general behavior of the converter as a source of dc harmonics; second, to highlight the factors which should be considered when analyzing dc-side harmonic performance; and, finally, to describe the modeling and circuit analysis methods used in the design of dc filters and other equipment needed to satisfy the specified interference limits. With these general objectives in mind, the material is organized in the following way. First, a description of the harmonic behavior of an *ideal* converter is presented. Second, the general assumptions regarding the behavior of the converter for harmonic frequencies are reviewed, and the implications for appropriate converter modeling are described. Finally, the techniques used in the calculation of harmonic driving voltages, and the circuit analysis methods used in the calculation

of harmonic currents, are described. Clause 5 concludes with a general discussion of harmonic flow on the dc side, and the implications for dc filtering.

5.2 Behavior of an ideal converter

As a general introduction to the topic of dc-side harmonics, it is helpful to discuss briefly the behavior of an HVDC converter under what we could call *ideal* conditions, to provide a foundation on which a more extensive understanding of dc harmonics can be built. The discussion, which follows, is therefore based on several assumptions:

- a) The ac voltages are three-phase, sinusoidal, and balanced.
- b) The direct current is constant, i.e., without ripple.
- c) The converter's internal impedance is high (infinite) when viewed from the ac side, and low (zero) when viewed from the dc side.
- d) Harmonic current flow is confined to the main circuit path (converter transformers and valve bridges), i.e., no leakage paths to ground.
- e) The converter transformer reactance is identical and linear in all phases.
- f) The control system is perfect (no variation in firing instants).

It should be cautioned at this point that not all of the above conditions are satisfied in practice, and that the discussion which immediately follows is not, by itself, sufficient for analysis of the harmonic behavior of real HVDC systems. This will become clearer when the validities of these assumptions are reviewed in 5.3.

The above conditions lead to the well-known and traditional observation that HVDC converters behave as a source of harmonic currents of orders $[np \pm 1]$ on the ac side, and harmonic voltages of orders $[np]$ on the dc side, with p equal to the pulse number of the converter, and n an integer.

The dc voltage waveform produced by an *ideal* HVDC converter contains an ac ripple superimposed over a mean dc value, produced by the switching action of the converter valve. Switching occurs at every 60° interval in a six-pulse converter, and every 30° in a twelve-pulse converter. This composite voltage waveform is made up of purely sinusoidal segments for ideal conditions.

5.2.1 Ideal six-pulse waveform

An ideal six-pulse converter, with repetitive switching at every 60° , produces a dc waveform as shown in Figure 2. Each of the firing intervals comprises a commutating period and a non-commutating period as shown. Voltage discontinuities at the instants of start and stop of commutation periods can be noticed. Fourier analysis of this ideal waveform gives dominant harmonics of order $6n$, with n an integer. Harmonics of order $6n$ are therefore termed *characteristic* for a six-pulse bridge.

5.2.2 Ideal twelve-pulse waveform

The power circuit arrangement for a twelve-pulse converter is illustrated in Figure 3. The twelve-pulse bridge comprises two series connected six-pulse bridges that are each connected to a three-phase voltage source with a 30° phase displacement between the two sources. Each six-pulse bridge is fired six times per cycle of source frequency, at 60° intervals. The phase shift between the voltage sources results in twelve-pulse operation with firing at 30° intervals. The voltage waveform produced by an ideal twelve-pulse system is illustrated in Figure 4.

For ideal conditions, this scheme results in the cancellation of the sixth harmonic between the two bridges. The dominant harmonics are then of order $12n$, and these harmonics are referred to as

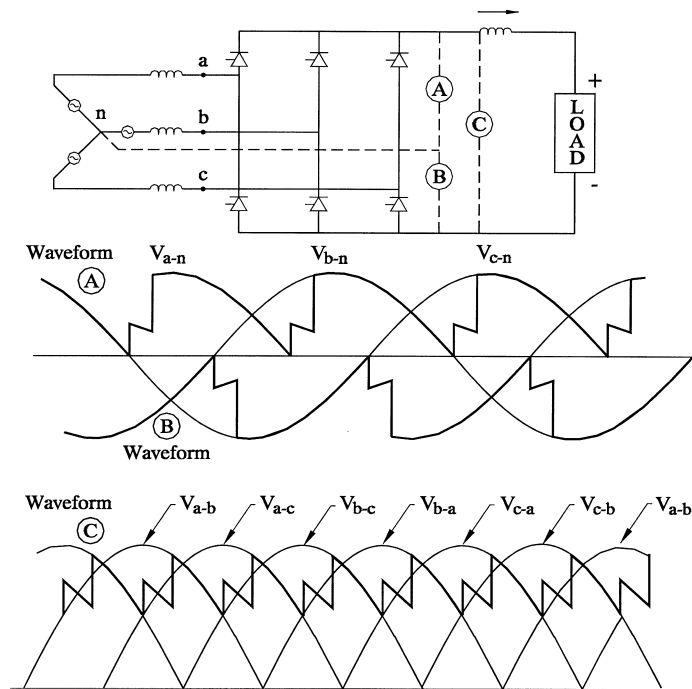


Figure 2—Ideal six-pulse converter voltage waveform

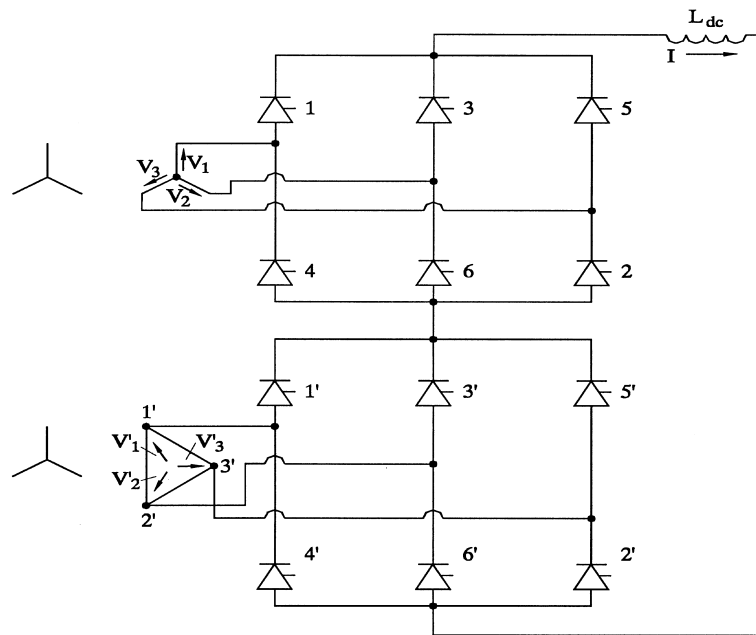


Figure 3—Twelve-pulse converter

characteristic for twelve-pulse operation. Because of the cancellation of the *six-pulse* harmonics 6, 18, 30, etc., and the corresponding reduction in filtering requirements, twelve-pulse systems are generally regarded as the most economical for HVDC applications.

Unfortunately, the ideal conditions previously described do not entirely apply to real systems. The requirements on converter modeling have been heavily influenced by this fact, and also by the choice of harmonic performance criteria.

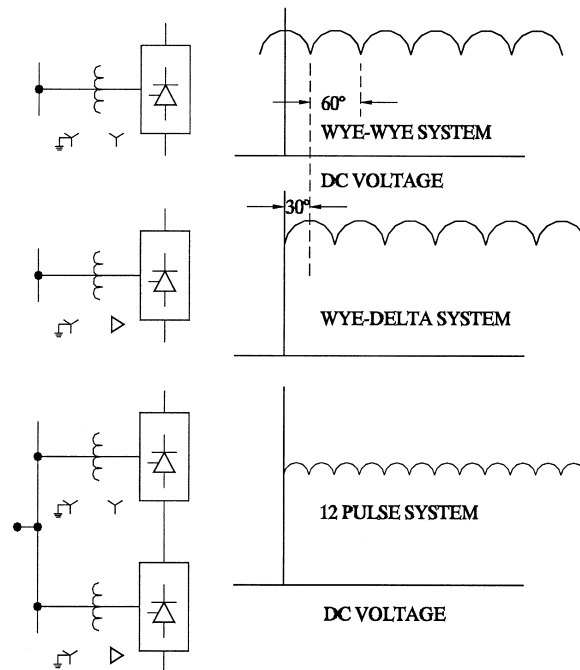


Figure 4—Effect of twelve-pulse operation on dc voltage

5.3 Modeling of converter for dc harmonic analysis

On the dc side, the general practice has been to limit the ground mode harmonic current, i.e., that current which flows from ground, through the converter, and then back to ground via the dc network. For an HVDC transmission system operating in balanced bipolar mode, the harmonic currents on the dc side tend to flow out on one pole line and back on the other, hence are balanced, and the magnetic fields produced by the harmonic currents cancel except in close proximity to the HVDC line. Since it is the magnetic field that causes voltages to be induced in telephone lines, these balanced (*pole mode* or *positive sequence*) harmonic currents are not significant contributors to telephone interference except where the telephone line is in or close to the HVDC right-of-way. Where the pole mode harmonic currents are not perfectly balanced, the difference current must flow in some other path, usually the earth. This current in the earth is the ground mode current and, since it does give rise to magnetic fields at significant distances from the HVDC line, the ground mode current is the main source of telephone interference.

A primary requirement on the converter model used in dc-side harmonic analysis is thus an accurate representation on the flow of harmonic current on the dc side, with particular emphasis on all possible mechanisms that can produce ground mode harmonic current. The converter model must therefore include detailed representation of all possible sources of harmonic generation and all possible *paths* of harmonic current flow within the converter, which can influence the external circuit.

5.3.1 Review of assumptions

The degree to which an actual plant adheres to ideal conditions determines the degree to which the simplified representation described in 5.2 may be applied. The presence of ac harmonic filters ensures that the ac voltage will be (reasonably) sinusoidal, and the presence of a relatively large smoothing reactor ensures that the dc current will be reasonably free of ripple. Normally, the smoothing reactance is large relative to the commutating reactance. Moreover, the ac source impedance is normally low and is shunted by ac filters, giving a relatively minor influence when reflected to the valve side of the

converter transformers. These impedance relationships give rise to the treatment of the converter using harmonic voltage sources (low internal impedance) on the dc side, and harmonic current sources (high internal impedance) on the ac side. Furthermore, modern HVDC firing controls are accurate, and it can be expected that transformer phase inductances will be well balanced. Assumptions a), b), c), e), and f) in 5.2 are, therefore, reasonably applicable to real systems. Deviations from these ideal conditions will result in the generation of noncharacteristic harmonics. Although the noncharacteristic harmonics caused by these deviations are small relative to the characteristic harmonics for typical parameters, it is normally necessary to include them in the performance calculations.

However, in practice, condition d) in 5.2 is *not* satisfied; i.e., harmonic current flow is not necessarily confined to the main circuit path. The presence of leakage current paths to ground within the converter has been found to have a direct and dramatic influence on the flow of all ground mode harmonic currents of orders $3n$ in the dc network (Dickmader and Peterson [B4], Garrity et al. [B5], Larsen et al. [B14], and Shore et al. [B20]). This fact defines the topology of the equivalent impedance network used to represent the converter for dc harmonic analysis. To account for these effects, it is necessary to use a representation of the converter's internal impedance, which includes the leakage paths formed by the stray capacitance between the converter transformer windings and ground, and it is necessary to represent explicitly the harmonic driving voltages between the stray capacitance paths and the converter terminals. The resulting equivalent network used for the converter is referred to in the literature as the *three-pulse model* (Dickmader and Peterson [B4], and Shore et al. [B20]).

5.3.2 Modeling approach

The primary requirements on the converter model used for analysis of dc-side harmonic flow are as follows:

- a) Correct representation of the ground paths formed by stray capacitances within the converter.
- b) Explicit representation of all harmonic driving voltages of order $[3n]$.
- c) Inclusion of the effects of other non-idealities, such as ac system imbalances, converter transformer reactance variations, and variations of the valve firing instants.

A convenient way of representing a six-pulse bridge is to divide it into two *three-pulse* halves, as the converter transformer windings and their associated stray capacitance leakage paths to ground are located between the upper and lower valve triplets in the bridge. It is also useful to decompose the familiar dc voltage waveform produced by the six-pulse bridge into two three-pulse voltage sources as shown in Figure 5. This three-pulse voltage is a mathematical convenience, which accurately simulates the behavior of the converter, while it is understood that it does not occur physically in the circuit. Its existence is derived heuristically in Shore et al. [B20].

The resulting model of the converter, which satisfies the above requirements, is shown in Figure 6 for a six-pulse bridge, and Figure 7 for a twelve-pulse bridge. The inductances L in Figure 6 are each one-half of the time-average value of the converter commutating inductance, and the capacitance shown in Figure 6 is a lumped representation of the total amount of stray capacitance to ground in the bridge. The voltage source $V_{3p}(t)$ and $V_{3p}(t - T/6)$ in Figure 6 are three-pulse voltage sources that are calculated as described in 5.4.

5.4 Calculation of harmonic driving voltages

As described in 5.3.2, the analysis of harmonic driving voltages must include explicit calculation of all harmonics of order $[3n]$, and must include the effects of various converter non-idealities such as ac system imbalances, converter transformer reactance variations, and variations in the valve firing