IEEE Std 1124™-2003

IEEE Standards

1124™

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

IEEE Power Engineering Society

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IEEE

Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

5 September 2003

Print: SH95083
PDF: SS95083

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

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Approved 20 March 2003

IEEE-SA Standards Board

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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Print: ISBN 0-7381-3574-7 SH95083
PDF: ISBN 0-7381-3575-5 SS95083

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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.

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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 (Dickmander 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.

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

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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 1137™-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

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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 (Ω-m) for swampy soil to 30 000 Ω-m or more for solid rock. A typical value of 100 Ω-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.

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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 dBrn corresponds to 1 picowatt (pW) of energy dissipated in a 600 Ω

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termination. The corresponding voltage across the 600 Ω termination is 24.5 μV. A 1000 Hz tone of 0 dBm (reference to 1 mW of power in a 600 Ω termination) has an interfering effect of 90 dBrnC. The telephone industry would like the total circuit noise caused by all sources on any voice frequency circuit to not exceed 20 dBrnC 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 dBrn, 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 dBrnC 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)

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— 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.

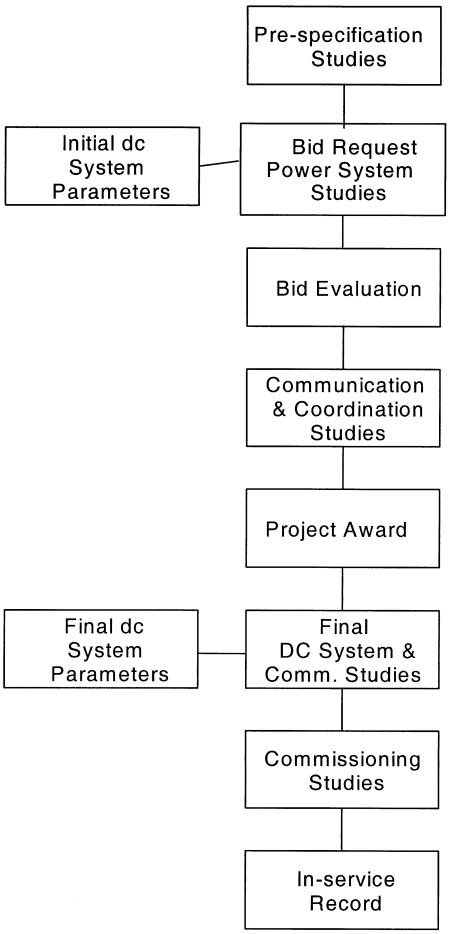

Figure 1—Methodology for HVDC inductive coordination study

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.

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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.

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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.

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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.

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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

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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

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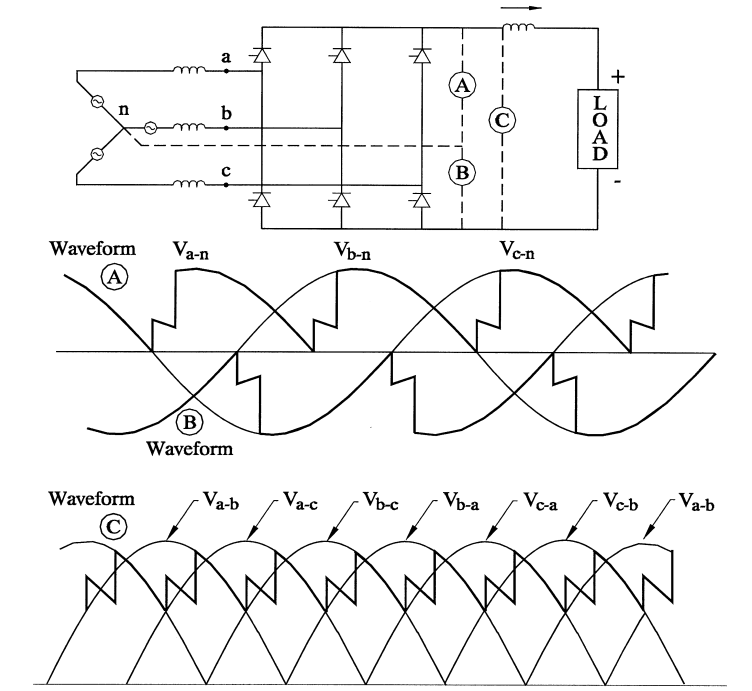

Figure 2—Ideal six-pulse converter voltage waveform

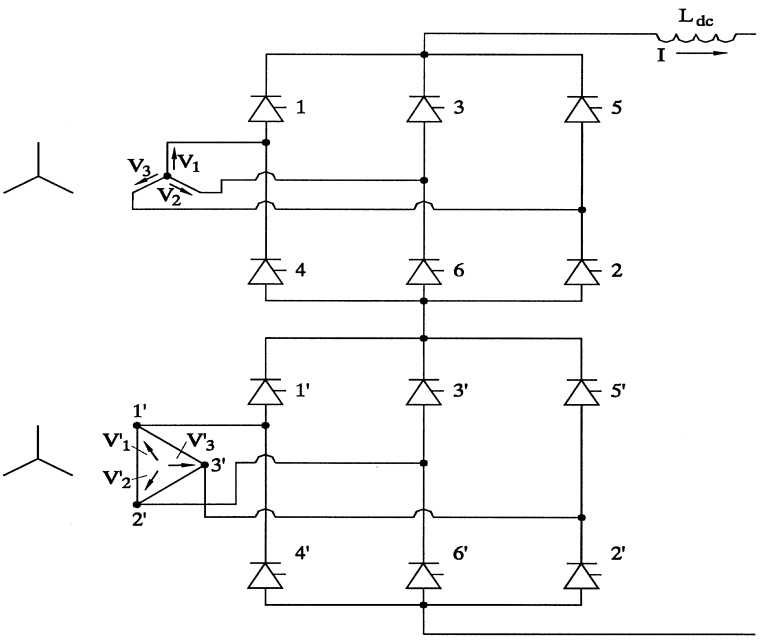

Figure 3—Twelve-pulse converter

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.

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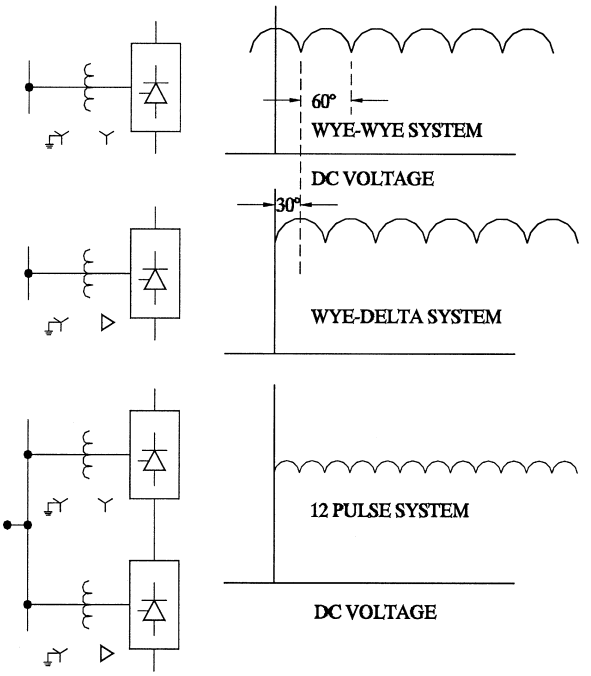

Figure 4—Effect of twelve-pulse operation on dc voltage

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

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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 (Dickmander 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* (Dickmander 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

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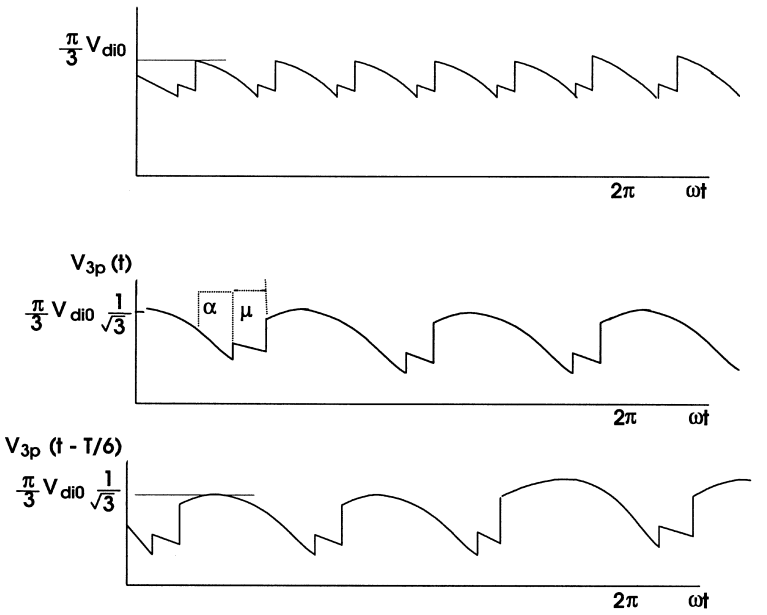

Figure 5—Decomposition of six-pulse waveform into three-pulse waveforms

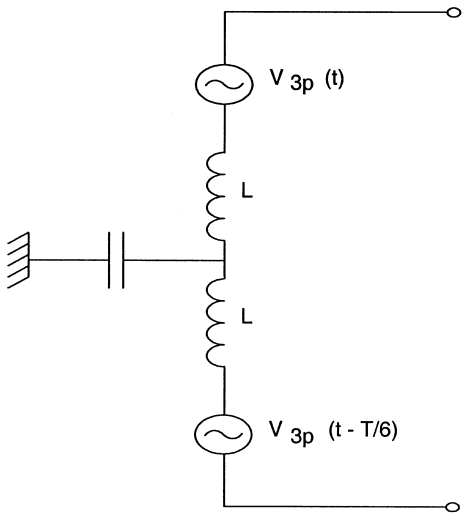

Figure 6—Six-pulse bridge modeled with three-pulse voltage source

instants. The present practice is to use a hybrid approach, whereby the [3*n*] harmonic voltages are calculated using a Fourier analysis of the three-pulse waveform, and the effects of non-idealities are analyzed using a piecewise linear method.

5.4.1 Three-pulse waveform analysis

A Fourier expansion for the three-pulse voltage waveform $V_{3p}(t)$ (Figure 5) is given in Shore et al. [B20], and is repeated in Equation (1):

$$V_{3p}(t) = \frac{1}{4} V_{dio} \left[(\cos\alpha + \cos\delta) + \sum_{k=1}^{\infty} [-1^k (a_{3k} \cos(3k\omega t) + b_{3k} \sin(3k\omega t))] \right] \quad (1)$$

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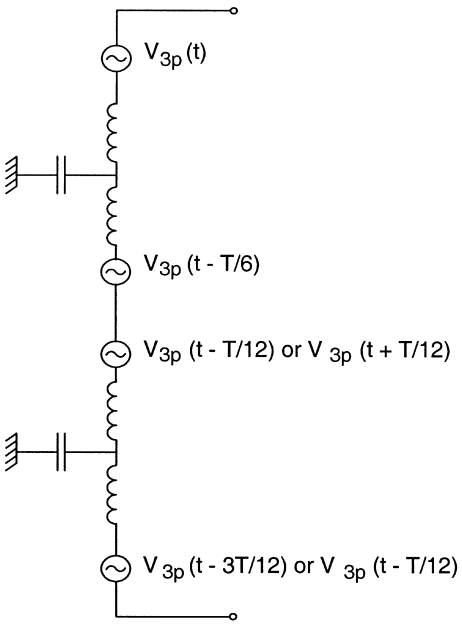

Figure 7—Twelve-pulse bridge modeled with three-pulse voltage source

where Equation (2a), Equation (2b), Equation (2c) show

$$\delta = \alpha + u \tag{2a}$$

$$a_{3k} = \frac{\cos[\alpha(1+3k)] + \cos[\delta(1+3k)]}{1+3k} + \frac{\cos[\alpha(1-3k)] + \cos[\delta(1-3k)]}{1-3k} \tag{2b}$$

$$b_{3k} = \frac{\sin[\alpha(1+3k)] + \sin[\delta(1+3k)]}{1+3k} - \frac{\sin[\alpha(1-3k)] + \sin[\delta(1-3k)]}{1-3k} \tag{2c}$$

The Fourier expansions for $V_{3p}(t - T/6)$, $V_{3p}(t - T/12)$, and $V_{3p}(t - 3T/12)$ are similar. Expressions of this type are useful in computing the driving voltages of order $3n$ for the three-pulse analysis. Table 1 gives the result of an example calculation of the Fourier coefficients for all three-pulse harmonic voltages up to the 84th. Note that it is necessary to retain the phase relationships among the three-pulse sources in order to obtain the correct harmonic current flow. Therefore, for each three-pulse source shown in Table 1, the two values given are the coefficients a_{3k} and b_{3k}, which define the orthogonal components of the Fourier series, and as such are in peak kilovolts.

5.4.2 Piecewise linear analysis

The expressions given in Shore et al. [B20] for the three-pulse Fourier series do not take into account possible asymmetries in valve firing, phase reactance, winding ratios, and imbalances in the ac voltages. These factors can influence many of the harmonic voltages of orders [$3n$], and can also produce noncharacteristic harmonics of other orders.

Because these non-idealities affect the periodicity of the dc voltage waveforms, explicit formulations of the Fourier series do not lend themselves easily to calculations of the noncharacteristic harmonics produced by these effects. For this reason, a *piecewise linear* approach is used to solve for the non-characteristic harmonics. This method solves for the instantaneous voltage and/or current values during each interval of the valve switching process, and then solves for the Fourier series using a numerical integration technique.

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Table 1—Example of three-pulse harmonic voltage calculation

All harmonic voltages in peak kV								
	$V_d = 500$ kV $V_{diON} = 285.2$ kV $v_{d6} = 250$ kV		alpha $= 20^\circ$ $I_{dN} = 2$ kA $V_{di0} = 284.255$ kV		Pd = 1000 MW dx = 6% overlap u $= 14.986^\circ$		fr = 60 Hz R1 = 0 Ω	
Harmonic number	$V_{3p}(t)$		$V_{3p}(t - T/6)$		$V_{3p}(t - T/12)$		$V_{3p}(t - 3T/12)$	
	a_{3k}	b_{3k}	a_{3k}	b_{3k}	a_{3k}	b_{3k}	a_{3k}	b_{3k}
3	49.901	27.293	−49.901	−27.293	−27.293	49.901	27.293	−49.901
6	4.542	−17.921	4.542	−17.921	−4.542	17.921	−4.542	17.921
9	−7.140	2.031	7.140	2.031	−2.031	7.140	2.031	−7.140
12	−2.322	1.502	−2.322	1.502	−2.322	1.502	−2.322	1.502
15	−1.591	3.258	1.591	−3.258	−3.258	−1.591	3.258	1.591
18	4.129	3.049	4.129	3.049	−4.129	−3.049	−4.129	3.049
21	3.404	−4.592	−3.404	4.592	−4.592	−3.404	4.592	3.404
24	−4.497	−3.075	−4.497	−3.075	−4.497	−3.075	−4.497	−3.075
27	−2.420	3.842	2.420	−3.842	−3.842	−2.420	3.842	2.420
30	2.745	1.728	2.745	1.728	−2.745	1.728	−2.745	−1.728
33	1.195	−1.399	−1.195	1.399	−1.399	1.195	1.399	1.195
36	−0.033	−0.915	−0.033	−0.915	−0.033	−0.915	−0.033	−0.915
39	0.882	−1.143	0.882	1.143	1.143	−0.882	−1.143	0.882
42	−1.976	1.014	−1.976	1.014	1.976	−1.014	1.976	−1.014
45	1.189	2.389	−1.189	−2.389	2.389	−1.189	−2.389	1.189
48	2.393	−1.279	2.393	−1.279	2.393	−1.279	2.393	−1.279
51	−1.190	−2.072	1.190	2.072	2.072	−1.190	−2.072	1.190
54	−1.556	0.881	−1.556	0.881	1.556	−0.881	1.556	−0.881
57	0.374	0.987	−0.374	−0.987	0.987	−0.374	−0.987	0.374
60	0.487	0.253	0.487	0.253	0.487	0.253	0.487	0.253
63	0.888	−0.137	−0.888	0.137	0.137	0.888	−0.137	−0.888
66	0.041	−1.415	0.041	−1.415	−0.041	1.415	−0.041	1.415
69	−1.739	−0.075	1.739	0.075	−0.075	1.739	0.075	−1.739
72	−0.028	1.808	−0.028	1.808	−0.028	1.808	−0.028	1.808
75	1.623	−0.022	−1.623	0.022	0.022	1.623	−0.022	−1.623
78	−0.007	−1.236	−0.007	−1.236	0.007	1.236	0.007	1.236
81	−0.734	−0.110	0.734	0.110	−0.110	0.734	0.110	−0.734
84	−0.328	0.215	−0.328	0.215	−0.328	0.215	−0.328	0.215

5.4.2.1 Solution method

The circuit model used for this type of analysis includes the complete structure of the valve bridge, the individual transformer phase inductances, and the individual ac-side phase voltages. In the model, the combination of the remote terminal and dc network is represented either by a constant current source or by a counter emf. In the former case, the dc voltage waveform produced by the switching action of the valves, and its associated harmonic spectra, are solved directly. In the latter case, the dc current

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waveform and its associated spectra are solved, and the harmonic voltages are then calculated using the harmonic currents and the internal impedance of the converter.

The thyristor valves of each bridge are numbered in accordance with their relative firing order (Figure 3). Consider that the operation is in steady state and that thyristor 1 is now fired. In accordance with the firing orders, and with the requirement for continuous conduction, thyristors 5, 6, 5′, and 6′ will also be in the conducting state. The equivalent circuit now involved is illustrated in Figure 8a). A commutation or transfer of current from valve 5 to valve 1 now takes place, and after an interval of overlap, *u*, the current in valve 5 extinguishes. At that instant, voltage V_3 is disconnected from the equivalent circuit, and the circuit becomes as shown in Figure 8b). This non-overlap interval is followed by the next overlap interval, which is initiated by firing valve 1′ at 30° after the firing of valve 1. Matching the circuit boundary conditions at the end of overlap intervals with the start of non-overlap intervals, and at the end of non-overlap intervals with the start of overlap intervals, forces a piecewise-linear solution defining the mechanism.

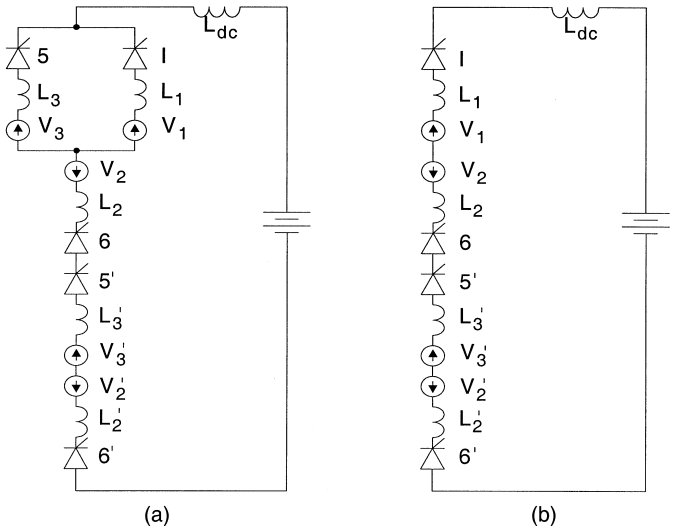

Figure 8—Piecewise linear analysis: a) before commutation; b) after commutation

Expressions for the converter dc voltage waveform, or the dc current waveform, during the overlap intervals and the non-overlap intervals are readily determined. The harmonic components of the dc voltage are then calculated. The maximum values of the noncharacteristic harmonics may then be calculated by using a statistical method, which involves running an appropriately large number of such cases with each parameter varied within an appropriate range.

5.4.2.2 Results of piecewise linear analysis for non-characteristic harmonics

If asymmetries are involved, the dc voltage waveform or dc current waveform calculated using the piecewise linear technique will have noncharacteristic harmonic components in addition to the characteristic harmonics. The non-idealities considered here are asymmetries phase commutating inductances, firing angles, and ac voltages.

Commutating inductance differences are of importance in the generation of noncharacteristic harmonics. The frequency multiplying effect on each bridge requires that a commutating inductance will be commutated into and commutated out of twice per period of source frequency, with these events displaced by a half period. This defines the maximum interval of dc current or dc voltage wave train repetition as a half period of source frequency. The commutating inductance imbalances can, therefore, only generate even noncharacteristic harmonics on the dc side, i.e., second, fourth, sixth, etc.

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Generally, the maximum tolerance on phase inductance is on the order of $\pm 2\%$ to $\pm 3\%$, with a typical standard deviation of 0.7%. The tolerance assumed by the manufacturer should be stated in his calculation. The distribution of this tolerance among the phases cannot be predicted until the transformers are actually built, so in the design phase the manufacturer should assume a distribution which will maximize the noncharacteristic harmonics, particularly the multiples of the 6th. Since the tolerance distributions can be different between the two poles of a bipolar transmission, the distribution should be chosen so as to maximize the ground mode component of the pole 1 and pole 2 harmonic voltages.

The imbalances in ac commutating voltages, generally expressed as a negative sequence component on the order of 1% or 2% of the positive sequence, produces predominantly harmonics order $12n \pm 2$, where $n = 0, 1, 2, 3, \ldots$ on the dc side. The magnitude of the second harmonic peak is approximately equal to the no-load dc voltage multiplied by the negative sequence component of the ac system voltage in per unit.

Small perturbations in the firing angle may occur in practice due to unbalance in the ac commutating voltage and deviations from ideal firing instants in the firing control system. These perturbations are usually very small, and in some studies they have been ignored. The effect of these perturbations depends on whether the deviations follow some pattern or are random in nature, and the magnitude of the deviation in each valve. In general, each pattern of deviation in firing gives a different set of harmonics, or at least a different set of dominant harmonics. Since an infinite number of patterns are possible, the expected harmonics can be of all orders.

The noncharacteristic harmonics calculated using the piecewise linear technique are then distributed evenly among the three-pulse voltage sources used to represent the converter. For bipolar analysis, a conservative approach is to assume a 90° phase difference in the noncharacteristic harmonics in the two poles, except where a lower angle can be justified, such as for the $12n \pm 2$ harmonics, which are caused primarily by negative sequence in the ac system, and for which the phase relationships can be calculated.

5.4.3 Effects of variations in operating point on harmonic voltages

The magnitude of individual harmonic voltages is dependent on the converter firing angle and the overlap angle. The overlap angle itself is a function of the commutating ac voltage, firing angle, and the dc current. Theoretical curves of characteristic harmonics, expressed as a percentage of no-load dc voltage, are provided in Kimbark [B13].

As the harmonics follow complex curves, which vary with the operating point of the converter, the complete operating range must be scanned to determine which operating conditions may cause the highest ground-mode current.

An accurate, but computation-intensive, approach is to run complete harmonic load flows for many different operating points as the dc power is increased from minimum to maximum, and to repeat this procedure for each different operating mode (e.g., bipolar, monopolar, reduced voltage, etc.) of the transmission. An alternative approach, which offers savings in computational effort, but which gives more pessimistic results, is to define a *worst nonconsistent set* of harmonic driving voltages for each operating mode of the transmission. These worst nonconsistent sets are defined by individually maximizing the harmonic driving voltages as the dc power is increased from minimum to maximum. A single harmonic load flow can then be run for each converter operating mode, using the worst nonconsistent set for that mode. This approach is somewhat pessimistic in that the individual harmonic maxima do not occur simultaneously as the converter power is increased from minimum to maximum.

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5.5 Calculation of harmonic currents

After the harmonic driving voltages are calculated using the techniques outlined in 5.4, the resulting harmonic current flow in the dc circuit components and the dc line are calculated using standard frequency domain analysis techniques. Usually, the frequency spectrum from 60 Hz to 3000 Hz, or somewhat higher (up to 5000 Hz), is studied.

5.5.1 DC line representation

For long transmission lines, the nonlinear effects of the earth and the conductors with respect to frequency are important (Lasseter et al. [B15]). Generally, leakage resistance is neglected. The distributed parameters of the line are expressed by the impedance and admittance matrices $Z(w)$ and $Y(w)$ evaluated at the angular frequency w.

The influence of ground is of particular importance in this type of analysis, and should be included using Carson's equations [B1]. The Carson terms may be evaluated using the approach of Mullineux and Reed [B16].

In calculating the line parameters, certain simplifying assumptions concerning the line configuration and the structure of the earth may be made. The sag of the line may be replaced by a constant height in the usual manner. The ground wire is normally assumed to be continuously grounded, and the earth is considered to be homogeneous. The coupled differential equations resulting from $Z(w)$ and $Y(w)$ for a multiconductor transmission line are solved using modal analysis. The result of the modal analysis is a generalized A, B, C, and D matrix formulation shown in Equation (3):

$$\begin{pmatrix} V(x) \\ I(x) \end{pmatrix} = \begin{pmatrix} A(x) & B(x) \\ C(x) & D(x) \end{pmatrix} \begin{pmatrix} V(O) \\ I(O) \end{pmatrix} \tag{3}$$

where the matrices A, B, C, and D are each 2×2 matrices for a two-conductor line. These matrices are related to $Z(w)$ and $Y(w)$ through the modal surge impedance and propagation constants. The elements $V(x)$ and $I(x)$ are 1×2 vectors for the modal voltages and currents related to each pole. The variable (x) is a point on the line as measured from the reference end.

Multiterminal systems (Shore et al. [B21]) use the same principles as the two-terminal system, but network solution is more complex because of the increased number of modes and matrix sizes. The presence of an electrode line on the same towers as the dc line will also increase the size of the matrices used to represent the line. Care should be given to an accurate representation of the electrode line and its terminating impedance, as studies have shown that the ground mode current on the electrode line can be a major factor in designing the filtering equipment (Dickmander and Peterson [B4]).

5.5.2 DC-side equipment representation

The dc-side equipment, which must be represented for harmonic analysis, includes a model of the converter (Figure 4), the smoothing reactor, the dc pole filter, and the neutral bus filter. Other equipment, which should be considered for inclusion in the model, include any equipment for power line carrier (PLC) or radio interference (RI) filters, if their impedances are significant in the telephone interference range.

The inductance of dc buswork is generally small and may be neglected for the frequency range in question. However, it may be necessary to include the bus inductances in cases that involve unusually long spans of dc buswork. The stray capacitance of the smoothing reactor should be represented if it forms a resonance with the smoothing inductance within the telephone frequency range.

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For analysis of bipolar operation, imbalances in the dc circuit equipment between the two poles should be considered. For example, detuning of filters in opposite directions between the two poles, and differences in smoothing reactors, may be significant.

5.5.3 Solution method

The harmonic currents at each point along the dc line, and the harmonic currents in the dc filters and other equipment, are solved using standard steady-state analysis techniques. Superposition is normally used to calculate the harmonic current contribution from each dc terminal at each point along the line. The resulting current contributions are then combined to calculate the total harmonic current at each point on the line at each harmonic frequency.

As the phase relationships between the harmonic sources of the various terminals are not normally known, the harmonic current contributions at each point along the line are normally combined using a root-sum-of-squares (RSS) calculation. An alternative method, which is somewhat pessimistic, would be to use arithmetic summation of the contributions. For typical studies the arithmetic summation has been found to give results somewhat greater (in the order of 10%) than the maximum calculated by vectorial addition at any location on the dc line for the worst phase angle. The RSS summation is generally regarded as quite realistic.

The result of this analysis is a standing wave pattern of total ground mode equivalent disturbing current, I_{eq}, versus distance along the dc line, or, alternatively, the total induced voltage on an open-circuit test line of a given length at a given distance from the dc line. An example calculation of induced voltage versus distance is shown as Figure 9. The large discontinuities in induced voltage in Figure 9 are caused by parallel sections of electrode line at the ends of the dc line.

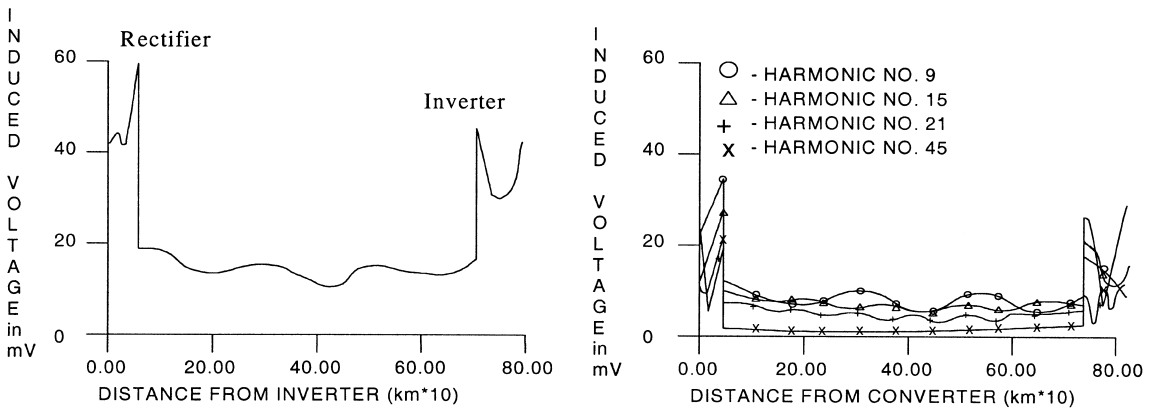

Figure 9—Example calculation of induced voltage versus distance

5.6 Harmonic current flow

As mentioned earlier, the presence of stray capacitance paths to ground within the converter significantly complicates the analysis of harmonic current flow on the dc side. For a detailed analysis of the phenomenon, the reader is referred to Shore et al. [B20]. The following discussion is taken to a large extent from that paper, to give a general orientation to the subject. The discussion in 5.6.1 deals with bipolar operation.

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5.6.1 Bipolar operation

If the harmonic driving voltages for each three-pulse source are calculated as described in 5.4.1, then the relative phase angles for each source of a bipole in balanced operation are as shown in Figure 10 for the following four types of harmonics:

a) Odd triplens (3, 15, 27, etc.)
b) Odd triplens (9, 21, 33, etc.)
c) Even triplens—not twelve-pulse (6, 18, 30, etc.)
d) Even triplens—twelve-pulse (12, 24, 36, etc.)

For simplicity, in each case the phase angle is shown relative to the uppermost generator, which is taken arbitrarily as 0°. From Figure 10 we may deduce several important aspects of the behavior of the three-pulse harmonic currents.

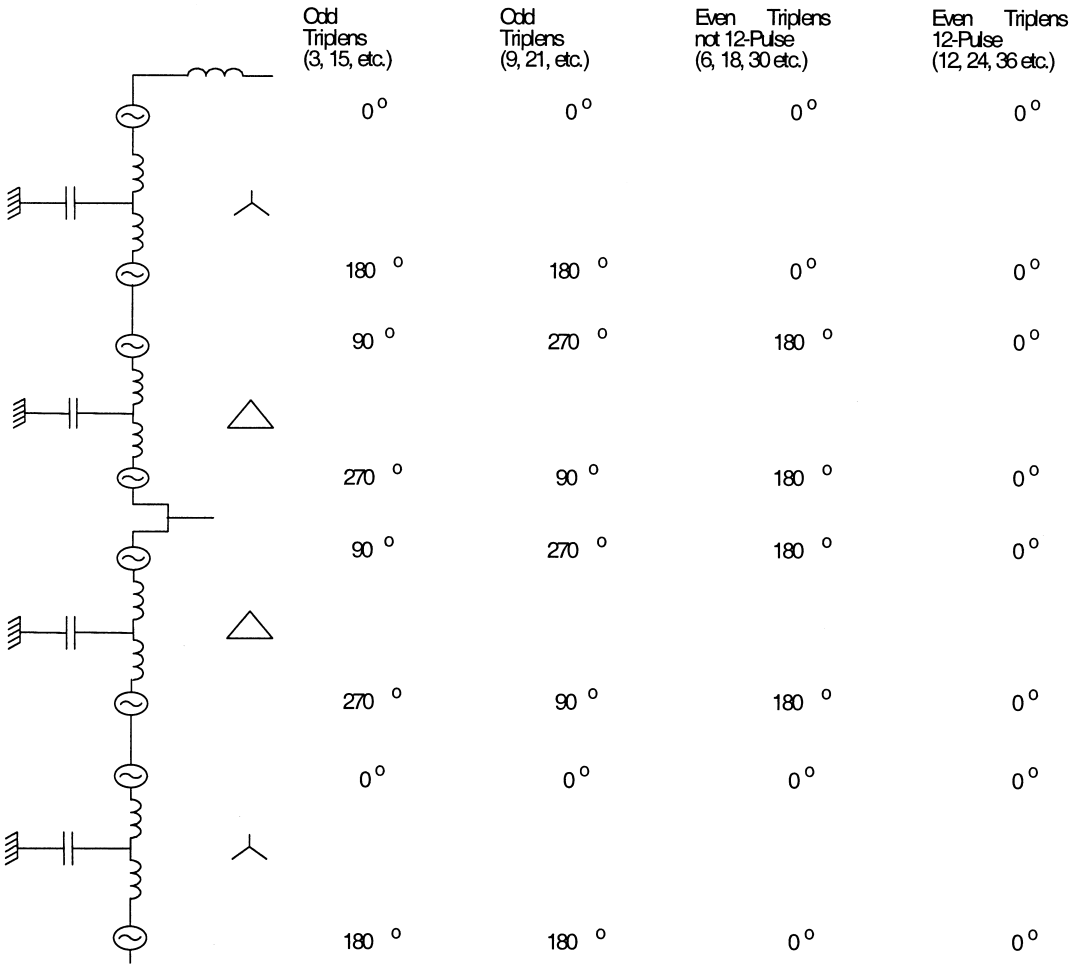

Figure 10—Relative phase displacement of three-pulse sources (balanced bipolar operation)

5.6.1.1 Even triplens

For the non-twelve-pulse even triplens, the phase relationships are such that all current flow in the stray capacitances cancels; i.e., current circulates in the ground mat of the station, but there is no

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residual external ground mode. This is illustrated in Figure 11a). An external pole mode current will flow as illustrated, but the interference effect of this is slight. For the twelve-pulse even triplens, all voltage sources are in phase, and an external pole mode current will flow.

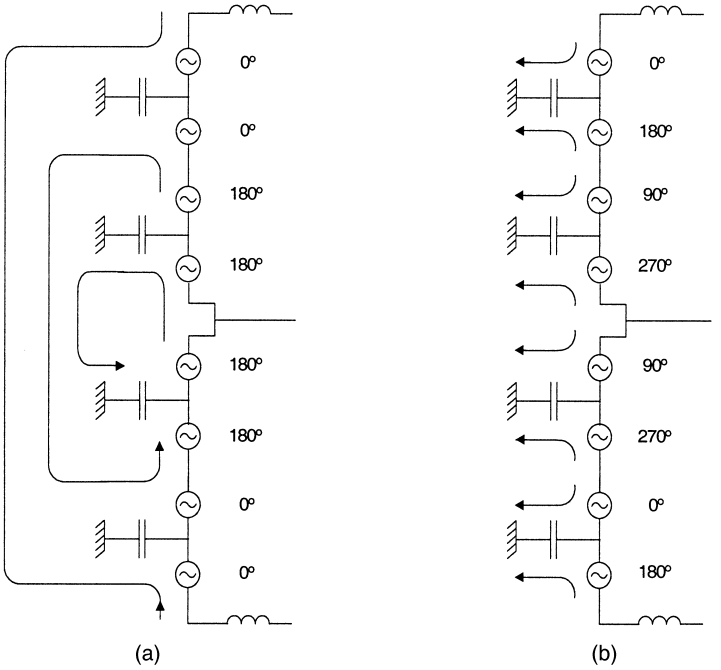

Figure 11—Current flow for even order a) and odd order b) triplen harmonics

5.6.1.2 Odd triplens

For odd triplens, the symmetrical three-pulse sources in the two poles are in phase opposition and so a residual harmonic current into the ground is produced as shown in Figure 11b). Evidently, to complete the current loop, this residual harmonic current must return to the converters via the neutral bus or the pole paths.

5.6.1.3 Residual voltages

The flow of stray capacitive current through the internal impedances of the converter will produce a residual voltage over each pole, even though the source voltages themselves cancel for all but the twelve-pulse characteristic harmonics. For even triplens, this residual pole voltage is in the pole mode, but for the odd triplens it is in the ground mode.

5.6.1.4 Unbalanced bipolar operation

During normal operation of a bipolar transmission in nominally bipolar operation, the direct current, voltage, and firing angles differ slightly between the two poles due to errors and tolerances. Hence, the harmonic voltages produced by the two poles differ in magnitude and phase angle, and the above discussion of balanced bipolar operation must be modified as follows:

a) For the even non-twelve-pulse triplens, i.e., 6, 18, 30, etc., the ideal in-station cancellation is lost, and a residual ground mode current flows out of the converters.
b) For the odd triplens, a modification in the total current occurs, as the net stray capacitive currents in the two poles move out of phase.
c) For the even twelve-pulse triplens, the ideal pole-mode current cancellation is lost, and a residual ground mode current flows.

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From this analysis, it may be concluded that the worst-case conditions for even-order triplen ground mode current is with maximum phase difference between harmonic voltage sources between the two poles, i.e., maximum unbalance. For the odd triplens, however, this maximum phase difference between poles is achieved during perfectly balanced operation. It is important to consider this difference when determining worst-case harmonic voltages in a dc filter study.

5.6.1.5 Return paths for ground mode currents

It was shown in 5.6.1.4 that a net ground mode harmonic current of all non-twelve-pulse triplen orders can flow out of the converters through the stray capacitances in normal unbalanced bipolar operation or in monopolar operation. This current must return to the converter through one or more of the following paths: a) through the electrode line to the ground electrode; b) through the neutral bus filtering; c) through capacitive coupling from ground to the pole conductors; or d) through remote station ground to the pole conductors.

5.6.2 Design stage remedial measures

The simplified equivalent circuit for a single pole shown in Figure 12 is useful in visualizing what remedial measures may be effective in reducing the triplen ground mode currents in the pole and electrode lines, and hence minimizing telephone interference problems.

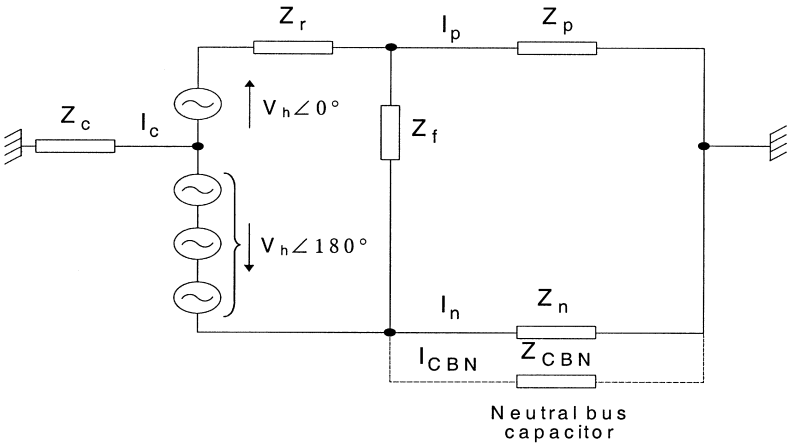

Figure 12—Simplified return paths for current in upper stray capacitances

It is apparent that if an effective grounding is provided at the harmonic frequencies at the neutral bus, then both pole and electrode line paths will be short-circuited and will carry no ground mode current. This may be achieved most economically by the installation of a large capacitor from the neutral bus to ground.

If the internal impedances of the converter are considered, it can be seen that the flow of the triplen harmonic ground current through the internal impedance will produce a residual voltage at the pole level as described in 5.6.1.3. It may be concluded, therefore, that effective pole-to neutral filtering at the triplen harmonic frequencies may be required in addition to the neutral capacitor.

5.6.2.1 Effect on twelve-pulse characteristic harmonics

In a normal HVDC scheme, where reasonably effective filtering is provided at the characteristic twelve-pulse frequencies, a ground mode current will flow in the stray capacitances and return via the pole and electrode lines, thus producing interference levels at the characteristic frequencies somewhat greater than would be predicted if the stray capacitances were neglected. Furthermore, the inclusion of

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pole-neutral filters is ineffective in inhibiting these currents unless coupled with the inclusion of a low-impedance path from the neutral bus to ground.

The inclusion of a neutral bus capacitor will provide an effective in-station return path for the characteristic stray capacitance currents in the analysis of the other triplens discussed earlier.

On the other hand, such a capacitor will decrease the total ground mode impedance seen by the classical twelve-pulse ground mode pole voltages, and will therefore tend to increase the interfering current in this path. Thus the introduction of a neutral bus capacitor may necessitate an increase in the size of the pole-neutral filters in order to restore the former impedance ratio of pole circuit and dc filter ground mode paths.

6. Induced noise analysis

This Clause deals with the calculation of the voice frequency noise induced in communication circuits by the harmonic currents flowing in an HVDC line.

Simplified theoretical analysis of induced noise is presented and the concept of equivalent disturbing current is explained. The application of the analysis of induced noise at both the pre-specification stage and in the coordination and optimization studies is discussed. Finally, guidance on the selection of harmonic current limits, verification of assumptions, and verification of performance is included.

This section is limited to the analysis of the interference caused by longitudinal electromagnetic induction. It does not consider transient effects or the effect of faults since these are related more to safety than to customer annoyance. Electrostatic induction is also ignored as modern communication circuits in cables are effectively shielded against electrostatic effects.

The calculation of the noise induced on communication circuits by harmonic currents flowing in a dc line is required both in the pre-specification studies (4.1) and in the coordination and optimization studies (4.3).

In the pre-specification stage it may be assumed that the preliminary line route has been established and that at least approximate values for earth resistivity, balance and shielding factors, and noise limits have been selected. At this stage the objective is to determine the harmonic current level(s) and the factor(s) characterizing the susceptibility to interference of the communication circuits in the area to include in the specification.

In the coordination and optimization study phase the objective is to identify the specific communication circuits that may require remedial measures and to investigate the most cost effective way of reducing the noise induced in the communication circuits to acceptable levels. To this end exposure data (relative location of telephone conductors with respect to HVDC line conductors), earth resistivity, and HVDC and electrode line configuration should have been updated and the harmonic currents resulting from at least the initial power circuit analysis should have been calculated for the full length of the HVDC lines.

6.1 Basic theory

Harmonic currents flowing in any conductor of a power transmission line create an alternating magnetic field that can cause harmonic voltages to be induced in any other conductors within the zone of influence of the magnetic field. The extent of the zone of influence depends on the physical arrangement of the *go* and *return* paths and on other factors as discussed in this section.

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The induced voltage in the communication circuit conductor is related to the harmonic current in the transmission line conductor by the mutual impedance Z_m. Since Z_m is dependent on frequency and on the conductors being considered the total induced voltage on one communication line conductor induced from all HVDC line conductors at one harmonic is given by Equation (4):

$$V_{cn} = \left(\sum_{j=1}^{j=k} I_{jn} Z_{mjn} \right) \quad \text{volts} \tag{4}$$

where

- n is the harmonic number,
- j is the conductor number,
- k is the number of conductors on the HVDC line, including electrode line conductors (see 7.3.3),
- V_{cn} is the common mode voltage at harmonic n,
- I_{jn} is the current vector in conductor j at harmonic n,
- Z_{mjn} is the mutual coupling impedance in Ω between conductor j, and the communication circuit conductor at harmonic n.

Note that Z_{mjn} is the value taking into account the screening effect of grounded shield wires or other grounded conductors (see 6.3.3).

The induced voltage appears between one end of the exposed conductor and the other, hence is a longitudinal voltage. This longitudinal voltage is *not* the actual interference voltage appearing at a subscriber telephone set except in the specific case of a single conductor, ground return telephone line and, in communication system parlance, is called the *common mode* voltage. High common mode voltages (50 V rms or more) should be avoided because of possible safety and operational problems.

Present day communication systems contain very few, if any, ground return circuits and use pairs of conductors (called the *tip* and *ring* conductors). In these circuits the annoying interference voltage is the *difference* between the longitudinal voltages induced in the tip and ring conductors and is known as the *transverse* or *metallic mode* voltage. The ratio between the transverse and longitudinal voltage is the *longitudinal balance* of the circuit, B_n, which is usually expressed in decibels and is frequency dependent.

In addition, modern communication circuits are usually twisted pairs (which improves the balance) in a shielded cable. This shield is grounded frequently and is assumed to be continuous. The effect of the shield is to reduce the induced voltage at the telephone set by the *shielding factor*, K_n, and is also frequency dependent.

The human ear hears some frequencies better than others; hence, some frequencies are more or less annoying than others. Standard weighting curves have been developed to reflect the frequency dependence of the ear, the response of the telephone receiver, and to allow the effective annoyance level of the spectrum of individual harmonic noise contributions at random phase angles to be calculated. In North America the most common standard is *C message weighting*. In Europe *psophometric weighting* is commonly used. In either case, the individual harmonic components are multiplied by the appropriate weighting factor and the total effective noise is given by the root of the sum of the squares of the weighted individual components.

The total C message weighted metallic mode noise voltage is therefore given by Equation (5):

$$V_m = \sqrt{\sum_{n=1}^{n=m} \left(\left(\sum_{j=1}^{j=k} I_{jn} Z_{mjn} \right) K_n B_n C_n \right)^2} \quad \text{volts} \tag{5}$$

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where

m is the highest order harmonic of interest,
C_n is the C message weighting factor at harmonic n,
V_m is the metallic mode, C message weighted noise voltage,
K_n is the communication circuit shielding factor at the nth harmonic frequency,
B_n is the communication circuit balance at the nth harmonic frequency.

Derivation of I_{jn} is discussed in Clause 6. Z_{mjn} is discussed in 7.3; values of K_n and B_n are (usually) provided by the telephone utility; C_n is standard and is shown in Figure 11; and the allowable value of V_m is discussed in 6.5.

6.2 Equivalent disturbing current

Equation (2) involves several frequency dependent terms and illustrates that, to determine the induced noise, the current in each HVDC line conductor has to be found at each harmonic frequency.

In the CCITT directives [B2], the concept of an *equivalent disturbing current* is introduced. This current is a single reference frequency current flowing in an imaginary single conductor located geometrically between the transmission line conductors, which produces the same weighted noise in the nearby communication circuit. This representation allows the noise voltage, V_m, to be expressed as Equation (6):

$$V_m = I_{\text{eq}} Z_{m1} K_1 B_1 \quad \text{volts} \tag{6}$$

where

I_{eq} is the C message weighted equivalent disturbing current,
Z_{m1} is the mutual coupling impedance between the notional conductor and the communication circuit at the reference frequency (1 kHz), including the screening effects of shield wires and other grounded conductors,
K_1 is the communication circuit shielding factor at the reference frequency,
B_1 is the communication circuit balance at the reference frequency.

In Equation (6), the equivalent disturbing current, I_{eq}, is related to the effective disturbance current at each frequency by Equation (7):

$$I_{\text{eq}} = \sqrt{\sum_{n=1}^{n=m} (I_n H_n C_n)^2} \quad \text{amperes} \tag{7}$$

where

I_n is the effective disturbance current at harmonic n,

H_n is the weighting factor to account for the general nature of the frequency dependent coupling exhibited by the communication circuits near the HVDC line, normalized to 1 kHz (i.e., similar to h_f in the CCITT directives),

C_n is the C message weighting factor at harmonic n.

The expression for the induced noise voltage, V_m, can therefore be rewritten as shown in Equation (8):

$$V_m = \sqrt{\sum_{n=1}^{n=m} (I_n H_n Z_{m1} K_1 B_1 C_n)^2} \quad \text{volts} \tag{8}$$

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The effective disturbing current is conveniently derived from the actual HVDC line currents by resolving the line currents into *balanced mode* and *residual mode* components. In a bipolar HVDC line (or monopolar with metallic return), the balanced mode and residual mode components are calculated by Equation (9) and Equation (10), respectively:

$$I_{bn} = (I_{+n} - I_{-n})/2 \quad \text{amperes} \tag{9}$$

$$I_{rn} = (I_{+n} + I_{-n}) \quad \text{amperes} \tag{10}$$

where

I_{bn} is the balanced mode current at harmonic n per pole,
I_{rn} is the total residual mode current at harmonic n per line,
I_{+n} is the phasor current in the positive pole at harmonic n,
I_{-n} is the phasor current in the negative pole at harmonic n.

The mutual impedances between the HVDC line and the communication circuits are different in the balanced and residual modes as shown in 6.3.1 and 6.3.2. At this stage, it is sufficient to note that, provided the balanced mode currents are not more than about 50 times greater than the residual mode currents, the noise induced in communication circuits by HVDC lines is predominantly caused by the residual component of the harmonic current, I_{rn}, as shown in Equation (11):

$$I_{rn} = \sum_{j=1}^{j=k} I_{jn} - I_n \quad \text{amperes} \tag{11}$$

The mutual impedance in the residual mode is the same for all conductors, provided the separation between the HVDC line and the communication circuit is large relative to the pole spacing. Hence,

$$Z_{mjn} = Z_{mn} \quad \text{ohms} \tag{12}$$

where

Z_{mn} is the mutual coupling impedance between the hypothetical single conductor and the communication circuit at harmonic n applicable to the residual mode.

Substituting Equation (8) and Equation (9) into Equation (2) yields Equation (13):

$$V_m = \sqrt{\sum_{n=1}^{n=m} (I_n Z_{mn} K_n B_n C_n)^2} \quad \text{volts} \tag{13}$$

which is virtually identical to Equation (5). Basically, the frequency dependency of $Z_{mn}K_nB_n$ has been replaced by a single frequency dependent term H_n such that in Equation (14):

$$(Z_{mn}K_nB_n) = (Z_{m1}K_1B_1H_n) \tag{14}$$

Provided that the factor H_n correctly reflects the frequency dependencies of mutual impedance (Z_{mn}), shielding (K_n), and balance (B_n), the effective disturbing current (I_n) is closely equal to the residual mode current (I_{rn}). This allows the equivalent disturbing current (I_{eq}) to be calculated easily from the (phasor) currents in each conductor, the standard listing of C message (or psophometric) weighting factors, and a listing of the frequency correction factors appropriate to the specific project.

The derivation of the frequency correction factor (H_n) for a specific project is based on an assessment of the frequency dependencies of mutual impedances, shielding factor, and balance. It should, if possible, be developed at the pre-specification stage.

While an initial assumption that H_n is equal to unity is unlikely to result in an error of more than a few decibels in the noise induced in the majority of communication circuits, it can result in a filter design

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that includes very expensive low-order harmonic branches. The significant improvement in balance at the lower frequencies shown in Figure 21 can, in practice, make low-order harmonic branches less necessary. Conversely, the less effective balance at higher frequencies requires better filtering. However, this is relatively easy to achieve without significant cost.

It is therefore strongly recommended that the values for the term H_n be developed at the pre-specification stage as described in 6.4.

The separation of the calculation of I_{eq} and V_m is particularly helpful in the early stages of an HVDC project because it allows:

a) Analysis of the noise induced in the communication circuits without having to know the particular frequency spectrum of the disturbing current.
b) DC harmonic filter design and specification to proceed using given general criteria for the equivalent disturbing current without the need to calculate the noise induced in the nearby communication systems.

6.3 Calculation of mutual impedance

The mutual impedances (Z_{mjn}) between the HVDC line(s) and individual communication circuits have to be calculated in inductive coordination studies. The mutual impedance is extremely difficult to calculate accurately, particularly when the current return occurs in an environment with losses. The problem has been discussed by several authors (Carson [B1], Deri et al. [B3], Mullineux and Reed [B16], Olsen and Pankaski [B17], and Rogers and White [B19]); however, the Dubanton equations (Deri et al. [B3]) give satisfactory results over an extensive range of frequencies, separation distances, and earth resistivities. Various simplifying assumptions have to be made in calculating the mutual impedance for a typical practical exposure, but the accuracy expected (within 2 or 3 dB) is reasonable bearing in mind the accuracy of other data, e.g., earth resistivity, shielding, balance, and the disturbing harmonic currents themselves.

There are a number of methods available for calculation of mutual impedance. Four of these are as follows:

1) The Mathcad computer program solves Carson's equation directly;
2) Parker's algorithm is a good approximation for calculating mutual impedance with a hand calculator;
3) The EPRI program, CORRIDOR, calculates mutual impedance between overhead power lines and aerial or buried telecommunications cables; and
4) The electromagnetic transients program (EMTP) calculates mutual impedance between overhead power lines and aerial telecommunications cable.

It should also be noted that the calculation of the coupling for a particular exposure involves breaking down the exposure into a series of parallel sections typically as shown in Figure 13, and adding these together to obtain the total coupling (Table 2). This implies lines of finite length for which specialized equations (Rogers and White [B19]) are strictly required. Similarly, earth resistivity may differ between one section and another. These effects change the depth of the fictitious return plane assumed in the Dubanton equations; nevertheless, the depth is assumed to be that predicted assuming infinite lines and the average earth resistivity of the area as opposed to that of the specific section.

6.3.1 Dubanton equations

The depth of the fictitious ground return plane used in the calculation of impedance is a complex number given by Equation (15):

$$p = 1/\sqrt{j\omega \mu_0 / \rho} \quad \text{meters} \tag{15}$$

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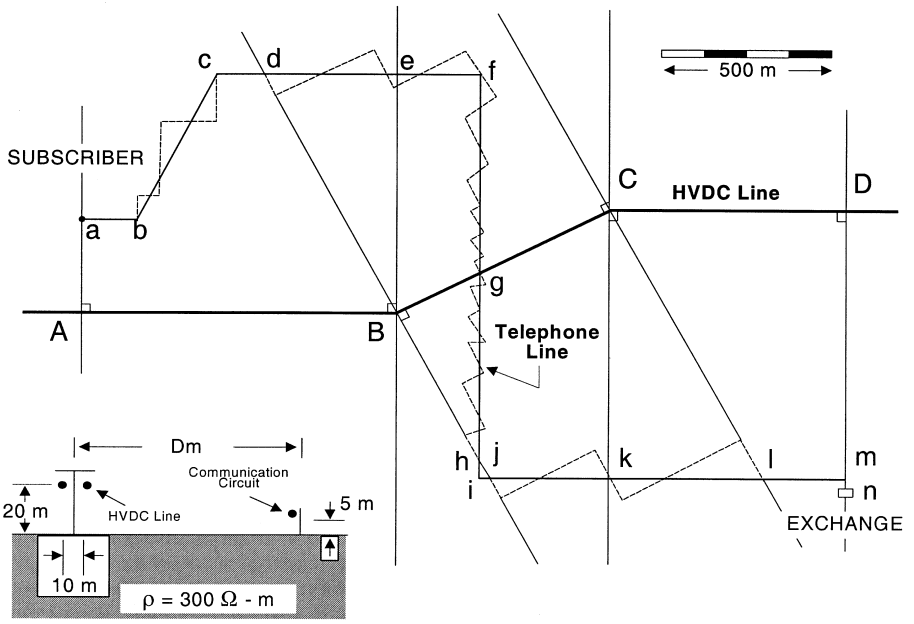

Figure 13—Mutual impedance for line exposure

where

- p is the complex depth of ground return plane,
- j is the $\sqrt{-1}$,
- ω is the angular frequency of harmonic being considered ($2\pi f_n$),
- μ_0 is the magnetic permeability of a vacuum ($4\pi \times 10^{-7}$),
- ρ is the earth resistivity (Ω-m),
- f is the fundamental frequency,
- n is the harmonic number,

(at 1000 Hz and 300 Ω-m, $p = 194.9\angle 45^\circ$ or $= 137.87 - \text{j}\,137.83$).

The values of self- and mutual impedance can then be calculated from Equation (16):

$$Z_s = \frac{\text{j}\omega\mu_0}{2\pi} \ln\left[\frac{2(h+p)}{r}\right] \quad \text{ohm/meter} \tag{16}$$

where r is the radius of the conductor (m) and [Equation (17)]:

$$Z_m = \frac{\text{j}\omega\mu_0}{2\pi} \ln\left[\frac{(h_1+h_2+2p)^2 + D^2}{(h_1-h_2)^2 + D^2}\right]^{1/2} \quad \text{ohm/meter} \tag{17}$$

where

- D is the horizontal separation distance between the power and communication circuit conductors in meters,
- h_1 and h_2 are the heights of the two conductors above ground in meters.

The impedances in Equation (16) and Equation (17) are also complex and must be considered as phasor quantities when calculating the total coupling of a communication circuit exposure if the exposure is not parallel to the HVDC line.

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Table 2—Mutual impedance for line exposure shown in Figure 13

HVDC line section	Communication line section	Separation (D) in meters				Calculated mutual impedance in OHMS	
		Maximum	Minimum	Average	Length meters	Real part	Imaginary part
	a–b	400	400	400	200	0.094	0.069
A–B	b–c	600	400	500	100	0.036	0.023
		1000	600	800	200	0.032	0.008
	c–e	1000	1000	1000	700	0.073	0.007
	d–f	1120	920	1020	400	0.041	0.004
		920	780	850	280	0.04	0.007
		780	500	640	140	−0.034	−0.016
		500	300	400	100	−0.047	−0.035
		300	200	250	50	−0.033	−0.035
		200	100	150	50	−0.04	−0.062
		100	50	75	25	−0.022	−0.051
B–C		50	0	25	25	−0.023	−0.081
	g–h	50	0	25	25	−0.023	−0.081
		100	50	75	25	−0.022	−0.051
		200	100	150	50	−0.04	−0.052
		300	200	250	50	−0.033	−0.035
		500	300	400	100	−0.047	−0.035
		720	500	610	110	−0.029	−0.015
	j–l	980	780	880	400	0.053	0.008
		1230	980	1105	500	0.042	0.004
C–D	k–m	1100	1100	1100	900	0.077	−0.007
Total impedance for the entire exposure						0.095	−0.422[a]

[a]NOTE—Total may have round-off errors.

It may be noted that

$$\ln (A + \mathrm{j}B) = \ln (A^2 + B^2)^{1/2} + \mathrm{j}\theta$$

where

θ is the angle $(\tan^{-1} B/A)$ expressed in radians.

These equations are based on the assumption that the permittivity of the earth is equal to that of free space (μ_0). A correction factor is developed in Deri et al. [B3]. It is also shown that, for the large values of $D/(h_1 + h_2)$ typical of most communication circuit exposures, the error in the audio frequency range can be high at particular frequencies. Overall, however, the error in the total induced noise calculated by these equations is expected to be acceptable bearing in mind the probable errors in the other data used in the calculations.

It should also be noted that the equations assume a homogeneous earth. A method for developing the equivalent resistivity of a multilayer earth is described in Larsen et al. [B14] and is further discussed in 6.3.5.

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6.3.2 Modal coupling impedances

As noted in 6.2, both balanced- and residual-mode coupling impedances have to be considered. In the residual mode, the HVDC line (and electrode line if located on the HVDC line tower or close to it) is represented by a single conductor and Equation (12) and Equation (14) define the mutual impedance between the equivalent conductor and the communication circuit. With the arrangement shown in Figure 13, the residual mode impedance at 1000 Hz and $D = 500$ m becomes [Equation (18)]:

$$\begin{aligned} Z_{mr} &= 0.35185 + \text{j}0.13878 \quad \Omega/\text{km} \\ &= 0.37823\Omega \angle 21.53^\circ \quad \Omega/\text{km} \end{aligned} \tag{18}$$

The mutual impedance in the balanced mode may be found by subtracting the mutual impedance phasors between the communication circuit and each of the pole conductors. For separations that are large relative to the pole spacing, the two impedances are very close to being equal and thus the resulting impedance is small. This subtraction is justified since the balanced mode currents are equal and opposite in the two poles. With separation distances of 495 m and 505 m, respectively, the balanced mode mutual impedance at 1000 Hz becomes [Equation (19)]:

$$\begin{aligned} Z_{mb} &= (0.35724 + \text{j}0.14288) - (0.34655 + \text{j}0.13482) \quad \Omega/\text{km} \\ &= 0.01339 \angle 36.98^\circ \quad \Omega/\text{km} \end{aligned} \tag{19}$$

The effects of changes in separation distance (at 1000 Hz, 300 Ω-m), earth resistivity (at 1000 Hz, 500 m), and frequency (at 300 Ω-m, 500 m) on both residual and balanced mode coupling impedances are shown in Figure 14, Figure 15, and Figure 16, respectively. It is shown that the mutual impedance for the balanced mode is significantly less than for the residual mode, by a factor between 20 and more than 100 times.

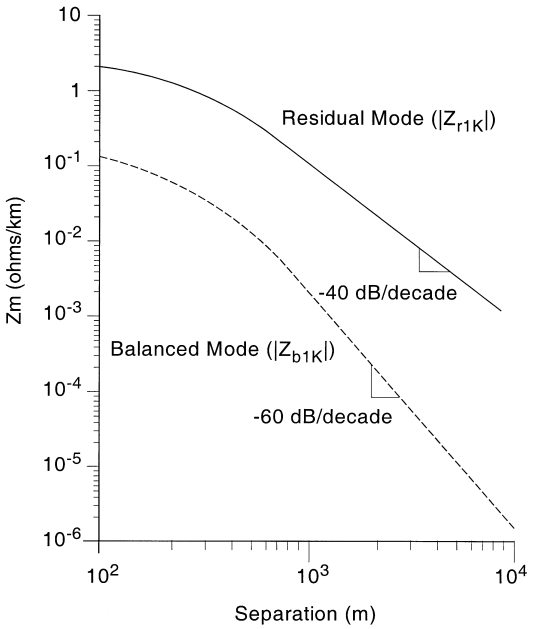

Figure 14—Effect of separation distance on residual and balanced couplings

In practice, the communication circuits are rarely parallel to the HVDC line over the full length of the exposure, and angled approaches and even crossings must be considered. In these cases, the exposure must be broken down into sections, which are then assumed to be parallel over the length of the section. The parallel sections are joined by lines at right angles to the HVDC line in which no noise is

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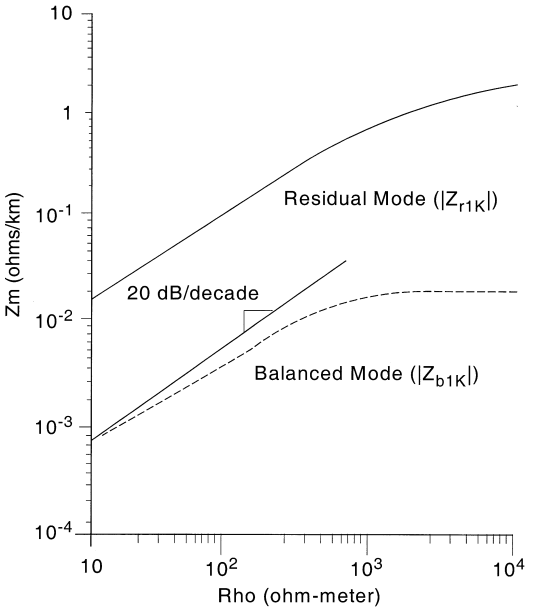

Figure 15—Effect of earth resistivity on residual and balanced couplings

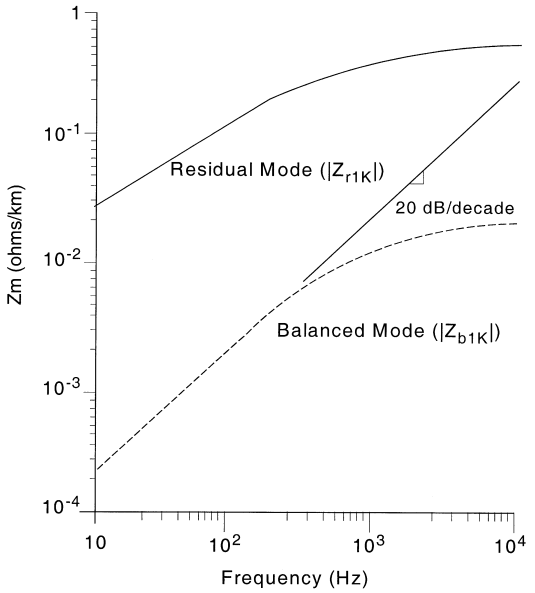

Figure 16—Effect of frequency on residual and balanced couplings

induced. The length of the section has to be decreased as the separation decreases, which makes calculation by hand tedious.

Depending on the geometry, the ratio between residual and balanced mutual impedances decreases significantly as the separation distance decreases; hence, the balanced mode becomes relatively more important. If, however, the communication line crosses the HVDC line, the balanced mode practically disappears as the noise voltage induced at a given distance on one side of the HVDC line is opposite in phase to that on the other side. This is because, in the balanced mode, the interfering source is effectively a horizontally oriented dipole. In the residual mode, the dipole is vertically oriented and the cancellation does not occur.

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As shown in Figure 17 and Figure 18, the residual mode coupling impedance for a diagonal typical crossing is significantly greater than for a typical parallel exposure.

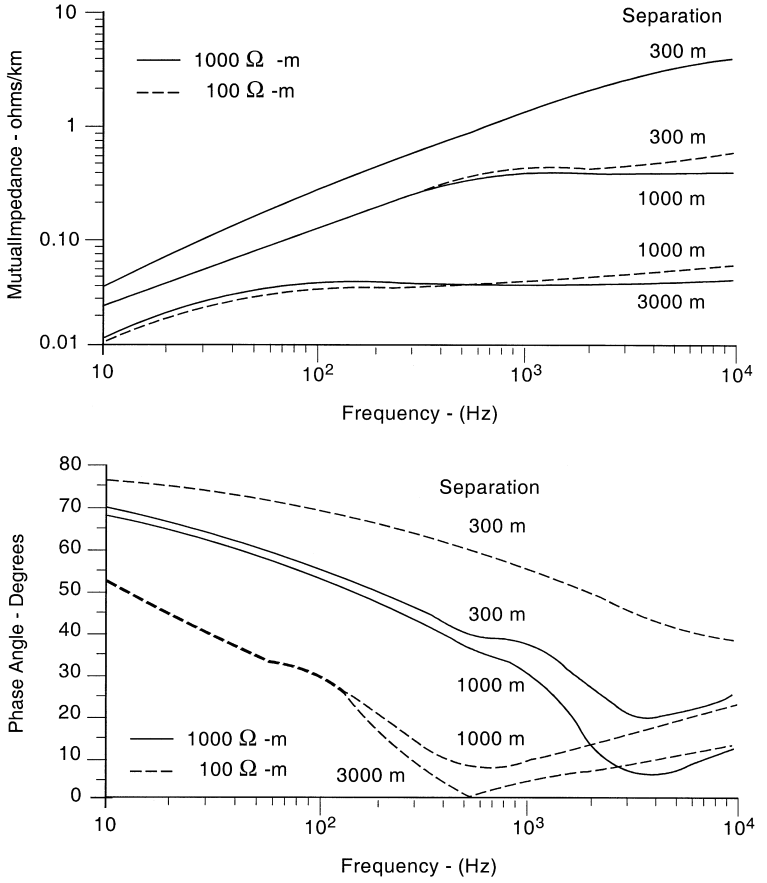

Figure 17—Mutual impedance of parallel conductors for earth return circuits, residual mode

It is concluded that the balanced mode harmonic current component can be neglected in inductive coordination studies unless:

a) The balanced mode component is in excess of 50 times the residual mode component, or
b) The communication circuit terminates within about 400 m of the HVDC line, or
c) The angle of crossing changes significantly within about 200 m of the HVDC line.

6.3.3 Screening

Currents may be induced in other conductors such as ground or neutral wires, rails, pipelines, or other conduits, etc., if such conductors are grounded through relatively low impedances. These currents modify the magnetic field seen by the communication circuit and thereby provide screening. Screening should not be confused with the shielding given by the communication circuit shield, as the currents in the latter do not affect the magnetic field seen by the communication circuit as a whole.

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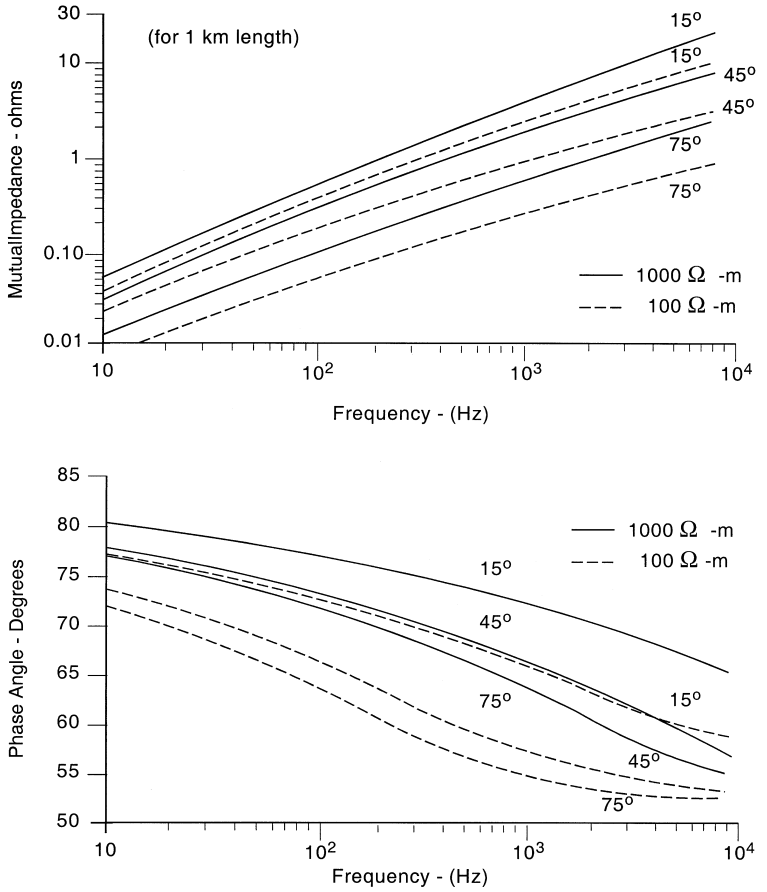

Figure 18—Mutual impedances and phase angles of crossing conductors for earth-return circuits, residual mode

To be theoretically correct, the presence of these other conductors should be allowed for in the calculation of mutual coupling impedances by calculating the self- and mutual impedances for all conductors using Equation (13) and Equation (14) and resolving the resultant circuit using matrix methods or a suitable circuit analysis program (such as electromagnetic transients program—EMTP).

In practice the shielding provided by the (usually steel) ground wires of the HVDC line reduces the induced noise by about 3 dB and is relatively independent of frequency, earth resistivity, separation, etc.

6.3.4 Electrode lines

Electrode lines also carry harmonic currents and must be included in inductive coordination calculations if they are also magnetically coupled to the communication circuit exposure being considered.

If the electrode line is on the HVDC line tower, or is within the same right-of-way, the distances separating the power circuit conductors remain small relative to the separation to the communication line in most cases. In such cases, the electrode line currents can be included in the residual component per Equation (8) and the assumption of a single disturbing conductor with ground return remains reasonable.

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When close approaches or crossings are involved or when the *balanced* mode currents must be taken into account, it is necessary to calculate the coupling impedances between all the power conductors and the communication circuit and to add the various components of induced voltage vectorially.

The same applies when the electrode line is separate and the magnitudes and phase angles of the harmonic currents in the pole conductors and electrode line are known. When this is not known, or when no fixed relationship between the phase angles exists, it is usual to root sum square the contributions from the HVDC and electrode lines.

It may be noted that harmonic currents are injected into any HVDC line section from both ends and that, in general, the relative phase angles of the harmonics are not fixed—even if the converter stations are connected into the same ac system. It is also usual to use the root sum of squares method to determine the total effect of the two sets of harmonic currents.

6.3.5 Earth resistivity

The return path for the residual mode current is the earth, but the current is spread throughout the entire mass of the earth. About all that can be said is that the higher the frequency, the shorter the line, and the lower the earth resistivity, the greater the proportion of the return current that will be found near to the line.

In inductive coordination studies, the frequency range from fundamental frequency to about 5000 Hz is of interest. Earth resistivities up to 30 000 Ω-m may be encountered, particularly in the oldest rock formations; hence, the depth of the fictitious earth return plane (p) can exceed 5000 m and the resistivity of the earth at depths of several times p can influence the mutual impedances.

It follows that the earth resistivities at significant depths must be obtained if inductive coordination studies are to be undertaken. Measurements of earth resistivity using probes separated by only a few hundred meters are unlikely to be sufficient.

Earth resistivity usually varies with depth and, for inductive coordination studies, it is necessary to represent the stratification in order to calculate the effective earth resistivity in the area of the communication circuit exposure being considered. In Deri et al. [B3], it is shown that a multilayer earth can be (approximately) represented by a homogeneous earth. Since the depth of the fictitious complex return plane is frequency dependent, the effective earth resistivity will also be frequency dependent.

6.4 Calculation of frequency dependency (H_n)

The frequency dependency factor, H_n, was defined by Equation (11) in 6.2. H_n is theoretically different for each exposure and each harmonic.

To make the equivalent disturbing current method useful in practice, it is necessary to develop a single frequency dependent function that is representative of all the critical exposures along the length of the HVDC line and any associated electrode lines.

The average value of H_n is defined as shown in Equation (20):

$$H_n = \frac{1}{t}\sum_{s=1}^{s=t}\left[\frac{Z_{msn}k_{sn}B_{sn}}{Z_{ms1}K_{s1}B_{s1}}\right] \tag{20}$$

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where

s is the communication circuit exposure,

t is the total number of critical exposures considered,

Z_{ms} is the residual mode coupling in ohms of exposure s at harmonic n (Z_{msn}) and at reference frequency of 1 kHz (Z_{ms1}),

K_s is the shielding factor applicable to exposure s at harmonic n (K_{sn}) and at reference frequency of 1 kHz (K_{s1}),

B_s is the balance factor applicable to exposure s at harmonic n (B_{sn}) and at reference frequency of 1 kHz (B_{s1}).

Clearly, the calculation of H_n involves a major inductive coordination study and should ideally be developed prior to the issue of the converter station specification. The communication circuit exposures chosen to determine H_n must also be representative of the overall characteristics of the critical exposures; hence, exposures with completely different characteristics (such as open wire lines, etc.), exposures that will obviously require relocation or change to carrier, and exposures that are obviously not critical should be excluded.

The degree by which the value of H_n for a specific exposure differs from the average is indicative of the error that is introduced in the estimate of noise.

While K and B are both frequency dependent functions, the values of K_n/K_1 and B_n/B_1 are likely to be the same for all critical exposures, since these are characteristic of the communication circuit cables and the particular communication utilities installation and maintenance practices. It is recommended that the communication utilities be approached at the earliest possible stage to provide their typical minimum acceptable K_n and B_n functions.

The value of Z_{mn} over the range of frequencies of interest varies widely depending on separation and earth resistivity, but particularly on whether or not the exposure crosses the HVDC line and the angle of crossing. The value of Z_{mn}/Z_{m1}, however, is less dependent on the details of the actual exposure. As shown by Figure 17 and Figure 18, for exposures with significant Z_m (hence, more likely to be critical), Z_{mn}/Z_{m1} is typically between 0.15 and 0.3 at 200 Hz and between 2 and 4 at 5000 Hz. With a range of variation of the order of 2 : 1, the typical error is $\pm 40\%$; hence, the error in noise level is unlikely to exceed 3 dB. It may also be noted that, where the low-frequency noise is being underestimated by the typical exposure assumed, the high-frequency noise is being overestimated and vice versa. The error in the total noise is therefore likely to be less than 3 dB.

It is concluded that the calculation of H_n using average values of Z_{mn}/Z_{m1}, K_n/K_1, and B_n/B_1, is unlikely to result in induced noise estimates, which are wrong by more than 2 or 3 dB. This is an accuracy level that is tolerable, bearing in mind the overall objectives of the equivalent disturbing current method.

6.5 Application of the equivalent disturbing current method

Calculation of mutual impedances as discussed in 6.3 is required whether the induced noise is being calculated on an exposure by exposure basis using specific harmonic currents, etc., per Equation (2) or, in general, using the equivalent disturbing current method per Equation (3).

In this subclause, some practical considerations in the application of the equivalent disturbing current approach for the specification of HVDC converter stations are discussed.

The equivalent disturbing current approach can be used for the pre-specification and coordination and optimization studies described in 4.1 and 4.3; however, the final filter design verification and

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communication circuit mitigation requirement studies should be based on the more exact approach of Equation (2).

6.5.1 Selection of I_{eq}

Even the initial selection of I_{eq} is an iterative process. As noted in 4.1, it is desirable to express the permissible induced noise in terms of the equivalent disturbing current; however, the relationship between induced noise and I_{eq} is highly project dependent. This guide cannot recommend levels of I_{eq} to be included in a specification; but past experience has indicated that values in the 0.1–1.0 A range are typical for normal bipolar operation.

It should be recognized that the level of I_{eq} specified should ideally be that at which the incremental cost of improving the filtering is equal to the incremental saving in mitigation required in the communication circuits. In practice, I_{eq} levels have been selected to err on the low side of the ideal because the communication system is more likely to expand than to contract, and because improving filtering after commissioning is usually extremely difficult. New telephone communication technology such as fiber optics, which is immune to electromagnetic induction, will avoid the interference problem.

If the initial studies do not, with the initially selected value of I_{eq}, indicate of the order of tens of circuits, which could require mitigative measures, then the value of I_{eq} is likely to be uneconomically low. On the other hand, if there are hundreds of circuits that could require mitigation, reduction of I_{eq} by improved filtering is likely to be economically justified.

6.5.2 Acceptable values of noise voltage

The level of noise that is acceptable has to be defined in cooperation with each telecommunication utility. This definition should be sought at the earliest possible phase.

Communication circuit noise is defined relative to 1 pW in 600 Ω, i.e., relative to an applied voltage of 24.5 μV, and is expressed in decibels above this level.

The communication industry has determined performance thresholds for metallic mode C message weighted noise on normal business or residential lines. A noise level of 20 dBrnC is considered acceptable; however, 30 dBrnC or more is considered unacceptable in most cases. Noise from any single source should be 3 dB below objective (equivalent to not more than half the power) to allow for contributions from other sources.

The balance of a modern communication cable pair should be of the order of 60 dB. To some extent, this depends on the particular utility standard; however, any value lower than 50 dB could be considered somewhat sub-standard and implies some onus on the communication utility to at least bear part of the cost of any mitigation measures found necessary.

Assuming a balance of 60 dB, a communication circuit with a longitudinal induced voltage, V_c, of less than 0.245 V (80 dB) (including the effect of shielding—see Figure 19) is unlikely to require any corrective action; however, if V_c is above 0.775 V (90 dB), mitigative measures are likely to be required.

In addition to establishing the acceptable noise levels, the power circuit conditions have to be considered. The communication utility may, for example, accept higher noise for short-term configurations such as monopolar with earth return than for normal bipolar operation. Again such short-term limits should be agreed with the utility at the earliest possible time.

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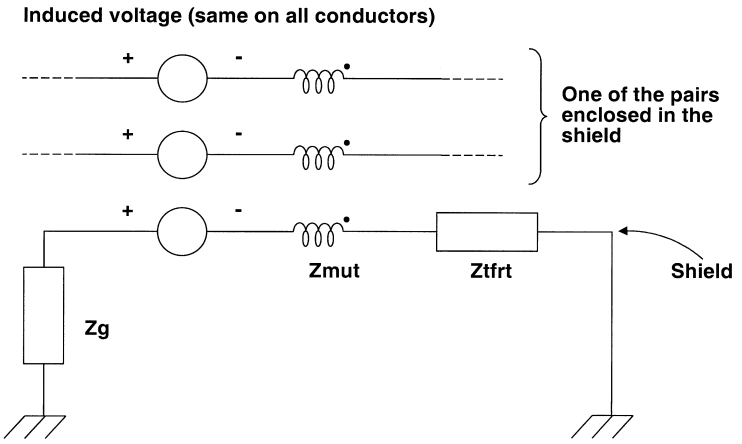

Figure 19—Equivalent circuit showing shielding effect

6.5.3 Zone of influence

The zone of influence, expressed as a distance on either side of the HVDC line, should be selected to give reasonable assurance that all communication circuits, which might require mitigative measures, are identified.

The width of the zone will depend on the general earth resistivity in the area, the density and average length of subscriber circuits, the predominant type of circuit (open wire, overhead/buried cable, down-drop type and length, etc.), and the maximum equivalent disturbing current expected.

For example, if it is estimated that in a given region the HVDC line is the only exposure, the telephone lines are predominantly shielded cable, the earth resistivity is of the order of 1000 Ω-m, and the top end of the I_{eq} range being considered is 2000 mA, then using Equation (3) and Figure 14, Figure 15, Figure 20, and Figure 21:

a) V_m should not exceed 0.25 mV (20 dBrnC from 6.5.2)
b) I_{eq} is 2000 Ma
c) K_1 will be about 0.35 (Figure 20)
d) B_1 will be about 1/750 (Figure 21, −57.5 dB)

Hence, Z_{mn} should not exceed 0.27 Ω in total.

If it is assumed that the longest effective exposure for a subscriber line just outside the zone is 10 km, then Z_{mn} must be limited to 0.027 Ω/km. If the area earth resistivity were 300 Ω-m, then the required separation would be 2000 m (Figure 14); however, this is increased to 5000 m to account for the increase in earth resistivity to 1000 Ω-m (Figure 15).

Based on the above reasoning, the zone of influence would be 5 km on either side of the HVDC line. It should, however, be noted that any open-wire circuit within several tens of kilometers of the HVDC line could experience excessive interference under the above conditions, and that a much wider zone of influence must be considered for such open wire lines.

It should also be noted that all communication circuits with any significant (say more than 1 km) part of the circuit within the zone of influence should be included. It is not just the terminations of the circuit that matter.

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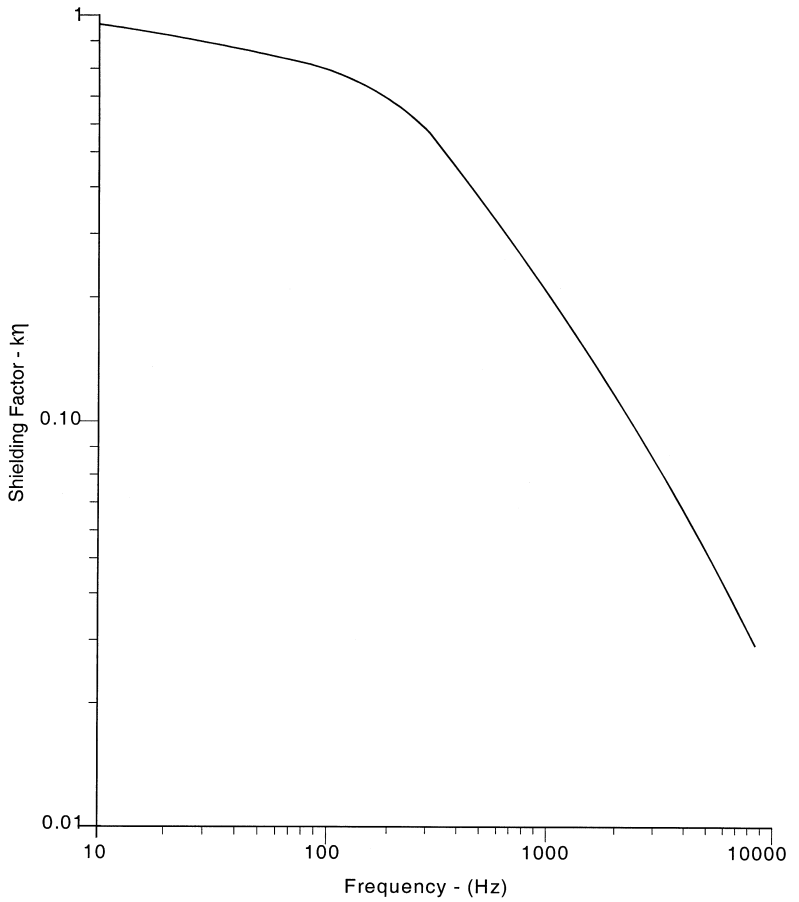

Figure 20—Example of typical shielding factor for multigrounded telephone cable

6.5.4 Initial inductive coordination study

Based on preliminary values of earth resistivity, balance and shielding factors, and exposure data, the approximate level of noise induced in each exposure may be calculated as a function of I_{eq}. It is convenient to rank the exposures in descending order of V_m/Amp of I_{eq}.

It is then possible to estimate the probable cost of mitigative measures as a function of I_{eq}, but it is theoretically necessary to compute the mutual coupling impedance for each of the exposures, of which there could be several hundred; however, initial inspection should allow the noncritical exposures to be identified and eliminated. Also, it should be noted that at this stage only the reference frequency impedance (Z_{m1}) is required for all but the most critical exposures.

In parallel with the development of the noise/Amp tabulation, it is recommended that an estimate of the total filtering cost as a function of I_{eq} be sought from the converter station manufacturers for at least normal bipolar operation and for the most likely monopolar operating mode.

This will allow the optimum value of I_{eq} to be selected for various operating modes; however, as noted in 6.5.1, a value of I_{eq}, which is lower than the optimum, would normally be selected for the specification. At the same time, the values of H_n based on the average of the most critical exposures would be computed and included in the specification.

If there are a significant number of exposures involving terminations within about 400 m of the HVDC line, or where the angle of crossing changes close to the line, it may be necessary to ensure that the

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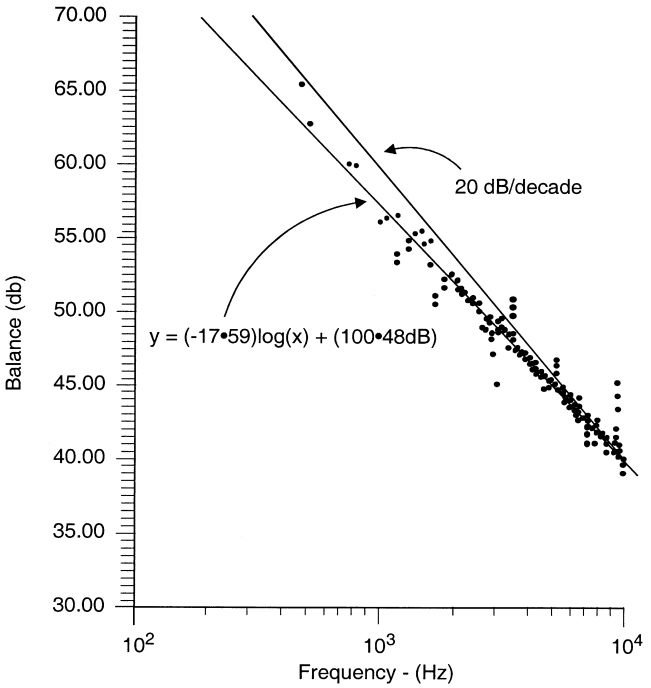

Figure 21—Example of a balance measurement on a shielded telephone pair terminated with a standard 600 Ω balanced pair

balanced mode coupling is included in the calculation of I_{eq} by the converter station supplier. In this case, the effective disturbance current, I_n, is not closely equal to the residual mode current and a further factor K_b may have to be computed from the most critical exposures where Equation (21) gives:

$$K_b = Z_{mb1}/Z_{mr1} \tag{21}$$

where

Z_{mb1} is balanced mode coupling at reference frequency
Z_{mr1} is residual mode coupling at reference frequency

The effective disturbance current should, in any case, be specified as shown by Equation (22) (see Equation (6) and Equation (7)):

$$I_n = \sqrt{(I_{rn})^2 + (K_b I_{bn})^2} \tag{22}$$

and K_b should not be less than about 0.02 (see 6.3.2).

Care should be exercised in the selection of K_b, as a value in excess of 0.05 will probably increase the cost of filtering substantially; hence, if only one or two exposures have a value of K_b in excess of about 0.05, they should be discounted.

It has to be recognized that the schedule for the HVDC project as a whole, or lack of reliable data, may preclude sufficient pre-specification coordination studies to allow the optimum value of I_{eq} to be derived. In such cases, alternative I_{eq} limits may have to be included in the converter station specification, and a final selection of I_{eq} made after the supplier is selected.

In this context, it should be noted that converter station prices cannot generally be assumed to vary linearly with I_{eq} or to bear any other continuous relationship to it. It is therefore important that the alternative I_{eq} limits specified at least cover the likely extreme cases.

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6.5.5 Filter design verification

Following pre-specification, coordination, and optimization studies, the performance of the dc-side filters should be verified to determine the actual exposures that will probably require mitigation and to establish the best method of achieving it.

At this stage, the harmonic content of the individual conductor currents is assumed to be known and earth resistivity, frequency dependency of balance and shielding factors, and exposure details are all established.

The induced noise on each of the exposures identified in the previous studies as possibly requiring mitigation based on I_{eq} levels should be recalculated using the exact method per Equation (2). The list of exposures may have to be expanded, if the exact method is resulting in significantly higher levels of noise than indicated previously.

The values calculated using Equation (2) represent the best evaluation of induced noise that can be obtained prior to actual operation. The choice of mitigating measures to apply to each exposure can then be made according to the degree by which the calculated noise exceeds the agreed limits and the frequency spectrum of the induced noise.

Whether to wait for commissioning test operation to verify the need for mitigation, or whether to proceed with mitigation immediately, is subject to negotiation with the communication utility. If the need for mitigation based on calculation is marginal, it is probable that any mitigating measures actually required can be installed quickly; however, it is strongly recommended that the shielding and balance of all marginal exposures be checked and brought up to the agreed levels, if necessary, before the HVDC system commences test operation.

Verification of the HVDC filter performance by measurements in operation is discussed in Clause 9.

7. Mitigation

7.1 Introduction

Interference problems can be avoided or minimized, by routing transmission lines as far away as possible from the communication facilities. However, the prevailing regulatory and environmental factors force the electric and other utilities to be in common corridors rather than separate routes. Hence, there is not much leeway for achieving separate rights of way. Design of proper and adequate filters in HVDC converter stations also reduces interference. However, the great care and effort expended during planning, design, construction, and commissioning of HVDC projects does not guarantee that there will be no interference to nearby telecommunications circuits. This is due to many uncertain factors on the power system as well as communications systems that could result in interference situations. Also, it is prohibitively expensive to design an HVDC system that guarantees absolute noninterference. Thus, consideration of mitigation is a logical and economic course of action to solve localized interference problems.

Four steps during mitigation are as follows:

a) Evaluating the level of mitigation required
b) Identifying the locations
c) Identifying the types of mitigation to be used
d) Scheduling the implementation

The results from the analyses and measurements provide the necessary information for evaluating and identifying problem areas. Coordination between the liaisons of the electric, telephone, pipe line, and railroad companies can greatly assist in the evaluation and identification of the locations of the required mitigation. In recent years, the electric utilities (transmission companies) also own telecom

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circuits, mostly in the form of fiber optics. In such cases, common ownership not only makes coordination much easier, but also may not be necessary due to use of fiber optics.

7.2 Mitigation methods

Once interference problems have been identified, there are many different techniques available to electric utilities, telephone, railroad, and pipeline companies to mitigate interference on telecommunications circuits. Several mitigation techniques are also discussed in IEEE Std 1137-1991[4] (Shore et al. [B20]). They are as follows:

a) Modify HVDC filters
b) Active dc filters
c) Improve customer loop balance
d) Improve interoffice trunk balance
e) Replace open-wire circuits with cables
f) Relocate customer drops and cables
g) Reconfigure the outside telephone plant
h) Addition of bridged ringers
i) Eliminate grounded ringers
j) Improve cable shield grounding
k) Verify cable shield continuity
l) Apply noise chokes
m) Apply induction neutralizing transformers
n) Subscriber loop carrier systems
o) Optical fibers

7.3 Mitigation examples

7.3.1 DC filter modifications

If it is shown that the majority of the telephone noise problems are due to higher than expected levels of harmonics on the dc side, then it may be possible to modify the dc filters to eliminate the telephone noise on many exposures. The economics will ultimately decide the desirability of making these changes. An example of modification of a 12th harmonic filter to provide 12th and high-pass filtering is shown in Figure 22. The filtering characteristics are shown in Figure 23. This modification reduced noise-metallic voltage by about 10 dB (Hancock et al. [B7]). With the development of three-pulse models for calculating harmonic generation, it will be possible to compute higher order non-characteristic harmonics more accurately. This should establish the need for filtering on the dc side. Hence, any surprising interference due to higher order noncharacteristic harmonics is less likely and so is the need to modify the dc filter.

7.3.2 Balance of customer loops and subscriber equipment

The induced voltage is of noise to ground type, whereas actual noise perceived by the telephone subscriber is noise metallic or circuit noise. The difference is called balance. Improvement in balance of customer loops results in reduction of the noise metallic. The improvement will not only result in a reduction of telephone noise but also will improve the overall quality of telephone service. Several factors contribute to poor balance. They are as follows:

a) Party line ringer unbalance
b) Defective carbon blocks

[4]Information on references can be found in Clause 2.

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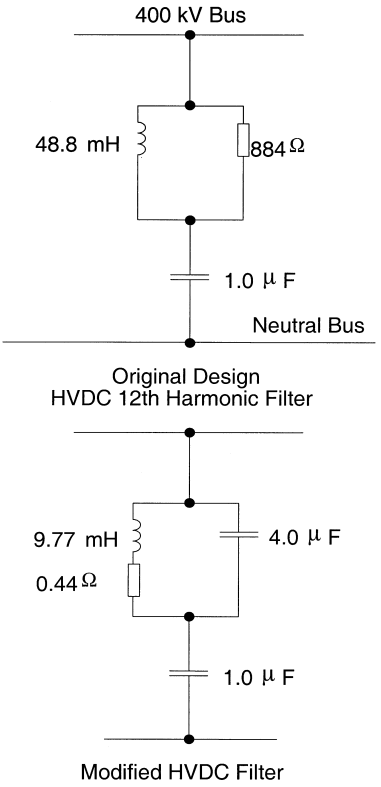

Figure 22—Modification of an HVDC filter

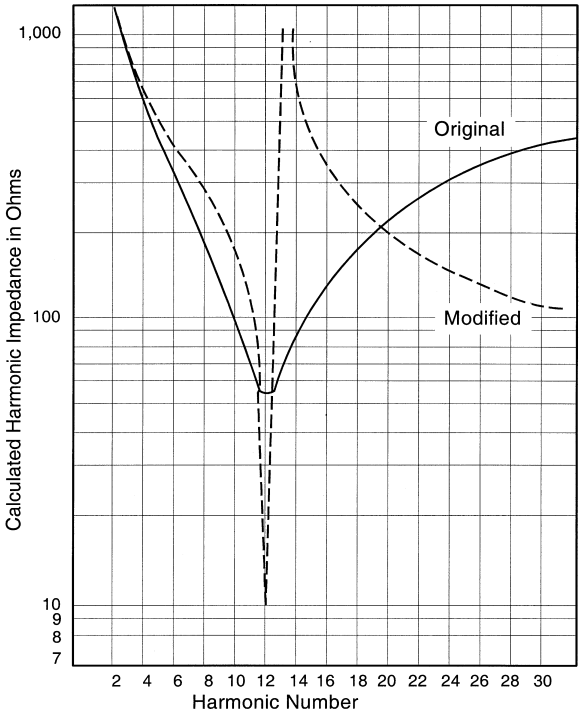

Figure 23—Harmonic impedances calculated for HVDC filters

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c) Defective foreign devices
d) Foreign material, such as insects or spider webs in carbon blocks
e) Longer unbalanced customer drops
f) Unbalance in private branch exchange or telephone company's central office equipment
g) Pair resistance balance
h) Line to ground capacitance balance
i) Water in cable
j) Metallic crosses
k) Unbalanced bridge taps, or
l) Unbalanced loading

These factors involve central office equipment, loop cable or wire facilities, and subscriber terminal equipment. Installation of proper equipment and good operations and maintenance practices provide good longitudinal balance and reduces noise interference. Improvement in balance of exposed wire line interoffice trunks also reduces the interference possibilities.

7.3.3 Replacement of open wires with buried cables

This technique can result in a significant reduction in noise metallic caused by power system harmonic currents for three reasons:

a) Increased separation to the dc line reduces the noise-to-ground induced voltage
b) Improvement in balance of buried cables reduces the noise metallic
c) The cable shield reduces the noise to ground induced voltage

By replacing open wires located near the power lines with buried cables at some location, the separation between the twisted pairs and the power line would be increased. The increased separation may result in a small reduction, i.e., 1–2 dB of noise to ground due to the small reduction in the mutual impedance between the telephone cable and the power line.

The improvement in balance of buried cables to open wires may be greater than 15 dB. Many cables manufactured today have balances as high as 70 dB, while outside open wire circuits may have balances of about 45–50 dB.

It would not be surprising that replacing open wire facilities with buried cable, or even well shielded aerial cable, would reduce the circuit noise caused by higher order harmonics by more than 25 dB. These benefits may not be fully realized if the primary cause of noise is low-order power harmonics, as the reduction from these may be about 15 dB. If the fundamental power system frequency is the problem, the shield factor for cables at 50 Hz or 60 Hz may only be 1 dB or 2 dB.

This mitigative technique should be considered when many open wire pairs serving a number of customers are located near a power line. Many open wires could be replaced by a single buried cable. This technique could be used when there is the need to reduce low-frequency noise by 15 dB, or circuit noise from higher order harmonics by 20 dB or greater. Telephone companies may also realize additional benefits, such as higher reliability of buried cables and installing a cable with more numbers of pairs for future expansion. These additional benefits should also be a factor in determining the implementation of this technique.

7.3.4 Relocation of telephone cables and customer drops

Relocation of telephone cables far away from the dc line can solve the induced voltage problem. However, this method is seldom a first or even a preferred choice. Relocation is expensive and requires

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acquiring a new right-of-way. Customers served by drops from the troubled cable still require telephone service. Relocation is usually done after other alternatives have been considered and rejected.

The benefits that can be realized from relocation depend on the frequency and the ground resistivity. The reduction in the induced voltage can be estimated by computing mutual coupling impedances between the power line and telephone line.

7.3.5 Reconfiguration of buried plant

The relocation of long buried cables, which parallel the HVDC circuit, is expensive. If telephone service can be provided to customers near the HVDC line from new cables located perpendicular to the HVDC line, then the telephone noise on the affected cables near the line can be substantially reduced. In the example shown in Figure 24, the longitudinal induction from the HVDC line is impressed over a substantially shorter telephone cable [compare the two mile long exposure shown in Figure 24a) with the 1/4 mile long exposure of Figure 24b)]. The telephone noise to the subscribers on the far (right) end of the existing buried cable near the HVDC line is reduced by $20\log(0.25/2)$ or 18 dB.

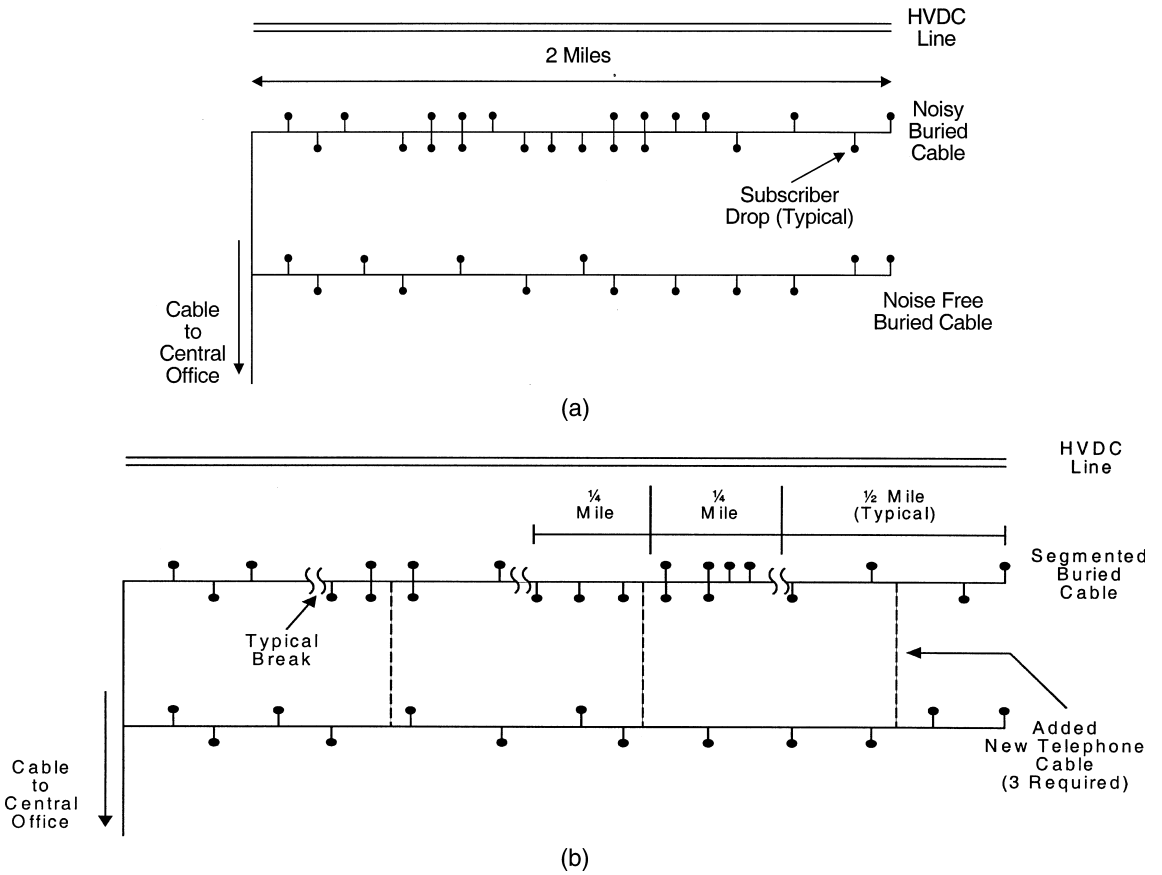

Figure 24—a) Existing telephone service near HVDC line; b) Telephone cable configuration for noise reduction

This corresponds to reducing the longitudinal induced voltage without substantial capital expenditure and can be implemented quickly.

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7.3.6 Bridged ringers

Replacing grounded ringers with bridge ringers can improve the balance of a twisted pair that provides party line service. Grounded ringers are connected between ground and a coupling unit (normally, a capacitor) to either the tip or ring. If different ringers or coupling units have unequal impedances, there is unbalance between the tip and ring. Hence, there is higher circuit noise for a given noise to ground.

On lines with two party service, it may be possible to connect each ringer across tip and ring. If it is possible to superimpose the ac ringing signal on a dc voltage of either polarity, it is possible to provide full selective signaling to two bridge connected ringers. The improvement in balance resulting from the replacement of grounded ringers with bridged ringers is directly related to the imbalances of grounded ringers.

7.3.7 Ringer isolators

Ringer isolators are coupling circuits between the tip and/or ring conductors and ground connected ringers. These isolators replace the capacitor with solid-state components such as SCRs, which sense the ac ringing signal on tip or ring. With the ac ringing signal present, the SCRs of the isolator circuit breakdown and the ringing signal is passed to the ringer circuit.

The advantage of such a circuit is to normally isolate a ground connected ringer from tip and/or ring except when a proper ringing signal is present. Thus, the application of ringer isolators is a technique to improve the balance of a telephone circuit during normal operation.

Solid-state modules mounted in the housing with the station protector are often used to provide the ringer isolating function, automatic number identification (ANI), and allow a customer to use standard telephones with bridged ringers on a party line.

7.3.8 Induction neutralizing transformers

An induction neutralizing transformer (INT) is generally most effective in reducing 60 Hz and other low-order harmonic voltages (Gundrum [B6]). An INT used to reduce telephone noise on a buried telephone cable is different from the three-winding high-voltage neutralizing transformer (HVNT) used to protect telephone circuits entering a HVac substation. An INT is used to neutralize a maximum of 50 V (ac rms), while a three-winding HVNT typically used at substations can neutralize up to thousands of volts resulting from rise in station ground potential. The effectiveness of INT in limiting higher order harmonic voltages is reduced because harmonic currents flowing on the excitation pair(s) tend to be shunted to earth through the excitation-pair-to-ground capacitance leaving less induced current available to excite the INT (Stoneman [B22]). The location of an INT is important (Gundrum [B6]).

Efficient carrier systems, such as pulse code modulated systems, are also susceptible to effects of low-frequency induction. Pulse code neutralizing transformers (Stoneman [B23]) can successfully limit the longitudinal induced voltage on PCM pairs to levels far below those which can interrupt the operation of the PCM repeaters.

7.3.9 Subscriber carrier systems

A subscriber carrier system is a very effective means of reducing telephone noise caused by an HVDC line. This system uses a 40 kHz to 100 kHz carrier where up to twelve subscriber phones can be

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multiplexed onto a single pair. The carrier frequency is well above the telephone noise band and is generally immune to induced telephone noise from the line.

Digital carrier on subscriber loops is now in common use. Twenty-four subscriber analog lines are multiplexed onto one digital system. The digital line is dc powered and is generally immune to power line harmonics. High levels of induced voltage from unbalanced power line load current and induction from ac power line faults to ground can adversely affect the digital line.

7.3.10 Optical fiber

Optical fiber cables have often been used to combine growth needs with mitigation of fundamental frequency induction problems. Replacing the copper wire with an optical fiber eliminates all induction effects—longitudinal and metallic. Fiber optics is being used for high-density long distance including trans-Atlantic telephone and data transmission. According to a recent article (Shumate [B21]), about 250 000 km (nearly 10%) fiber optic feeder lines (central office to remote terminals near residential development) have been installed in the U.S. Also, more than a dozen manufacturers are field testing fiber optic equipment for customer drops, the so-called *last mile of the line*. Initially, these may be expensive, but fiber optics is a serious contender as a mitigation option. Optical fiber in the last mile is still in the demonstration stage. With the growing number of vendors and significant cost reductions for facilities and advances in engineering, fiber optics can be considered as a technically viable alternative to mitigating even severe problems.

8. DC filter performance specification

This clause deals with items that should be considered for performance specification purposes, as far as dc-side harmonics and filtering are concerned. Filter component and equipment ratings are not addressed here.

Once the inductive noise analysis study is completed, the results must be integrated into a dc filter performance specification. The main performance criterion is the level of permissible interference. However, because of the many factors involved in an actual system, the dc filter specification needs to be properly defined. It must include details necessary for an optimal dc filter design that best suits the particular HVDC scheme.

All of the information included in the performance specification may have an impact on the dc filter design. It should also be kept in mind that the manufacturer has the responsibility to design the lowest cost dc filters that meet the performance specification. The filter performance specification will be the basis for all subsequent discussions with the manufacturer. The performance specification should therefore be complete, take into account any possible changes in the project, and cover all the needs of the utility.

The performance specification should include:

a) The operating conditions that should be considered
b) The data to be used for the filter design
c) The general methodology to be utilized in calculating harmonic performance:
    1) The criteria for defining the dc-side harmonic performance requirements
    2) Information to be provided by the bidders
    3) Information to be supplied by the contractor
    4) The performance verification method and criteria, where needed

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8.1 Description of the dc system

All planned operating conditions have significant impact on dc harmonics. The operating conditions for which the performance requirements have to be met should be clearly specified.

8.1.1 Circuit configurations

A general description of the scheme and of the circuit configuration should be provided, including:

a) Principle single-line diagram of the scheme
b) Staging of the project
c) For multiterminal operation, if applicable, tapping with indications on the type of the tapping scheme (series or parallel)
d) Presence of nearby, existing, or planned HVDC plants and connection to the new HVDC system (e.g., on the ac or the dc side)
e) Converter number for each station and for each pole (indicate six or twelve pulses, series, or parallel connection)
f) Route, configuration, and length of the dc transmission and electrode line sections (overhead and/or cables)
g) Ground electrode resistance

Any possible range of variation of this data should be indicated. Particular attention should be paid to the length of the dc and electrode lines. These are often not finalized at the time the filter specification is issued and are, therefore, susceptible to change in the early stages of the project. The electrode resistance is usually determined by calculation at this stage and can deviate appreciably from the final *as-built* value.

8.1.2 Operating modes

The possible main operating modes are the following:

a) *Balanced bipolar*: this mode is with both currents and voltages nominally balanced between poles.
b) *Unbalanced bipolar*: the unbalance could involve voltage or current or both and could result from either a design or operational unbalance between the two poles.
    1) A *voltage unbalance* could be obtained by a design unbalance such as an asymmetrical converter configuration on the two poles or an operational unbalance, e.g., where one pole is operated at reduced voltage, and
    2) A *current unbalance* could occur by design where, for example, only a single pole is tapped for a multiterminal system. Examples of operating current unbalance would be the case where parallel converters are installed in each pole at each end of the line and an outage occurs on one of the converters and a bipolar dc system where the currents in each pole are controlled to different values.
c) Monopolar with ground or metallic return.

For multiterminal dc systems, a list of all combinations of stations in operation that have to be considered in the dc filter design must be given. For projects with many stations, it may not be practical for the filter designer to consider all of the combinations in the short tender period. In such cases, the most usual configurations and the expected worst case must be specified. The specification should allow for the modification of the design after the award of the contract, if verification shows that excessive interference occurs for other configurations.

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8.1.3 Special operating conditions

Any other operating condition having an impact on dc harmonics and dc filter design is to be indicated, including:

a) Bipolar operation with the loss of a filter branch.
b) Reduced dc voltage operation. This mode of operation may be used occasionally, e.g., during temporary high pollution level on the line insulators. Operation at a lower dc voltage that may require high firing angles of the valves may be used.
c) Use of converter for ac voltage/reactive power control and/or power/frequency control resulting in relatively large firing angles.

8.1.4 Range of operating parameters

The nominal voltage and current rating of the scheme should be specified. For each of the operating modes described in 8.1.2 and 8.1.3, prescribed limit on dc voltages and currents should be given.

8.1.5 Arrangement of filter banks

Different filter options may be considered to meet the performance requirements, and these options should be evaluated with regard to maintenance practices and availability requirements. If the replacement of failed components cannot be made quickly, available transmission capacity may be adversely affected. Spare filters may be specified where potential cost of power transmission capacity lost is sufficient to justify installation of spare filters. These spare filters can then be used in monopolar mode since the performance requirements are more difficult to fulfill in this mode. Alternatively, it may be necessary to switch filters from one pole to the other when operating in monopolar mode. In bipolar mode, operation may be allowed when there is loss of some part of the dc filters even though higher interference may be the result. This will affect the branch design and switching requirement. Any limitation on these options should be stated in the specifications.

8.2 Basic data to be considered for harmonic calculation

8.2.1 DC transmission line data

The configuration of the dc connections (overhead lines and/or cables), including their geographical lay-out and component lengths, must be supplied. The ground electrode resistance must be supplied for all stations.

Data necessary for the calculation of electrical parameters could be given, i.e., conductor type, size, geometry, and the permeability of the steel (including shield wires for overhead lines and sheath/armor for cables, tower and span geometry, sag, and ground resistivity). Where ground resistivity varies appreciably with depth, the resistivity of the different layers could be given.

As an alternative, electrical parameters as a function of frequency (e.g., up to 5 kHz) could be supplied for each of the dc connections. The electrical parameters would include the resistance for each pole and electrode conductor, as well as the self- and mutual inductive reactances and capacitive susceptances. Variation of the dc line impedances due to temperature, sag, and error in earth resistivity estimation should be given so that they can be considered in the performance calculation.

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8.2.2 AC system data

Indications should be given concerning:

a) AC voltage unbalance, i.e., the value(s) of the negative sequence component of the converter ac bus voltage to be considered for filter performance calculations.
b) AC frequency deviation to be used (both maximum and minimum frequencies).
c) Background ac side harmonic voltage distortion (harmonic voltage at the bus without the dc equipment in service). Note that the converter and the ac filters for the HVDC system will alter this level, but the filter designer should take into account the influence of this equipment. The data supplied should include the frequency, magnitude, and sequence (positive or negative) of each of the major components of the background harmonic distortion.
d) AC lines, parallel and in proximity to the dc line. Induction of fundamental and higher frequencies onto the dc line may occur. These may not be insignificant and could cause single-sided saturation of the converter transformers and generation of noncharacteristic harmonics. It should be specified whether harmonics induced on the dc line by ac lines in parallel have to be taken into account for performance calculations (and also for measurements). Data necessary for the calculation of the coupling should be supplied.

Care should be exercised not to use blanket values for these parameters. While values used for rating purposes usually correspond to emergency conditions, which are likely to be infrequent and of short duration, the values used for performance calculations should represent the more probable and long duration condition. For example, the probability that high unbalance ac voltage occurs simultaneously at all of the converters is low. The ac voltage unbalance may rise at one station only due to the loss of an ac line, which increases the current in another untransposed line feeding the HVDC system. A good characterization of these parameters is thus necessary to avoid unreasonable dc filter requirements.

8.2.3 Deviation of parameters and tolerances to be considered

The following sources of imbalances affect the harmonic behavior in different ways. The data may not be available to the user during the specification phase. Nevertheless, it should be indicated that these imbalances have to be taken into account for dc harmonic performance calculation and that the values adopted by the manufacturer have to be indicated and guaranteed.

a) Tolerance in the converter transformer reactance among phases, bridges, and poles
b) Converter transformer turn ratio imbalances
c) Nonsynchronized operation of tap changers
d) Differences in firing angle among valves of a pole
e) Differences of firing angle between poles
f) DC filter capacitor tolerance, aging, and failure level
g) Variation of ambient temperature
h) Tuning accuracy of filters
i) Tolerances between the smoothing reactor inductance of different poles

Variation of ambient temperature is specified by the utility. The range of temperature variation should be chosen with considerations that it is used for performance calculation. An extreme temperature range, experienced for short durations, once every 50 years may not be reasonable.

8.3 Methods for harmonic calculation

The calculation of harmonic currents in the dc line is based on many assumptions due to the complexity of HVDC and ac systems and to the limitations of the calculation tools. The method(s) to

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be used in the calculation of the harmonic performance should be included to standardize the approaches used by the different bidders.

8.3.1 Harmonic driving voltages

Specifications typically require that the most onerous combination of ac and dc parameters be considered in the calculation of both the magnitude and angle of the characteristic and triplen harmonic driving voltages. The parameters normally included are the following:

a) DC current levels over the entire range for each operating mode
b) DC voltage variation within the specified limits
c) Firing angle variations within the specified limits
d) AC bus voltage variations
e) DC smoothing reactor variations with varying dc current level
f) Variations between poles when in bipolar operation including
    1) DC voltage
    2) DC current
    3) Firing angle
    4) Tap changer positions
    5) No load converter voltage
    6) Total converter transformer leakage

In the calculation of other noncharacteristic harmonic driving voltages, factors listed in 8.2.2 and 8.2.3 should be considered in addition to those previously listed. A statistical procedure may be used. Hence, the specification should address the limit on the probability of exceeding the statistically calculated voltages. The use of a 90° angular displacement of the noncharacteristic harmonic voltages of the two poles in a bipole is usually applied, except where a lower angle can be justified (refer to 5.4.2).

The harmonic voltages should be calculated at a sufficient number of steps within the full range of dc transmitted power to enable the worst case condition to be ascertained.

The specification should indicate whether a nonconsistent worst set and/or consistent sets of harmonics should be adopted in the calculations. In the first case, the worst individual harmonic voltages over the whole operating range of the converters is selected and filter performance calculated for that set of harmonics. In the second case, the performance for each *consistent* set of operating conditions is evaluated and the filter is designed to ensure that the performance is achieved for every set of conditions evaluated. The nonconsistent approach requires less studies, but the final result can be a significantly over-designed dc filter scheme. The specification could allow either method to be used. For multiterminal systems, the nonconsistent worst set may be the only practical option due to the large number of possible operating modes and conditions.

8.3.2 DC network harmonic currents

The harmonic currents, which flow on the transmission network, are normally calculated using a linear, but frequency-dependent, model of components that make up the electrical network. The model would include not only the transmission components, but also an electrical model of the components within each of the converter stations. In the calculation model, the stray capacitances within the converters must be taken into account as they will have a significant impact on the calculations of current flow at the triplen harmonics.

Because the electrical network is linear, it is convenient to treat the harmonic voltage sources from each converter separately and rely on superposition to establish the composite harmonic current due to all sources and at all locations along the transmission network.

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The maximum order of harmonics to be considered (e.g., 50th, 60th, or higher) and the summation criteria for each harmonic contribution must be specified. The telephone system is theoretically sensitive to induction up to 5 kHz which corresponds to the 83rd harmonic. In the past, it was common to limit the frequency range to the 50th harmonic because it was considered that, above this level, the harmonic currents were of negligible magnitude due to the increasing impedance of the smoothing reactors. However, triplen harmonics of significant magnitude can circulate in the dc line (without circulating in the smoothing reactors) at high harmonic order due to the decreasing impedance of the stray capacitance with frequency. It may therefore be advisable to consider higher harmonic order, especially where interference levels are critical.

The following alternatives could be considered for the treatment of the superposition of currents at each harmonic:

a) *Absolute value summation*. This is the most conservative criterion and would normally only be used in the treatment of harmonics associated with a common converter ac bus.
b) *Phasor summation*. This alternative is difficult to apply. The actual phase relationships between the phasors of the converter ac bus voltages must be known. Where the ac systems are asynchronous, the phasor method cannot be applied because of the difficult-to-predict phase angles between the harmonics of each converter, particularly the noncharacteristic harmonics.
c) *Root-sum-square (rss)*. This criterion is equivalent to assuming a 90° phase displacement between each of the harmonic components. It is the most commonly used method.

8.4 Performance requirements

The studies described in Clause 6 dictate the performance requirements to specify for a given HVDC scheme. These requirements should be defined in the specification with the necessary details to reflect accurately the HVDC line influence on the telecommunication lines and should give the appropriate information on the planned system to allow the design of efficient HVDC filters for the particular project.

The specification should define the formula for the derivation of I_{eq} from the individual harmonic currents calculated on the dc and electrode line conductors. The following formula is used as suggested in Clause 6:

$$I_{eq} = \sqrt{\sum_{n=1}^{n=m} (I_n H_n C_n)^2} \tag{23}$$

where

n is the harmonic order,
I_n is the effective disturbing current at harmonic n,
C_n is the C message weighting factor at harmonic n,
H_n is the weighting factor to account for the general nature of the frequency dependent coupling exhibited by the communication circuits near the HVDC line, normalized to 1 kHz.

Where the balanced currents may influence significantly the telecommunication system, a factor K_b should be included in the definition of the effective disturbing current (refer to 6.5.4). Where an electrode line is parallel to the HVDC line, the conductor currents summation method should be defined in accordance with 6.3.4. Otherwise, I_n is equal to the vectorial sum of current in each conductor [Equation (8)].

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The I_{eq} limits should be indicated for each operating modes and operating conditions considered in 9.1. Each of these operating modes and conditions should be evaluated with regard to their probable duration and rate of occurrence. More stringent levels have to be adopted in normal conditions, while higher values should be tolerated for uncommon and/or short duration conditions. Recent specifications dictated three levels of I_{eq} limit in light of performance thresholds for metallic mode C message weighted noise on normal business or residential lines:

a) A given I_{eq} for normal conditions and operating mode (bipolar mode)
b) Twice this level for temporary conditions or operating modes (metallic return)
c) Three times this level for short-time or infrequent conditions or operating modes (earth return)

Performance limits should be defined precisely for the locations at which they are considered necessary and not applied as blanket restrictions over the whole dc line route. Ideally, the I_{eq} limits should be expressed as a profile reflecting the telephone sensitivity along each dc line section. An electrode line parallel to the dc line, for a short distance, may carry high-residual harmonic currents. Special care should be exercised in addressing such situations, since the influence of these harmonic currents may be more economically mitigated in the telecommunication system.

When pre-specification coordination studies are insufficient to allow the optimum value of I_{eq} to be derived, alternative I_{eq} limits may be included in the performance specification and a final selection of I_{eq} made after the supplier is selected. The two extreme limits should correspond to levels for which there will be respectively none and extensive changes required in the facilities located in the area of influence of the HVDC lines. The specification should request cost information for filters designed for the two limits. Costs for intermediate filtering levels could be requested after the supplier has been selected.

8.5 Bid information

Since the maximum values of I_{eq} in the HVDC line can generally not be precisely verified by measurements, the dc filter proposal compliance with the specification is usually demonstrated by calculations. In addition, the final design verification require information on the harmonic content of the individual conductor currents and the effective I_{eq} profile along the HVDC line sections. The specification should then require the following information to be provided:

a) Details of the models used in the calculations.
b) Method of handling temperature changes, frequency variation, and component tolerances.
c) Values of the deviation of parameters and tolerances considered in the study.
d) Description of the method and assumptions used to determine the most onerous sets of harmonic voltages.
e) Tables of worst harmonic driving voltages for each converter station, and the specified operating modes and operating conditions.
f) Worst profiles of I_{eq} along the HVDC line sections for the specified operating modes and operating conditions.
g) Each I_{eq} profile should be accompanied with a profile of its main harmonic contributions; however, this information is needed only for the final design.

8.6 DC-side harmonic field measurement

For major HVDC projects where many telecommunication lines are present, it may be desirable to verify the dc filter performances with field measurements. When field measurement is foreseen, a measurement specification should be prepared and included with the performance specification to avoid any further contractual disagreement.

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This measurement specification should include at least the following details:

a) The acceptance limits for each operating condition and mode to be tested.
b) The precision of the measuring method should be specified (note that when measuring harmonic currents in the pole conductors, magnitude and phase-angle accuracy is needed for the calculation of I_{eq}).
c) Usually a Fast Fourier transform is done on a minimum number of samples recorded during a given period of system operation, the minimum number of samples and the sample duration should be specified (note that the harmonic currents should fluctuate due to the drifting between ac voltage of the converters and that increasing the sample duration will tend to average the results, the human ear does not respond to fluctuation within 200 ms).
d) A statistical approach may be adopted to discard the glitches that may distort the I_{eq} measurement; for example, the value not exceeded by 98% of the samples may be retained.
e) The conditions prevailing during the measurements at each converter should be specified.
f) AC voltage range.
g) Maximum voltage unbalance.
h) Maximum frequency deviation.
i) AC voltage maximum harmonic content.
j) Maximum temperature range.
k) Maximum current in parallel ac lines.
l) Others.

For determination of the acceptance level, it should be noted that the performance calculation method specified must lead to conservative results because it covers a range of theoretically worst case conditions (temperature, frequency deviation, ac unbalance, and so on, that are unlikely to occur during the measurement period. It is recommended to require from the supplier a I_{eq} profile calculated with a set of normal conditions that will probably prevail during the tests and that this profile be used as a basis for the acceptance of the dc filter performance.

Another aspect, which needs to be considered in the determination of the acceptance level, is the location of the measurement site along the line. The I_{eq} profile along the line is likely to vary irregularly and, moreover, may change from one operating mode to the other. It appears impractical to move the measuring facilities along the line to scan the whole length. On the other hand, choosing the measurement location based on the calculation results implies that you assume that the calculations are exact, which should be demonstrated by measurements. The acceptance level should then be chosen based on the calculated profile and on a practical measuring site location, but the frequency content of the measured I_{eq} can give indications on the validity of the I_{eq} evaluation.

9. HVDC filter performance measurements

Measurements of HVDC harmonic filter performance consist of measuring the harmonics on the dc overhead conductors and/or measuring the influence of these harmonics on parallel telecommunication circuits. Each measurement provides only a single snapshot in space and time of one of an unlimited number of possible operating conditions and locations along the line route. Validation of filter performance by direct measurement is therefore very difficult. Many sets of measurements and associated calculations are required.

Most measurements of current are made during commissioning. With the possible exception of full load operation, most of the various dc operating modes are exercised during this time. In addition, installation, and subsequent removal of temporary transducers required for the measurements can be incorporated into the schedule. Obtaining outages for this purpose may be very difficult once the dc system is in commercial operation. Direct measurement of induced noise can be made at any time once

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the dc system is operating. However, during the commissioning period, a large range of operating modes can be validated in a relatively short period of time.

A large range of instrumentation for harmonic measurements is available. In terms of complexity (and cost), the equipment could consist of:

a) Hand-tuned harmonic analyzer
b) Selective level voltmeter, which uses a low-frequency heterodyne receiver
c) Single or multiple-channel digital signal analyzer, which uses a Fast Fourier algorithm to calculate harmonic content.

The latter can provide the phase angle of the harmonic current with respect to some reference. This information is important if the combination of direct current or voltage measurement and calculation is to be used to validate the filter performance.

Although specifications may require the inclusion of all harmonics of power frequency up to 5 kHz in calculations of filter performance, it may be possible to take advantage of some of the inherent characteristics of the dc system to restrict measurements to a reduced set of harmonics. In twelve-pulse operation, all but the even multiples of the sixth harmonic theoretically cancel. However, imbalances in converter transformer impedances and converter firing angles can result in incomplete cancellation, possibly leaving some level of these harmonics in the current waveforms. In spite of this, it may still be possible to monitor, say, only multiples of the sixth harmonic without significantly affecting the overall results. Similarly, in practice, the magnitude of harmonics above the 48th or 54th are usually so low that their contribution to interference is small and, in general (under most circumstances), could be ignored. Before limiting the number of harmonics that are routinely measured, it would be prudent to scan the entire audible band (0–5 kHz) to ensure that system resonances do not amplify the harmonics at a given frequency, resulting in a higher contribution to interference than projected.

Where a dc system is exposed to potential electromagnetic induction from parallel ac lines, it is of interest to confirm that the levels of induced fundamental frequency and harmonic currents on the dc line without the dc system in service are less than the levels included in the converter equipment specification. Measurements with the converters out of service and with the transmission line grounded at both ends would provide a *background* level of harmonics. These measurements could be carried out even before commissioning of the converter stations has begun, provided that the transmission line was available. Measurements with the converters in service, but the parallel ac line(s) out of service, would also be of interest. Such measurements, however, may not be practical.

9.1 Test probes

Induced noise from the transmission line in the audible bandwidth can be measured directly from a test circuit, which is installed parallel to the dc transmission line, but with no electrical connections to the line. Ground rods are driven at both ends of the test circuit. The remote end of the test circuit is connected to its ground rod and the harmonic measuring instrument connected between the test circuit and the ground rod at the test site.

The length of the test circuit, and its separation from the dc transmission line, could range from a 1 km test line 1 km away from the dc circuit to a 100 m test probe connected 100 m away from the center of the HVDC line. The 1 km test line is representative of a typical communication circuit. The latter has the advantage of much reduced costs, easier setup, and lower maintenance. The 100 m long probe-wire could be used when the geography, or land development alongside the HVDC measuring site, precludes the use of a 1 km test site.

The results measured are the induced voltages between the two ground rods at various harmonic frequencies. From the geometry of the HVDC line and its overhead ground wire and the earth resistivity of the ground at the measuring site, the mutual impedance between the probe and a fictitious

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conductor at the geometric center of the HVDC line can be determined. From the voltages induced in the probe and the mutual impedance, the equivalent current that would flow down the fictitious conductor can be calculated. This current can be used to calculate voltages induced across any facility parallel to the HVDC circuit which in turn can be used to compute the associated interference by any of the methods specified.

9.2 Direct measurement of current

An alternate approach is to measure the harmonic content of the current in each of the HVDC overhead conductors. A digital signal analyzer is required, which provides both the magnitude and relative phase angle of the current at each frequency. The vector summation of these currents gives directly the current flowing in the fictitious conductor at the geometric center of the dc line. Similar to the test-probe voltage method, the equivalent current can be used to compute the associated interference on adjacent communication facilities.

One method of obtaining the current is to install a resistive shunt in the HVDC pole conductors. From the voltage drop measured across the shunt and the resistance of the shunt, the current through the shunt, and hence in the overhead conductor, can be determined. The method suffers from high losses associated with the large dc component in the current (typically in the kiloampere range). In addition, it becomes difficult to detect milliamperes of harmonic current in the presence of such a large dc component. The shunts can only be connected during the test period due to the high losses, and hence require outages to insert them and remove them. For this method, it is practical only to obtain measurements at the station. Harmonics at other locations along the line route must be calculated.

An alternate method is to install a split Rogowski coil with a nonconductive core on each of the HVDC pole conductors at the harmonic test site. The split allows the installation of the coil around the conductor bundle without having to open a conductor span. It may be necessary to install smaller coils on the overhead ground wires (OHGWs) if they are carrying harmonics, e.g., to a remote earth electrode for the dc line. The Rogowski coil produces a voltage proportional to the derivative of the ac current flowing in the conductors.

A shielded enclosure to protect the coil from corona damage provides space for a small battery, and an electronic package to convert the analog voltage to an FM signal. The signal is transmitted to ground via fiber optics, where it is converted back to an analog signal. This is in turn calibrated and analyzed for the harmonic content in the overhead conductor.

For both methods using direct measurement of current, the currents in all overhead conductors must be measured simultaneously to obtain the correct phase relationship. A multichannel spectrum analyzer or data-logger is therefore required.

9.3 Measurement of driving voltages

A third approach to measurement of harmonic filter performance is to measure the harmonic driving voltages on the line side of the smoothing reactor. From the harmonic voltages on both poles and from knowledge of the harmonic impedances and topology of the dc pole equipment and transmission line, the harmonic current on each of the HVDC conductors can be calculated.

Voltage is monitored using the HVDC voltage divider. A high-input impedance digital signal analyzer is used to process the low-voltage analog signal.

Similar to the method using direct measurements of current, the voltages in both poles must be measured simultaneously. Currents at any location along the line route must be calculated.

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10. Review of specification and performance of dc filters for the recent HVDC projects

The dc filter specification and performance data for nine recently completed or specified projects is summarized. This data was received in response to a questionnaire mailed to ten organizations, who are owners of recent HVDC projects. Thyristor valves were used in all the projects and, except in one case (the PI upgrade), all projects were designed for exclusive twelve-pulse operation. DC system ratings, line lengths, and other pertinent data for the several HVDC projects is tabulated and shown in Table 3.

10.1 Filter performance specification

The performance of DC filters has been specified in terms of any of the following three methods:

a) Induced noise voltage (INV) method
b) Equivalent disturbing current (EDC) method
c) Limits to line harmonic currents

10.1.1 Induced noise voltage method

The DC filter performance for most of the early projects was specified in terms of a standardized *C message* weighted induced voltage on a parallel telephone line of 1 km length, at a distance of 1 km from the dc line. This is generally referred to as *induced noise voltage* (*INV*) *method*, sometimes also referred to as *probe wire method*. Different limits are usually specified for bipolar, monopolar, ground, and metallic return operating conditions. It is also typical practice to specify the limits to a normalized soil resistivity of 100 Ω-m. The INV method of filter specification was used for the four projects surveyed.

10.1.2 Equivalent disturbing current method

In the equivalent disturbing current method, the composite interfering effect of all harmonics on a power line can be represented by a current at a single frequency, which would produce the same interfering effect. This is discussed in Clause 6. Two projects have specified filter performance in terms of the equivalent disturbing current method.

10.1.3 Limits on harmonic currents

Two projects have specified limits to the line harmonic currents.

10.2 Performance values actually agreed

It is often required to prepare specifications before data is available on transmission line routing and the adjacent communication lines, and the extent of coupling between them, and without the cost/performance data. To overcome this problem, four projects included more than one set of performance values in the specifications. In all cases, the final values selected were the more restricted values. It was perhaps determined that the extra cost of filter designs (to meet the restricted performance values) is justified in avoiding the potential interference problems.

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Table 3—Summary of dc filter specification and performance

	DC system ratings						
Name of project	**MW**	**KV**	**A**	**Line length km**	**Year (to be) commissioned**	**Performance method/values**	**Interference complaints**
IPP	1600	±500	1600	782	1987	INV (Note 1)	Yes
C-U	1000	±400	1250	702	1979	INV (Note 1)	Yes
PI Upgrade	2000	±500	2000	1390	1985	INV (Note 1)	No
ITAIPU	6300	±600	2610	806	1984/1987 Bipole I − Bipole II	Line currents (Note 2)	Yes
HQ-NE Phase I	690	±450	768	171	1986	INV (Notes 1 and 4)	Yes
HQ-NE Phase II	1800 (Note 3)	±450	2000	1477	1990	EDC (Note 5)	
Nelson River Bipole II	1800	±500	1800	904	1978	Line currents (Note 6)	Yes
Delhi-Rihand	1500	±500	1563	830	1991	NVC	
Gezhouba-Shanghai	1200	±500	1200	1000	1988	EDC (Note 7)	
Gotland I	20	±100	100	96	1984		
Gotland II	130	147	910	100	1983	INV 200 mV monopolar	
Gotland III	260	±150	867	103	1987	INV Industrial I_n	
New Zealand I	600	±250	1200	609	1965		
New Zealand II	992	+270 − 350	1600	617	1992	I_{eq} 2.5 A	
Konti-Skan I	250	250	1000	180	1968		
Konti-Skan II	300	285	1053	150	1988	INV 120 mV monopolar	

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Table 3 (*continued*)—Summary of dc filter specification and performance

	DC system ratings						
Name of project	**MW**	**KV**	**A**	**Line length km**	**Year (to be) commissioned**	**Performance method/values**	**Interference complaints**
Skagerrak I	250	250	1000	240	1976		
Skagerrak II	500	±250	1000	240	1977		
Skagerrak III	440	350	1257	240	1994	INV 10 mV—Denmark I_{pe} 800 mA—Norway	N/A
SACOI II	200	200	1000	415	1986		
Fenno-Skan	500	400	1250	200	1989	For monopolar INV 40 mV—Sweden I_{pe} 400 mA—Finland	
Pacific Intertie Expansion	1100	±500	1100	1362	1989	INV 10 mV bipolar 20 mV monopolar	
Baltic Cable	600	450	1333		1994	I_{pe} 400 mA monopolar	N/A
Chandrapur-Padghe	1500	±500	1500	754	1997	I_{eq} 400 mA bipolar 800 mA metallic return 1200 mA ground return	N/A

NOTES—N/C) The project is not yet commissioned.

1) 10 mV/km for bipolar operation; 20 mV/km for monopolar metallic return; 30 mV/km for monopolar ground return.
2) See Table 4.
3) This is a multiterminal system. These are the ratings of the Sandy Pond terminal. Line length given in the total from Radison (HQ) to Sandy Pond (NE).
4) 20 mV/km was used for either metallic or ground return operation.
5) 100/200/500 mA—three levels were specified for evaluation purposes.
6) See Table 5.
7) Option I: 500 mAp [bipolar/1500 mAp (monopolar ground return)]; Option II: 150 mAp [bipolar/450 mAp (monopolar ground return)].

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Table 4—The performance values specified for the dc harmonic filters in the Nelson River BP2 specification

Harmonic	Maximum current (A)
1	5.0
2	2.0
3	1.0
4	0.7
5	1.4
6	0.8
7	0.49
8	0.34
9	0.24
10	0.18
12	0.25
18	0.56
24	0.34
30	0.5
36	0.5

NOTE—The dc harmonic filters shall be capable of limiting the currents from one pole on its respective transmission line to a value set out in this table. The currents will be allowed on a pole basis so that when operating the bipole, the net ground current will be reduced. The currents shall not be exceeded with any one valve group out of service.

In the case of HQ-NE Phase I, the final designed values are higher than the specified values. The designed values are

—53 mV/km bipolar

—260 mV/km monopolar metallic return

—453 mV/km monopolar ground return

The revised values were based on the contention "that the specified values were unrealistically strict at 4000 Ω-m earth resistivity."

In all other projects, performance values agreed were basically the same as those used in specification.

10.3 Performance values actually measured with the system in operation

Actual performance of systems in operation is one of the most important feedback available to guide future systems specification and cost. The information in 10.3.1 through 10.3.6 is extracted from the responses that were obtained from individual projects.

10.3.1 PI upgrade

Induced noise was measured with two test lines constructed, about 29 miles apart from each other at the southern end of the HVDC line. Two test lines were used to confirm that no errors were made

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Table 5—Maximum permissible harmonic current limits for ITAIPU HVDC project

Frequency (Hz)	Maximum current (A)	Frequency (Hz)	Maximum current (A)
50	5.0	800	0.3
60	5.0	840	0.3
100	2.0	850	0.3
120	2.0	900	0.3
150	1.0	950	0.3
180	1.0	960	0.3
200	0.8	1000	0.3
240	0.8	1020	0.3
250	0.8	1050	0.3
300	0.8	1080	0.3
350	0.5	1100	0.3
360	0.5	1140	0.3
400	0.4	1150	0.3
420	0.4	1200	0.3
480	0.3	1320	0.3
500	0.3	1380	0.3
540	0.3	1440	0.3
550	0.3	1500	0.3
600	0.5	1800	0.3
650	0.3	1800	0.3
660	0.3	2100	0.2
700	0.3	2400	0.2
720	0.5	2520	0.2
750	0.3	2880	0.2
780	0.3		

during the test and, also, that no standing waves were present (Kimbark [B13]. At the northern end of the HVDC line, a probe wire 100 m long, 100 m away from the transmission line was used to make harmonic measurements.

Results indicated that the 10 mV/km requirement for bipolar operation was not met for any bipolar operating configuration. For all groups in service, INVs of 23.3 mV/km and 27.2 mV/km were recorded for the two sites. For monopolar operation, test results indicated that the requirements were essentially met. Values of INV were 20.1 mV/km and 17.7 mV/km.

10.3.2 ITAIPU

Harmonic current levels were measured with dc system in operation. Harmonics of higher order were lower than calculated values, while the lower order harmonics were higher. Additional measurements were scheduled to be done during commissioning of bipole 2.

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10.3.3 IPP

Performance was measured with the system in operation by using two 1 km test lines parallel to dc transmission line. A very good description of the test procedure is published in IEEE-PES [B9].

Measured noise on the test line parallel to nonelectrode portion of the dc line was within specification limits for eight of the nine operating modes. The only mode not meeting the specification requirement of 20 mV/km was for monopolar ground return at 1.1 pu power level, where the value was 24.9 mV/km.

Noise levels for the test line parallel to electrode portion of the line were far beyond specification limits for all operating modes. The reason for this result is high-current amplitude zero sequence *odd triplen* harmonics of order $3(2n+1)$ on the electrode line.

10.3.4 HQ-NE phase I

Measurements were made using 0.403 mΩ resistive shunt devices installed in the pole line exits of the Comerford Station. The measurements showed that the communication interference to be above the designed levels due to generation of noncharacteristic harmonics of order $3(2n+1)$ on the dc side.

10.3.5 Nelson River bipole II

No tests were performed. It was intended to perform such tests, but circumstances prevented their occurrence.

10.3.6 C-U Project

Measurements were made by a probe wire 1 km from the dc line. Results were 3.64 mV/km for the monopolar metallic return, and 3.5 mV/km for the bipolar operation.

10.4 Mitigation methods used to solve interference problems

10.4.1 CU project

Interference in the area near the inverter end was experienced. The problem was most serious with the high noncharacteristic harmonics (45th, 33rd, 39th, and 57th). The CU smoothing reactor is located on the neutral side of the valves. The cause of the problem was the unbalanced voltages due to the unbalanced stray capacitance to ground from each valve. To compensate, CU installed a 200 μF capacitor to ground on the electrode line of each pole. In addition, the dc harmonic filter at Dickinson Station was changed from a single frequency filter tuned to the 12th harmonic, to a double frequency filter tuned to the 12th harmonic, with a high pass at the 24th harmonic.

10.4.2 PI upgrade

No complaints received to date.

10.4.3 HQ-NE phase I

There have been a few individual complaints of telephone interference by customers of New England Telephone. The Canadian National Rail Road has made complaints of interference on an open wire

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communication circuit along a railroad right-of-way. At present, the only mitigation measure that has been taken is the removal of the reactors in the neutral blocking filters. Also, the neutral capacitors were increased to 16 μF. This lowers the neutral bus to ground impedance. Results obtained with this change, although lower by 7 dB to 9 dB, are still well above the designed levels.

10.4.4 IPP project

Interference complaints were received from an adjacent telephone company for harmonics of order $3(2n + 1)$ on the electrode line at the inverter end. This interference was eliminated by installing a 12 μF capacitor-to-ground at the point where the electrode line left the HVDC transmission line right-of-way. The need for this capacitor disappeared after the telephone company upgraded to digital system. However, the capacitor was left in place to eliminate harmonic interference to electrode monitoring equipment at the electrode site.

10.4.5 Nelson River bipole II

There have been no complaints of interference that we are aware of except for the following incident. During the period 1978–1979, the telephone circuits adjacent to the bipole II electrode lines experienced high telephone noise when bipole II operated in monopolar mode. Subsequent tests indicated that the source of the problem was a sixth harmonic resonance on the electrode line. The telephone circuits in the vicinity were modified to a subscriber carrier system, which significantly reduced the telephone noise. The effectiveness of this system was demonstrated during the test period, when for one telephone subscriber location along the bipole II electrode line, a 55 dB noise reduction was measured.

10.4.6 ITAIPU

An extensive program of measurements and mitigations in the telephone circuits affected by the DC line were carried out, both in the voice and in the carrier frequency band, following procedures and criteria agreed with the telephone companies in the area.

a) *For the voice frequency circuits*: A circuit having induced calculated value of 245 mVp should be mitigated to get a calculated level of 111.8 mVp in bipolar operation. The mitigation should be done before the dc system energization. A circuit with an induced calculated value of 54 mVp should be, in principle, acceptable. Circuits with a calculated induced voltage between 54.8 mVp and 245 mVp should be included in the measurement program to be carried out after the dc system energization. If either of the two measured limits—111.8 mVp for bipolar and 353.5 mVp for monopolar—are not met, then further mitigation is necessary.
b) *For the open wire carrier frequency*: The psophometric power of the noise produced by the dc line should not be higher than 1000 pWop for trunk circuit and 100 pWp for private and subscriber circuits, considering a minimum unbalance of 40 dB in these telephone circuits.

    1) mVp—millivolt psophometric
    2) pWp—picowatt
    3) pWop—at reference zero

These mitigation efforts limited the interference complaints. An unexpected complaint was reported, and it was found that in the previous calculation the earth resistivity used for that area was underestimated.

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Annex A

(informative)

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[6]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

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