

IEEE Recommended Practice for Determination of Power Losses in High- Voltage Direct-Current (HVDC) Converter Stations

Sponsor
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of the
IEEE Power Engineering Society**

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Abstract: A set of standard procedures for determining and verifying the total losses of a high-voltage direct-current (HVDC) converter station is recommended. The procedures are applicable to all parts of the converter station and cover standby, partial-load, and full-load losses and methods of calculation and measurement. All line-commutated converter stations used for power exchange in utility systems are covered. Loss determination procedures for synchronous compensators or static var compensators are not included.

Keywords: converter stations, power losses, HVDC converter stations

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Foreword

(This foreword is not a part of IEEE Std 1158-1991, IEEE Recommended Practice for Determination of Power Losses in High-Voltage Direct-Current (HVDC) Converter Stations.)

This recommended practice was prepared by Working Group I6 of the DC Converter Stations Subcommittee of the Substations Committee of the IEEE Power Engineering Society.

Preparation of this recommended practice was begun during 1986 for the purpose of establishing guidelines and criteria for the determination of power losses in high-voltage direct-current (HVDC) converter stations. It presents an up-to-date summary of procedures for determining and verifying the total losses of an HVDC converter station.

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CLAUSE	PAGE
1. Introduction	7
1.1 Purpose and Scope	7
1.2 References	9
1.3 Definitions and Abbreviations	9
2. Value of Losses	10
2.1 Introduction	10
2.2 Losses	10
2.3 Concept of Establishing Loss Evaluation Factors	10
3. Determination of Total HVDC Converter Station Losses	11
3.1 Methodology	11
3.2 Summation of Equipment Losses	12
3.3 Ambient Conditions	12
3.4 Operating Parameters	13
4. Determination of Equipment Losses	14
4.1 Thyristor Valve Losses	14
4.2 Converter Transformer Losses	20
4.3 AC Filter Losses	23
4.4 Shunt Capacitor Bank Losses	24
4.5 Shunt Reactor Losses	24
4.6 DC Smoothing Reactor Losses	25
4.7 DC Filter Losses	26
4.8 Auxiliaries and Station Service Energy Consumption	27
4.9 Other Equipment Losses	28
5. Bibliography	30
Annex A (informative) Alternative Methods for Establishing Loss Evaluation Factors	32
Annex B (informative) Losses in HVDC Thyristor Valves	36
Annex C (informative) Losses in HVDC Converter Transformers	45
Annex D (informative) Auxiliaries and Station Service Energy Consumption	50

IEEE Recommended Practice for Determination of Power Losses in High-Voltage Direct-Current (HVDC) Converter Stations

1. Introduction

1.1 Purpose and Scope

It is the purpose of this document to recommend a set of standard procedures for determining and verifying the total losses of a high-voltage direct-current (HVDC) converter station. The procedures are applicable to all parts of the converter station and cover standby, partial-load, and full-load losses and methods of calculation and measurement.

HVDC converter stations consist of a number of different pieces of equipment, as shown in Fig 1. The loss mechanisms vary among various pieces of equipment, and it is the consensus of the industry that the total losses cannot readily be determined by either factory or field testing alone. When in operation at rated conditions, these stations develop losses typically in the range of 0.005 to 0.01 per unit of the converter station rating for each conversion.

Therefore, it has become an accepted practice to establish the losses of the total HVDC converter station by adding the losses from each piece of equipment as derived from component tests and calculations, as applicable. Due to the complexity of the overall converter station and to the nonlinear voltage and current waveforms encountered in its operation, different methods have been used for establishing total station losses, sometimes giving differing results.

The recommendations contained in this standard apply to all line-commutated converter stations used for power exchange in utility systems. In some applications, synchronous compensators or static var compensators (SVC) may be connected to the ac bus of the HVDC converter station. However, loss determination procedures for such equipment are not included in this document.

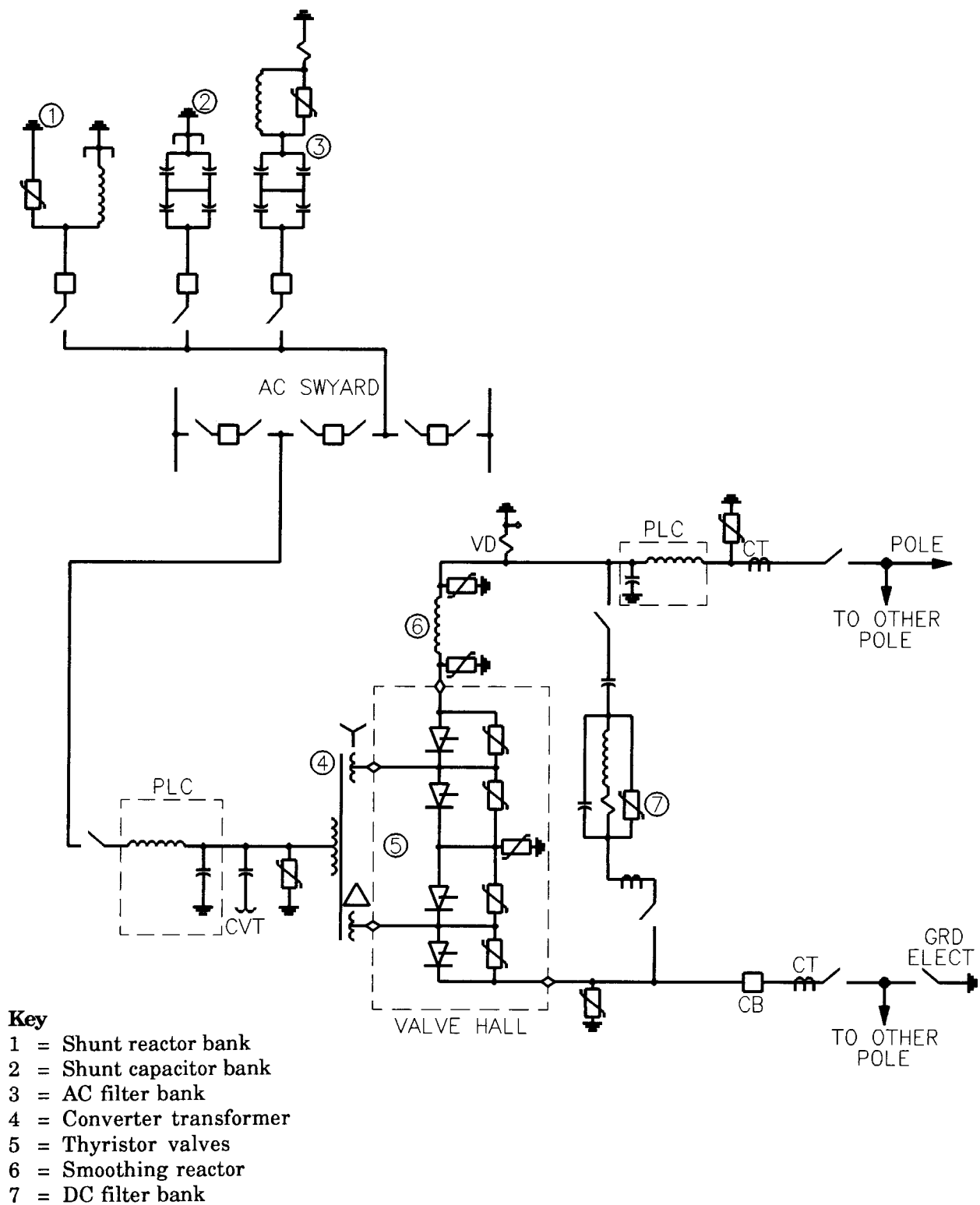


Figure 1— Typical HVDC Equipment for One Pole

1.2 References

This recommended practice shall be used in conjunction with the following publications:

- [1] IEC Pub 76, Power transformers.¹
- [2] IEC Pub 146-1-3 (1991), Semiconductor converters—General requirements and line commutated convertors—Part 1-3: Transformers and reactors.
- [3] IEC Pub 289 (1988), Reactors.
- [4] IEC Pub 747-6 (1983), Semiconductor devices—Discrete devices—Part 6: Thyristors.
- [5] IEEE C57.12.90-1987, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers; and Guide for Short-Circuit Testing of Distribution and Power Transformers (ANSI).²
- [6] IEEE C57.21-1990, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.
- [7] IEEE Std 3-1982, IEEE Recommended Practice for the Selection of Reference Ambient Conditions for Test Measurements of Electrical Apparatus (ANSI).
- [8] IEEE Std 18-1980, IEEE Standard for Shunt Power Capacitors (ANSI).
- [9] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronic Terms (ANSI).
- [10] IEEE Std 1030-1987, IEEE Guide for Specification of High-Voltage Direct-Current Systems Part I—Steady-State Performance (ANSI).

1.3 Definitions and Abbreviations

critical service loads: Station auxiliary loads that are sensitive to power supply disturbances and that have an immediate effect upon power transmission or whose outages could cause damage to the equipment.

essential loads: Those station auxiliary loads necessary to maintain full output of the station.

nonessential loads: Those station auxiliary loads not immediately necessary to maintain full HVDC station output.

standby losses: The losses produced with the HVDC converter station energized, but with the valves blocked.

station auxiliary losses: The electric power required to feed the HVDC station auxiliary loads.

total operating losses: The total station losses produced with the converter station energized and the valves operating.

SVC: Static var compensator.

i/V: Current versus voltage.

¹IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembré, CH 1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

2. Value of Losses

2.1 Introduction

When evaluating the economic costs of losses in a conventional ac substation, a distinction is made between no-load and load losses. This approach is due to the fact that transformer losses are the dominating factor in ac substations and that transformer losses can be broken down into two portions. One part, which is caused by magnetization, is present whenever the transformer is energized and is practically constant over the entire load range. It is called the no-load losses. The other portion is proportional to the load current squared and is called load losses.

On the other hand, there is no single piece of equipment that produces dominating losses in an HVDC converter station. (See Table A.1 in Appendix A for a typical breakdown of station losses.) The losses in an HVDC converter station are composed of the losses of various pieces of equipment, each of which has its own loss versus load relationship. For example, valve losses are not proportional to the load current squared (see Appendix B). Furthermore, when the station is energized, but in the standby mode described below, the thyristor valves will be blocked, and different loss mechanisms will apply from those that are found in normal operation. A further variation in the losses comes about because some equipment may be connected only at certain load levels. (For example, some filters and cooling towers may be required only at higher loadings.) Therefore, realistic values of the station losses can only be obtained if the losses are calculated at several points between standby (no-load) and full load.

2.2 Losses

When evaluating the losses of HVDC converter stations, it is recommended that two types of losses be distinguished: standby losses and total operating losses.

2.2.1 Standby Losses

These are the losses produced with the HVDC converter station energized but with the valves blocked. Under this condition, the ac filters and shunt compensating equipment are not required, and they are not connected to the ac bus. Smoothing reactors and dc filters, if any, are also not energized. However, the station service and cooling equipment are connected as required for immediate pickup of load. (Refer to Section 7.4.5 of IEEE Std 1030-1987 [10] for further explanation of the standby condition.) Standby losses can be considered as being equivalent to “no-load” losses in conventional ac substation practice.

2.2.2 Total Operating Losses

These are the total station losses produced with the converter station energized and the valves operating. When the converter valves are operating, the dc current is not permitted to drop below a defined minimum current, which is design-dependent and varies from project to project. Operating losses may be required to be evaluated at any load current between the minimum and maximum values. It is important to keep in mind that some of the equipment in the HVDC station is not used at all load levels; the ac filters are an example. Therefore, the calculation of the losses for a particular station loading must specify which apparatus is online for that load condition. In general, all equipment should be assumed to be connected, which is required to meet the specified performance at the particular load level. Total operating losses minus the standby losses can be considered as being equivalent to “load losses” in conventional ac substation practice.

2.3 Concept of Establishing Loss Evaluation Factors

Various methods are in use in the industry for making an economic evaluation of the cost of losses in electrical equipment; in particular, several methods have been suggested for use with HVDC converter stations (see

Appendix A). To date, however, no consensus has emerged that would allow the recommendation of a single technique for this evaluation.

2.3.1 General Principles

Most evaluation techniques recognize that the cost of equipment losses involves two factors:

- 1) A capacity cost, representing the capital cost required to increase the capacity of the electrical supply system so that it can supply the power losses in the equipment.
- 2) An energy cost, representing the cost of supplying the actual energy consumed in the equipment. Although the energy cost actually occurs over the life of the equipment, for comparison purposes, it is reduced to a single lump-sum cost through a present value calculation.

In principle, then, the cost of the losses in the equipment is the sum of the capacity cost plus the present value of the energy cost over the expected life of the equipment.

2.3.2 Concepts as Applied to HVDC Converter Stations

However, when the principles of 2.3.1 are applied to an HVDC converter station, there are several complicating factors. For example

- 1) As indicated in 2.1 and 2.2, the losses in the converter station vary in a complex way as a function of the load level.
- 2) In general, the HVDC converter station does not operate at a single load level, but the dc loading is dispatched to meet the needs of the ac systems. Therefore, the losses in the converter station will vary over time.
- 3) As indicated in 3.3, the losses in the converter station are dependent on the ambient conditions. (For example, for a given dc loading, the losses may be higher in the summer than in the winter.)
- 4) The economic value of the losses is dependent on the conditions in the system. (For example, losses that occur when the ac system is base loaded are usually less costly than losses occurring at peak load conditions.)

These factors are unique to each HVDC application, as will be the accounting practice of each utility. It is not within the scope of this document to recommend how the evaluation of losses should be carried out, but some examples are given in Appendix A. The underlying principle is that the owner of the station should establish a set of "loss evaluation factors" that are project-specific. These loss evaluation factors should be expressed in dollars per kilowatt of station loss (\$/kw), should be defined for each of the load levels of interest from standby to full load, and must take into account the percentage of time that the station will operate at each load level. The economic evaluation of station losses would then be arrived at as the sum of the losses at each load level times the evaluation factor for that load level.

3. Determination of Total HVDC Converter Station Losses

3.1 Methodology

As a general principle, it would be desirable to determine the efficiency of an HVDC converter station by the direct measurement of its energy losses. However, there are practical difficulties that prevent such a measurement, including the following:

- 1) Attempts to determine the station losses by subtracting the measured output power from the measured input power must recognize that such measurements have inherent inaccuracy, especially if performed at high voltage dc. Moreover, the losses of an HVDC converter station at full load are generally less than 1% of the transmitted power. Therefore, the difference between the measured input and output power is a small difference between two large quantities and, as such, is not likely to be a sufficiently accurate indication of the actual station losses.

- 2) In some special circumstances, it may be possible to arrange a temporary test connection in which the two converters are operated from the same ac source and are also connected together via their dc terminals. In this connection, the ac source only provides enough power to make up the losses in the circuit. However, it must also provide var support and commutating voltage for the two converters. Here again, there are practical measurement difficulties.

Because of the problems described above, it is recommended that the total station losses be calculated from the losses of the individual equipment. The equipment losses should be determined according to Section 4.

3.2 Summation of Equipment Losses

The total losses of the HVDC converter station should be arrived at as the sum of the losses of each piece of equipment. It is important to note that the actual losses in each piece of equipment will depend on the ambient conditions under which it operates, as well as on the operating conditions or duty cycles to which it is applied. Therefore, in order for the summation of the individual losses to be a sufficiently accurate representation of the actual total HVDC converter station losses, the ambient and operating conditions for each piece of equipment must be defined, based on the ambient and operating conditions of the entire HVDC converter station.

For some equipment or components, losses or electrical characteristics are measured at the factory under standardized ambient and operating conditions. In these cases, the results should be related to the actual conditions in the HVDC converter station through well-recognized calculation procedures.

The fundamental principle of this recommended practice is that the determination of the equipment losses is, in fact, based on physical tests on the actual equipment or components. Therefore, the sum of the equipment losses does give a dependable measure of the losses for the entire HVDC converter station.

3.3 Ambient Conditions

3.3.1 Introduction

A set of standard reference ambient conditions for determining power losses in HVDC converter stations is recommended below. In the event that equipment standards have established a reference ambient condition for loss determination, the applicable method referenced in the equipment standard shall be used and the losses so obtained be corrected to reflect the standard reference ambient conditions indicated below for determining the total converter station losses.

3.3.2 Standard Reference Temperature

3.3.2.1 Outdoor Standard Reference Temperature

In view of its history of acceptance and use in international comparisons of mechanical and electrical standards, an outdoor ambient temperature of 20 °C should be used as the standard reference temperature for determining the total converter station losses [7].

3.3.2.2 Cooling-Medium Standard Reference Temperature

Forced air or cooling fluids such as water are used to conduct heat from a piece of equipment and can influence the temperature rise and associated losses of certain pieces of equipment. Therefore, the cooling-medium temperatures and flow rates need to be established as a basis for determining the total converter station losses. Since the cooling-medium parameters are highly design related, the temperatures and flow rates should be established between the user and the supplier and utilized as a basis for determining the total converter station losses.

3.3.3 Standard Reference Altitude

The reference altitude to be used for the evaluation of total converter station power losses should be the actual altitude of the installation in question.

3.4 Operating Parameters

The losses of an HVDC converter station depend on its operating parameters according to a complex relationship (see Appendix A). In addition to ac system voltage and converter station loading, the converter firing angle introduces an additional variable. Also, the concept of reactive power compensation should be considered, as it would have an impact on the requirement for connecting shunt capacitors or shunt reactors. Whereas for rated conditions, the operating parameters of an HVDC converter station would be well defined by the performance specification and the resultant design criteria, at partial load, the control strategy adopted may have a major impact on total station losses.

3.4.1 General

In general, HVDC converter station losses should be determined for nominal ac system voltage and frequency. The transformer tap-changer should be assumed to be in the position corresponding to nominal ac system voltage.

3.4.2 Rated Load

Where a converter station is expected to be operated at rated load for most of the time, station losses should be determined for this condition only, assuming nominal firing angle, that shunt compensation and filtering equipment are connected to meet the performance requirements, and that auxiliary equipment (e.g., cooling-water pumps) is in operation to cope with the standard reference temperature (see 3.3).

3.4.3 Varying Load

Where the converter station is expected to be operated at widely varying loads or for reactive power compensation and ac voltage control, a prospective load duration curve should be used to determine a number of representative loading conditions; e.g., typically three to five.

Total converter station losses should be determined for these loading conditions, assuming that dc current, converter firing angle, shunt compensation, and filtering equipment are consistent with the respective loading condition and the performance requirements specified. Station service loads and auxiliary equipment should be connected to support the respective loading condition, assuming the standard reference temperature.

The losses at the individual loading conditions should then be weighted with factors representative of the system of the particular utility; e.g., as described in [B3], and added to obtain the equivalent losses for evaluation.

3.4.4 Standby

For the standby mode, converter transformers should be assumed to be energized and the thyristor valves blocked. All filters and reactive power compensation equipment should be assumed to be disconnected. Station service loads and auxiliary equipment (e.g., cooling-water pumps) should be assumed to be connected as required for immediate pickup of load for the converter station.

4. Determination of Equipment Losses

4.1 Thyristor Valve Losses

The procedures set out below will provide a total loss figure for valves based on the summation of individual loss components. The individual components of loss are determined by applying standardized calculation methods. Data should be obtained, where possible, from verifiable factory measurements.

All losses are determined on a per-valve basis, in which a “valve” is taken to be one arm of a three-phase, line-commutated converter bridge.

Standby losses are defined for the valves energized but blocked.

The auxiliary power losses of the thyristor valve cooling equipment are included in the auxiliary power energy consumption of the total converter station (see 4.8).

Valve losses and the methods adopted in the following subsections for their prediction are discussed more fully in Appendix B.

4.1.1 Thyristor Conduction Loss per Valve: W_1

This is the principal loss arising from the passage of load current through the thyristors of the valve (see B.3.1.3 and B.5.1).

$$W_1 = \frac{nI}{3} \left[\bar{V}_o + \bar{R}_o I \left(\frac{2\pi - u}{2\pi} \right) \right] \quad (1)$$

where

- n = The number of series levels in the valve
- $\bar{V}_o$ = The current independent component of the ON-state voltage of the average thyristor (see NOTE 1), in volts
- $\bar{R}_o$ = The slope resistance of the ON-state characteristic of the average thyristor (see NOTE 1), in ohms
- u = The commutation overlap calculated for the operating conditions for which losses are being determined, in radians
- I = The mean dc bridge current for which losses are being determined, in amperes

NOTES:

- 1 — $\bar{V}_o$ and $\bar{R}_o$ are determined from the fully spread ON-state voltage measured at the appropriate current and junction temperature (see 4.1.10). The average value of ON-state voltage should be readily available from production records. If parallel connection of thyristors is employed, the appropriate current is the bridge current divided by the number of parallel paths.
- 2 — When the dc-side harmonic currents (root sum of squares) are more than 10% of the dc component, the modified formula given in B.5.1 should be used.

4.1.2 Thyristor Spreading Loss per Valve: W_2

This is an additional conduction loss of the thyristors arising from the delay in establishing full conduction of the silicon (see B.3.1.2 and B.5.2).

$$W_2 = n f \int_{\omega t = \alpha}^{\omega t = \alpha + 120^\circ + u} (v_1(t) - v_2(t)) \cdot i(t) d\omega t \quad (2)$$

where

- n = The number of series levels in the valve
- f = The system frequency, in hertz
- $V_1(t)$ = The instantaneous ON-state voltage of the average thyristor at the appropriate junction temperature measured with a trapezoidal current pulse exhibiting the correct amplitude and commutation overlap periods (see 4.1.10), in volts
- $V_2(t)$ = The predicted instantaneous ON-state voltage of the average thyristor at the same junction temperature for the same current pulse but with the conducting area fully established, in volts
- $i(t)$ = The instantaneous current in the thyristor, in amperes
- α = The firing delay angle, in degrees
- u = The commutation overlap angle, in degrees
- ω = $2\pi f$, in radians/second

Typically, instantaneous ON-state voltage data, including the effects of spreading, are not available from production records. Measurements of typical thyristor ON-state voltage, including spreading, should therefore be obtained during the valve periodic firing and extinction type test or, alternatively, from a separate type test in the laboratory.

4.1.3 Other Valve Conduction Losses per Valve: W_3

These are the conduction losses in the main circuit of the valve due to components other than the thyristors (see B.3.3.1.1 and B.5.3).

$$W_3 = \frac{I^2 R}{3} \left(\frac{2\pi - u}{2\pi} \right) \quad (3)$$

where

- I = The mean dc bridge current for which losses are being determined, in amperes
- R = The dc resistance of the valve terminal-to-terminal circuit excluding the thyristors, in ohms
- u = The commutation overlap angle calculated for the operating conditions for which losses are being determined, in radians

The value of R should be determined by direct measurement as a room-temperature type test on a representative valve section that includes all elements of the main circuit of a valve in the correct proportions, but in which the thyristors have been replaced by copper blocks of the appropriate dimensions. Alternatively, the dc resistance may be calculated, in which case the calculating methods should be documented.

4.1.4 “DC” Voltage-Dependent Loss per Valve: W_4

This is the loss in the shunt resistive impedance of the valve arising from the voltage appearing between valve terminals during the nonconducting interval. It includes losses in dc grading resistors, thyristor off-state and reverse leakage resistance, resistance of coolant in coolant pipes, resistivity effects of the structure, other grading networks, fiber optics, etc. (see B.3.3.2 and B5.4.) [B9].

$$W_4 = \frac{V_L^2}{2\pi R_{DC}} \left[\frac{4\pi}{3} + \frac{\sqrt{3}}{4} (\cos 2\alpha + \cos(2\alpha + 2u)) - \left(\frac{7}{8} + \frac{3m(2-m)}{4} \right) (2u + \sin 2\alpha - \sin(2\alpha + 2u)) \right] \quad (4)$$

where

- R_{DC} = The effective off-state dc resistance of a complete valve determined by measuring the current drawn during the valve terminal-to-terminal dc voltage type test, in ohms
- u = The commutation overlap angle calculated for the operating conditions for which losses are being determined (see Note 1), in radians

- α = The firing delay angle, in radians
 V_L = The rms line-to-line commutating voltage referred to the valve winding (see Note 2), in volts
 m = $L_1/(L_2 + L_1)$, where L_1 is the inductance, referred to the valve winding, between the commutating voltage source and the point of common coupling of the star and delta bridge valve winding connections. L_2 is the inductance referred to the valve winding between the point of common coupling and the valves (see Note 3).

NOTES:

- 1 — Eq 4 is only valid for $u < \frac{\pi}{6}(30^\circ)$.
- 2 — The commutating voltage source can normally be taken as the ac filter bus.
- 3 — When separate transformers supply the star and delta bridges, $L_1 = 0$; hence, $m = 0$. When three-winding construction is employed, a common line winding impedance and mutual coupling effects of the two secondary windings give real values for L_1 , which may be positive or negative. For more complicated transformer arrangements, e.g., filters connected to a low-voltage tertiary winding, the effective values of L_1 and L_2 must be determined with care.

With the valves in standby mode, that is, energized but blocked, the contribution to standby losses is

$$W_{4(\text{standby})} = \frac{V_L^2}{3R_{DC}} \quad (5)$$

4.1.5 Damping Loss per Valve (Damping-Resistor-Dependent Term): W_5

This is the component of loss that is dependent on the value of the resistive elements of those circuits that are ac coupled via series capacitors arising from the voltage appearing between valve terminals during the nonconducting interval. The principal circuits involved are the damping circuits (see B.3.2.1 and B5.5) [B9].

$$W_5 = 2\pi f^2 V_L^2 C_{ac}^2 R_{ac} \left\{ \left[\frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + (6m^2 - 12m - 7)\frac{u}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32} \right) \sin 2\alpha + \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32} \right) \sin(2\alpha + 2u) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8} \right) \cos 2\alpha + \frac{\sqrt{3}m}{16} \cos(2\alpha + 2u) \right] \right\} \quad (6)$$

where

- V_L , α , u , and m are as defined in Eq 4
 f = The system frequency, in hertz
 C_{ac} = The effective value of valve terminal-to-terminal capacitance (see Notes 3, 4, and 5), in farads
 R_{ac} = The effective value of the associated series-connected resistance (see Notes 3, 4, and 5), in ohms

NOTES:

- 1 — Eq 6 is only valid for $u < \frac{\pi}{6}(30^\circ)$.
- 2 — The above equation is derived from [B10]. A different equation can be derived from [B4], giving results that agree to within $\pm 0.5\%$ of the total thyristor valve losses. The difference in equations is due to differing, but equally valid, simplifications made in the two references.
- 3 — Unlike the case of dc OFF-state resistance, it is not possible to determine the values of C_{ac} and R_{ac} readily from, for example, the ac power frequency test. Since “stray” capacitance will have negligible influence on the current flow in the associated resistors, the design values for the grading network components should be used to derive C_{ac} and R_{ac} .
- 4 — If the valve employs more than one grading network branch that incorporates series-connected R and C , then each branch must be evaluated separately and the results summed.