**IEEE Std 857-1996**

(Revision of IEEE Std 857-1990)

# IEEE Recommended Practice for Test Procedures for High-Voltage Direct-Current Thyristor Valves

Sponsor

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**of the**
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**Abstract:** Information and recommendations for the type testing of thyristor valves for high-voltage direct-current (HVDC) power transmission systems are provided. These tests cover only the principal tests on the valves and do not include tests of auxiliary equipment associated with the valves.

**Keywords:** HVDC thyristor valves, HVDC power transmission systems, multiple-valve unit (MVU), thyristor levels

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The Institute of Electrical Engineers, Inc.

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# Introduction

(This introduction is not part of IEEE Std 857-1996, IEEE Recommended Practice for Test Procedures for High-Voltage Direct-Current Thyristor Valves.)

This recommended practice was prepared by the Working Group I1, Power Electronic Equipment of the IEEE High-Voltage Power Electronics Stations Subcommittee. Working Group I1 was established in 1994 with the goal of reaffirming or revising IEEE Std 857-1990 to conform with the five-year review cycle mandated by Article 1.4 of the IEEE Standards Board Bylaws. To keep up with the advance of technology in the high-voltage direct-current (HVDC) industry and to attempt harmonization with an IEC standard (IEC700-1 ) that was under preparation, Working Group I1 decided that IEEE Std 857-1990 , should be revised from a guide to a recommended practice.

This revised document achieved the goal of keeping up with the technology but only partially succeeded in the harmonization effort. While there were close communications and cooperation with the Chair of the IEC 22-F Working Group 06, IEC procedures prevent any IEEE input to or discussion of the revision of IEC 700-1 . To the extent supported by technical justifications, this revised IEEE standard incorporated many changes proposed by IEC members. At the time this document was reviewed and approved, the IEC revision was still under preparation. Further harmonization with the IEC 700-1 will be attempted by several Working Group I1 members through their respective representatives on the IEC National Committee.

As stated in the original IEEE Std 857-1990 , the purpose of this document is to complement other IEEE standards on HVDC power transmission systems and give guidance to the industry on how to treat the important subject of testing a thyristor valve that is a complex device. The tests recommended in this document cover only the principal electrical tests on the thyristor valves. This is not intended to be a comprehensive guide on valve testing because it does not have within its scope other valve tests, i.e., development tests, production sample tests, routine tests, loss determination tests, commissioning tests, site tests. Further, material flammability tests were not included.

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CLAUSE PAGE

# IEEE Recommended Practice for Test Procedures for High-Voltage Direct-Current Thyristor Valves

## 1. Scope

This recommended practice contains information and recommendations for the type testing of thyristor valves for high-voltage direct-current (HVDC) power transmission systems. Other equipment tests, such as development tests, production sample tests, routine tests, tests for the determination of losses, commissioning tests, and site tests are not within the scope of this recommended practice. Furthermore, the tests given here cover the principal tests on the valves only and do not include tests of auxiliary equipment associated with the valves, such as cooling system components.

This recommended practice applies to any type of line-commutated indoor thyristor valve, with metal-oxide surge arresters connected between the valve terminals, used in converters for HVDC power transmission systems. Any modifications to these tests and/or additional tests required for outdoor valves are to be considered separately.

## 2. References

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

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).[1]

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEC 60060-1 (1989-11), High-voltage test techniques—Part 1: General definitions and test requirements.[2]

IEC60060-2 (1994-11), High-voltage test techniques—Part 2: Measuring systems.

IEC 60071-1 (1993-11), Insulation co-ordination—Part 1: Definitions, principles and rules.

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

[2] IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembé, 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.

IEC 60071-2 (1996-12), Insulation co-ordination—Part 2: Application guide.

IEC 60099-4 (1991-11), Surge arrestors—Part 1: Metal oxide surge arresters without gaps for a.c. systems.

IEC 60146-1-1 (1991-04), General requirements and line commutated convertors—Part 1–1: Specifications of basic requirements.

IEC 60146-1-2 (1991-04), General requirements and line commutated convertors—Part 1–2: Application guide.

IEC 60146-1-3 (1991-04), General requirements and line commutated convertors—Part 1–3: Transformers and reactors.

IEC 60146-2 (1974-01), Semiconductor convertors—Part 2: Semiconductor self-commutated convertors.

IEC 60146-3 (1977-01), Semiconductor convertors—Part 3: Semiconductor direct d.c. convertors (d.c. chopper convertors).

IEC 60146-4 (1986-09), Semiconductor convertors—Part 4: Method of specifying the performance and test requirements of uninterruptible power systems.

IEC 60146-5 (1988-11), Semiconductor convertors—Part 5: Switches for uninterruptible power systems (UPS switches).

IEC 60146-6 (1992-12), Semiconductor convertors—Part 6: Application guide for the protection of semiconductor convertors against overcurrent by fuses.

IEC 60633 (1978-01), Terminology for high-voltage direct current transmission.

IEC 60700 (1981-01), Testing of semiconductor valves for high-voltage d.c. power transmission.

IEC 60747-1 (1983-01), Semiconductor devices—Discrete devices—Part 1: General.

IEC 60747-5 (1992-05), Semiconductor devices—Discrete devices—Part 5: Optoelectronic devices.

IEC 60747-6 (1983-01), Semiconductor devices—Discrete devices—Part 6: Thyristors.

## 3. Definitions

Definitions given in this recommended practice apply specifically to the testing of HVDC thyristor valves.

**3.1 failure of thyristor level:** A thyristor level is deemed to have failed if it becomes short-circuited or in any other way has degraded to the extent to make it functionally inoperative.

**3.2 multiple-valve unit (MVU):** A single structure comprising more than one valve.

**3.3 redundancy factor:** The ratio of the total number of series thyristor levels in the valve, $N_t$, to the same number minus the total number of redundant series thyristor levels in the valve, $N_r$. The redundancy factor, $f_r$, is defined by

$$f_r = \frac{N_t}{(N_t - N_r)} \tag{1}$$

**3.4 redundant thyristor levels:** The maximum number of levels in the series string of thyristors in a valve that may be short-circuited externally or internally during service without affecting the safe operation of the valve as demonstrated by type tests, and which, if and when exceeded, would require shutdown of the valve to replace the failed thyristors or acceptance of increased risk of failure of the valve.

**3.5 single-valve unit:** A single structure comprising only one valve.

**3.6 test withstand voltage:** The maximum value of a test voltage at which a new valve, with unimpaired integrity, does not show any disruptive discharge, nor suffer component failures above permissible levels, when subjected to a specified number of applications of the test voltage, under specified conditions.

**3.7 thyristor level:** A single thyristor, or thyristors if the valve has parallel connected thyristors, and associated components for control, voltage grading, protection, and monitoring that constitute a single voltage level within the valve.

**3.8 valve:** A converter arm in a three-phase, 6-pulse bridge converter connection.

**3.9 valve base:** The assembly that mechanically supports and electrically insulates the valves from ground.

NOTE — A part of a valve that is clearly identifiable in a discrete form to be a valve base may not exist in all designs of valves. A valve base could be a separate platform insulated from ground by post-type insulators that carries a live-tank valve unit, or a steel framework insulated from ground by post-type insulators on which the various modules of an MVU are mounted, or a raised platform of insulating material that is integral to the valve structure and forms the base.

**3.10 valve module:** The smallest assembly, comprising a number of thyristors and their immediate auxiliaries for firing and protection, voltage-dividing components, and distributed or lumped valve reactors, from which the valve is built up and which exhibits the same electrical properties as the complete valve but can withstand only a portion of the full voltage-blocking capability of the valve.

**3.11 valve section:** An electrical assembly comprising a number of thyristor levels and other components that exhibits prorated electrical properties of a complete valve.

# 4. Classification of tests

The type tests described in this recommended practice are classified under two major categories: dielectric tests and operational tests.

## 4.1 Dielectric tests

These tests are intended to verify withstand and voltage-related characteristics of the valve under various overvoltage conditions. The following tests fall under this category:

a) Dielectric tests on valve base
    1) DC voltage test
    2) AC voltage test
    3) Switching impulse test
    4) Lightning impulse test
    5) Steep-front impulse test
b) Dielectric tests on an MVU
    1) DC voltage test
    2) Switching impulse test
    3) Lightning impulse test
    4) Steep-front impulse test
c) Dielectric tests on a valve
    1) DC voltage test (dry and wet)
    2) AC voltage test

3) Switching impulse voltage test (dry and wet)
4) Lightning impulse voltage test
5) Steep-front impulse voltage test
6) Nonperiodic firing test
7) Turn-on stress test

### 4.2 Operational tests

These tests are intended to demonstrate the correct operation and capabilities of the valve under various operating conditions, including the worst-case fault condition. The following tests fall under this category:

a) Load test, including periodic firing and extinction test
b) Current-sharing test
c) Minimum alternating voltage test
d) Intermittent dc test
e) Recovery period forward impulse withstand test
f) Short-circuit current with subsequent blocking test
g) Short-circuit current without subsequent blocking test

## 5. Test requirements

### 5.1 General

Thyristor valves are usually of modular construction with identical modules connected in series to obtain the required valve voltage rating. This type of construction lends itself to simplifying the tests and the test equipment required. Great economy can be obtained when valve sections instead of whole valves are used for type tests. However, certain dielectric tests must be performed on complete valves, as these tests relate to characteristics that are defined only after a valve is completely built. All operational tests are carried out on valve sections. Simultaneous full-scale voltage and current tests are not considered essential for thyristor valves.

If a type test is conducted on valve sections rather than the whole valve, the minimum number of valve sections so tested should be equal to those in one complete valve. The preferred approach is for the valve section to be made up of single or integer multiples of valve modules. If this is difficult because of limitations in the ratings of the available test circuit, valve sections made up of thyristor levels fewer than those in complete module(s) may be used. The test valve sections should have a minimum of five series-connected thyristor levels. This minimum number of thyristor levels is recommended to ensure that the performance of the valve section reasonably reflects the performance of the complete valve as affected by the design tolerances in the characteristics of different thyristors in a complete valve. If the valve section under test has less than the recommended number of levels, it may be necessary to include an additional safety factor. The need for and value of this additional test safety factor will be design-dependent and should be agreed upon, in advance, between the purchaser and the supplier.

The choice of valve section should also take into consideration the representation of the valve reactors within the valve. The number of series-connected levels in the test valve section should preferably avoid test arrangements that require fractional reactors, which may have to be specifically fabricated and which may not therefore be fully representative of the actual valve reactors.

Sometimes operational tests may have to be performed at a power frequency that is different from the service frequency (e.g., 50 Hz instead of 60 Hz). Thyristor switching losses, snubber circuit losses, and $I^2t$ of short-circuit current are affected by the actual frequency during tests. When this situation occurs, the test conditions and valve characteristics should be reviewed and appropriate changes made to ensure that the valve stresses are at least as severe as they would be if the tests were performed at the service frequency.

The arrangement of the cooling system could also influence the choice of suitable valve section. In a liquid- cooled valve, a parallel, series, or series-parallel cooling arrangement could be used. In series or series-parallel arrangement, there would be some difference in the temperature of the cooling liquid, and hence the thyristor junction temperature, among different thyristor levels. The thyristors in the valve section should, as far as practicable, reflect the differences in thyristor junction temperature between thyristor levels in the complete valve.

The temperature, conductivity, and flow rate of the coolant during tests are important, especially for operational tests. With respect to these items, the test conditions should simulate the worst conditions that could be encountered in operation.

When a valve is of a new design, or an old design with significant changes, the valves are expected to undergo the full range of type tests. If a valve that has already been successfully type-tested for one project is to be used for a new project, it will be to the benefit of the purchaser to assess the need for, or the extent of, new type tests, based on an evaluation of the stresses associated with the new application and how well they have been covered by the previous type tests.

## 5.2 Valve temperature at testing

Because some important characteristics of thyristors and other solid-state devices used at thyristor potential in a valve are dependent on their junction temperatures, the valve temperature at testing should be selected to give the most critical stresses. However, to avoid unnecessary extra cost and also not to complicate the test arrangements, temperature conditions other than room temperature should not be called for unless they are significant for the results or the test at room temperature would not be representative of actual valve operating performance.

On the other hand, the forward blocking voltage withstand capability of thyristors is highly sensitive to rapid rise of voltage and decreases with increasing junction temperatures. Also, the solid-state devices in the electronic circuits at thyristor potential may be susceptible to spurious behavior under high $dV/dt$ and hot valve conditions, which could cause false triggering of thyristors. Therefore, the appropriate valve temperature condition for fast fronted impulse voltage tests (i.e., with fronts of 1.2 *ms* or less) corresponds to that of a hot valve.

A hot valve is defined to be one with the junction temperature of its thyristors equal to the maximum permissible steady-state temperature. This will generally be obtained at the maximum current rating (including overload capability) and the corresponding maximum permissible temperature of the cooling medium.

Recognizing the difficulties of conducting hot valve tests on a complete valve, the test may be conducted on a cold valve and on a number of hot valve modules, provided it has been demonstrated (e.g., by previous tests or analysis) that voltage distribution among modules within the valve is not dependent on valve temperature conditions, that the coupling effects into the gating circuits are the same for a module and a complete valve, and that the absence of spurious triggering is independent of module temperature conditions.

A cold valve is defined to be one with the junction temperatures of its thyristors corresponding to normal room temperature. It is known that the changes in those thyristor characteristics that degrade valve performance are very small, with decreases below normal room temperature. Therefore, it is not necessary to test the valve at its minimum ambient temperature except for extreme cases.

## 5.3 Treatment of redundancy for type tests

For all dielectric tests, with the possible exception of the nonperiodic firing test, the recommended practice is to carry out the tests with the redundant thyristor levels shorted out. If the nonperiodic firing test is also used for electromagnetic interference (EMI) tests, it is preferable not to short-circuit the redundant thyristors, but to increase the test voltage by the redundancy factor.

Normally, the location of the redundant thyristor levels to be shorted for the tests is left to the choice of the purchaser. However, in some valve designs, limitations may be imposed on the distribution of the short-circuited thyristor levels. For example, there may be an upper limit for the number of short-circuited levels in a single valve section. The supplier should inform the purchaser of the need for such exceptions before the purchaser agrees to the test procedures.

For all operational tests, the redundant thyristor levels shall not be short-circuited. The test voltage levels are proportional to the ratio of the number of series thyristor levels under test to the total number of thyristor levels in the valve adjusted upward by the redundancy factor except for the minimum alternating voltage test. For the minimum alternating voltage test, no consideration is given to redundancy.

## 5.4 Selection of impulse test withstand voltage levels

The impulse test withstand voltage levels are selected on the basis that the tests should confirm that the valve could withstand any impulse voltage not subject to limitation by the arresters used to protect the valves against overvoltages. The test withstand level is derived from the arrester protection level adjusted to take into account the following factors:

a) Test measurement error, $K_{mev}$
b) Test voltage tolerance, $K_{ttv}$
c) Tolerance in specified arrester protection level, $K_{at}$
d) Arrester aging factor, $K_{aa}$
e) Valve aging factor, $K_{ta}$
f) Air density factor, $K_d$

For test measurement error, consistent with ANSI and IEC standards, the value normally used is 3%. For test voltage tolerance, standards usually recognize a test as valid when the applied voltage is within ±3% of the specified value. Since these two factors related to test conditions are independent and can be assumed to vary randomly, it is reasonable to combine the two to give the measurement factor, $K_{mv}$, as

$$K_{mv} = 1 + \sqrt{[K^2{}_{mev} + K^2{}_{ttv}]} \tag{2}$$

For measurement error and test voltage tolerance, values different from those specified above may be used if the test conditions warrant it. If the calibration of test-measuring instruments demonstrates that the measurement error is different from ±3%, it is appropriate to use the calibrated value for $K_{mev}$. Usually the test voltages applied are equal to or greater than the specified value. If there is prior agreement between the purchaser and the supplier that, for the tests to be considered valid, the applied voltage should be equal to or greater than the specified value, $K_{ttv}$ can be neglected.

Typically, the arrester protection level of a new arrester could vary within ±3% of the published figure for nominal arrester protection level. To account for the difference between the nominal and maximum arrester protection levels, the factor $K_{at}$ of 1.03 would be used. Arresters for thyristor valves are usually not standard arresters, but specifically designed and built for each valve design. In such cases, sometimes the arrester protection level is specified in terms of the maximum value rather than the nominal value. The factor $K_{at}$ then would be 1.00.

It is recognized that aging of arresters can change the arrester protection level. Commonly specified variation of arrester protection level due to aging is ±5%. On that basis, the factor $K_{aa}$ will be 1.05.

There is no consensus in the industry on the effect of aging on the withstand capability of the valve. There is no published data that conclusively show either the existence or the absence of such an aging effect for thyristors. Proponents for discounting the aging effect argue that until there is clear evidence showing such an aging effect, there is no rational basis for taking it into account. On the other side, it has been suggested that the deterioration in dielectric properties due to aging is a widespread phenomenon in materials and, in this context, until proved otherwise, the presumption should be that such aging effects are more likely than not, and that the present situation reflects the failure of the industry to carry out the necessary comprehensive tests needed to resolve the issue. There have been informal reports from the Institut de Recherche d'Hydro-Québec (IREQ), one of the leading Canadian research laboratories, that their ongoing inconclusive experiments in this field indicate possible aging effects.

Given the present uncertainty about the subject, it is considered prudent to make some allowance for valve aging effects. Following the example of metal-oxide arresters, the recommended value for $K_{ta}$ is 1.05. It is further recommended that this factor be modified if published data resolve this uncertainty about thyristor aging effects.

Based on the above considerations, the impulse test withstand voltage levels for type testing of thyristor valves, $V_{imp}$, in terms of specified nominal arrester protection level, $V_{ar}$, should be

$$V_{imp} = V_{ar} \times K_{mv} \times K_{at} \times K_{aa} \times K_{ta} \tag{3}$$

From consideration of the practical values of the various factors discussed above, it can be concluded that the current practice of using test voltage withstand factors of 1.15 for switching and lightning impulse tests and 1.2 for steep-front impulse test should also be acceptable.

With thyristor valves having voltage breakover (VBO) protective firing in the forward direction, there is some question whether testing with the test voltage levels derived as described above is meaningful in demonstrating the voltage withstand capability of the valve in the forward direction. Protective firing will become active before the valve is subjected to the full voltage. Also, there is no demonstration of the variability of the level for protective firing or the margin between the valve withstand voltage in the forward direction and the protective firing levels. For these reasons, if it is practical, it is desirable to apply the full test voltage or at voltage 15% above the protective firing level in the forward direction with the protective firing disabled. However, depending on the valve design, VBO protective firing could be such an integral part of the valve design that it may not be practical to test the valve in this manner. In such cases, the test with VBO protective firing disabled is not recommended.

The above discussion of the selection of test voltage levels is not intended for an MVU. Instead, the test levels for an MVU are based on insulation coordination for the entire valve group of which the MVU is a part.

Another factor that should be taken into consideration for the valve base and MVU tests of air-insulated valves is the dependence of the dielectric strength of air on ambient air density. To account for the difference in the ambient air densities of the test location and the converter station where the valves are to be used, adjustments may have to be made to the test voltages. The necessary correction factor can be derived from IEEE Std 4-1995 .[3]

## 5.5 Wet type tests

For dc voltage and switching impulse tests on liquid-cooled valves, wet tests in addition to dry tests are recommended. For this, the valve is tested with cooling liquid leak on one of the top modules of the valve stack. The actual location of the leak should be agreed upon between the supplier and the user. The rate of liquid leak shall be a minimum of 15 L/h. The liquid shall leak for 30 min before the test is conducted. The conductivity of the liquid shall be 5% higher than the maximum conductivity that would initiate a high-conductivity alarm.

## 5.6 Criteria for successful type testing

The design of converter valves allows for a certain number of thyristor failures in the valves during operation of the converters in an HVDC system. This is based on industry experience that, despite any degree of care in the selection of thyristor units, it is not feasible to avoid some random failures. Even though these failures may be stress-related, they are considered random to the extent that the cause of failure or the relationship between failure rate and stress cannot be predicted or is not amenable for precise quantitative definition. This concept of random failures is based on the assumption that such failures would be rare and would not show any pattern that is indicative of inadequate design.

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

The valves are provided with redundant thyristor levels to prevent disruption of the operation of the converters by such random failures.

During type testing, a valve is subjected to stresses generally corresponding to the worst stresses it is likely to experience in its lifetime. The integrity of the valve is maintained during service by periodic replacement of failed thyristors and other components. In view of the above, and for reasons of economy in testing, the criteria for successful type testing could permit the failure of a small specified number of thyristor levels without lowering the standard of testing.

If, following a type test, more than 1% of thyristor levels in a complete valve has become short-circuited, then the valve shall be deemed to have failed the type tests.

If, during a type test, there has been thyristor-level failure of not more than 1% of the thyristor levels in a complete valve, the failed thyristor level(s) shall be restored and the type test repeated. If, on retest, further short circuits exceeding the 1% limit occur, or, if a failure occurs in the same location as previously, the valve shall be deemed to have failed type tests. If failures not exceeding the 1% limit occur in locations different from those failed thyristor level(s) in the previous type test, then the failed test level(s) shall be restored and the type test continued.

If the cumulative number of short-circuited thyristor levels during all type tests is more than 3% of the thyristor levels in a complete valve, then the valve shall be deemed to have failed the type test.

When type tests are performed on valve sections, the criteria for successful testing above also apply since the number of valve sections tested shall not be less than the number of sections in a complete valve. As in the case of type test on the complete valve, whenever thyristor-level failure occurs during one type test on any valve section, that type test shall be repeated with the failed thyristor level restored once to make sure that the failure is not location-specific. During the retest, if the failure occurs in the same location as in the previous test, or exceeds the 1% limit, the valve shall be deemed to have failed the type test.

The criteria discussed in this clause do not apply to the test of short-circuit current without subsequent blocking. Acceptable performance for this test, for partial discharge measurements, and for tests on valve structures are covered in the discussion of those tests in Clause 6.

At the completion of the test program, the valve and valve sections shall undergo a series of check tests, which shall include the following as a minimum:

a) Check for voltage withstand of thyristor levels in both forward and reverse directions
b) Check of the gating circuits
c) Check of the monitoring circuits
d) Check of the thyristor-level protection circuits by application of transient voltages above and below the protection settings
e) Check of the voltage grading circuits

Thyristor-level short circuits occurring during the check tests shall be counted as part of the 3% failure limit criteria for successful type tests defined above.

In addition to the permissible short-circuit levels specified above, the total number of thyristor levels exhibiting faults that do not result in thyristor-level short circuit, which are discovered during the type test program and the subsequent check tests, shall not exceed 3% of the series-connected thyristor levels in a complete valve.

In applying the 1% and 3% criteria to determine the permitted maximum number of short-circuit levels and the permitted maximum number of levels with faults that did not result in thyristor-level short circuit, it is the usual practice to round off all fractions to the next higher integer.

If the valve fails the type test, any subsequent testing should be based on a review of the causes of failures and their impact in relation to the valve design and test procedures and the criteria for subsequent testing should be agreed upon by the purchaser and the supplier.

## 5.7 Suitability of valve for type test

Care must be taken to ensure that “type tests” are really type tests on a representative valve and not on a valve made up of units that have gone through a special screening process to which the rest of the production units may not be subjected. For example, this could happen, possibly quite unintentionally on the part of the supplier, if the valve to be used for type tests was subjected to extensive tests before the tests required by the purchaser, and many units that failed during those tests were replaced.

For type tests on one valve and the batch of thyristors making up that valve, the presumption is that they are representative of all the valves that are not tested. Excessive replacement of failed thyristor units in the test valve always runs the risk of the valve being subjected to a process of weeding out of “bad” units. The question arises as to when a test valve should be considered to have had so many replacements that it is no longer suitable as a test valve. A similar question arises when a valve has failed type tests and the whole series of type tests have to be repeated. As a general rule, the recommended practice is to replace the whole batch of thyristors in a test valve when the total number of failures due to different causes exceeds the number of redundant thyristors.

## 5.8 Partial discharge measurements

### 5.8.1 Measurement of partial discharge

The quality of insulation in the valve support between highest potential valve and earth and between valve terminals shall be checked during the ac and dc voltage tests by measurement of partial discharges. Present experience in the application of HVDC valves shows that other techniques such as radio interference voltage (RIV) measurements are less indicative for the given purpose.

Partial discharge measurements shall be made in accordance with IEC 270 (1981).

### 5.8.2 Partial discharge during ac tests

The sensitivity of the partial discharge measurement for ac voltage depends on the capacitance of the test object and the magnitude of the background noise. In most valves the capacitance between the valve terminals is large (mainly due to the presence of the damping capacitors) compared to stray capacitance between the terminals for other equipments. Typical values for thyristor valves are in hundreds of nanofarads, and, for other equipment they are in tens of picofarads. Consequently, special measurement techniques may be necessary to fulfill the objectives of the test.

For this reason, and also because the ac dielectric test on a complete valve or valve base does not stress all components (e.g., damping resistors, saturable reactors, etc.), it is recommended that the partial discharge measurement be performed on all critical components or subassemblies as identified by the manufacturer. The purpose of partial discharge measurements on a complete valve during the dielectric tests is then to verify that there are no adverse interactions between individual components or high levels of partial discharge to air. The maximum value of partial discharge for a complete valve or valve base during ac tests shall be 200 pC provided that the valve is air-insulated and partial discharge of the critical components is within their own individual limits as demonstrated by the component test.

If the valve is not air-insulated, the value for partial discharge measured on a complete valve is subject to agreement between purchaser and supplier.

### 5.8.3 Partial discharge during dc tests

There is no generally accepted method for the determination of the partial discharge magnitude during tests with direct voltage. Dielectric stresses under steady state dc conditions are determined by the resistivity of the insulating material rather than by the dielectric constant. Due to the high value of the resistivity, the time constant of the system is rather long; therefore, partial discharges under dc conditions tend to be characterized by pulses of relatively high amplitude (hundreds to thousands of picocoulombs) at low repetition rates (seconds to minutes).

In the present case, the quality of insulation during tests with direct voltage is checked by counting the number of partial discharges per unit of time that exceed the specified levels. This means that, in general, test circuits and measuring instruments used with alternating voltages may also be used with direct voltages, with the addition of a multilevel pulse counting device. The dc voltage test levels and durations, together with the acceptance limits for partial discharge given in this recommended practice are based on the following considerations:

a) Expected service stresses, both in normal operation and during faults.
b) Previous service and test experience.
c) Recognition that thyristor valves contain many different dielectric materials, which have time constants spanning the whole range of likely values.
d) Recognition that tests of shorter duration with higher test safety factors will unrepresentatively overstress those valve components with short time constants.
e) Recognition that the magnitude of partial discharges and number per period of time when using positive polarity is significantly higher than when using negative polarity.
f) Recognition that, following initial application of opposite polarity, a larger amount of partial discharge than that occurring during steady-state dc voltage stress can be expected. The value of partial discharge versus time after selection of opposite polarity should decrease.

## 5.9 Valve insensitivity to electromagnetic interference

### 5.9.1 General

The principal objective is to demonstrate the sensitivity of the valve to the EMI arising from voltage and current transients generated within the valve and imposed on it from the outside. The sensitive elements of the valve are generally electronic circuits used for triggering, protection, and monitoring of the thyristor levels.

Generally, the valve insensitivity to EMI can be checked by monitoring the valve during other type tests. Of these, the valve impulse tests and the valve nonperiodic firing test are the most important.

The tests should demonstrate that the following are true, both in normal operation and during transients:

a) Out-of-sequence or spurious triggering of thyristors does not occur.
b) The electromagnetic protection circuits installed in the valve operate as intended.
c) False indication of thyristor-level faults or the sending of erroneous signals to the converter control and protection system by the valve base electronics, arising from receipt of corrupt data from the valve-monitoring circuits, does not occur.

Valve sensitivity to EMI applies only to the thyristor valve and that part of the signal transmission system that connects the valve to earth. It does not include tests to check the immunity of equipment located at earth potential nor characterization of the valve with respect to its behavior as a source of EMI for other equipment.

### 5.9.2 Test approach

The first approach is to simulate the source of EMI directly as part of a test setup. Such a test setup may require more than one valve in order to check for interaction between them. The geometric arrangements of the source of EMI with respect to the valve under test shall be as close as possible to the service arrangement (or worse from an EMI point of view).

The second approach is to determine the intensity of electromagnetic fields under worst operational conditions, either from theoretical considerations or by measurements. In a second step, these fields are simulated by a test circuit that generates correct (or worse) electromagnetic radiation at the respective frequencies. A valve or valve section is then exposed to this test source.

An essential prerequisite for the second approach is the determination of the field strength and direction at key locations in the valve; this can generally be obtained from search coil measurements taken during firing tests on a single valve. Alternatively, the field can be predicted from three-dimensional field-modeling programs. A valve section shall then be tested using a separate field coil to produce field intensity, frequency, and direction that are at least as severe as the predicted values.

The following conditions for the valve section under test should be met:

a) The valve section should have operational voltage (proportionally scaled) between its terminals and be forward biased at the time of energization of the field coil.
b) The electronics of the valve section under test should be energized.
c) Those parts of the valve base electronics that are necessary for the proper exchange of information with the valve section should be included.

### 5.10 Test sequence

Partial discharge measurements are intended to check the dielectric integrity of the valve. In order to verify that the dielectric tests have not impaired the valve insulation, the recommended practice is to conduct the tests involving partial discharge measurements, the dc voltage test (dry) and the ac voltage test, at the end of the dielectric tests. An exception may be made in the case of wet type tests. The wet type test could be conducted as the last dielectric test. In case of such an exception, partial discharge measurements at the maximum operating ac voltage should be made on the valve after it has been dried out. The rest of the dielectric tests may be carried out in any order to suit the convenience of the supplier.

The criteria for successful test for the short-circuit current without subsequent blocking test is less stringent than the criteria for other operational tests. Therefore, the preferred procedure would be to conduct this test at the end of the operational tests.

## 6. Test program

Most of the tests described in this clause are based on standard wave shapes and standard test procedures as developed for the testing of high-voltage ac systems and components. This approach offers great advantages to the industry because it allows much of the existing technology of high-voltage testing to be carried over to the qualification of HVDC converter valves.

### 6.1 Dielectric tests on valve base

The tests specified in this subsection apply to that part of a valve that constitutes the valve base as defined in 3.9. The tests are intended to verify the electrical design of the valve base (including ducts or pipes for the cooling medium, light guides, etc., within the valve base, etc.) for various types of overvoltages (dc, power frequency ac, switching impulse, lightning impulse, and steep-front impulse voltages). The tests should demonstrate the following:

a) Sufficient internal insulation has been provided to enable the valve base to withstand the specified test voltages.
b) Partial discharges will not occur under normal conditions and any such discharges under high-overvoltage conditions are within safe limits, to be defined for each particular design.

For all tests on a valve base given in this subsection, the highest voltage and the lowest voltage dc terminals of an MVU (or a valve, as the case may be) should be connected together and the test voltage then applied between the connected main dc terminals of the unit and ground.

Depending upon the application, it may be possible to eliminate some of the tests on the valve base described in 6.1.1 to 6.1.5.

For all ac and dc dielectric tests, the high-voltage terminal shall be grounded for a minimum of 2 h to minimize electrical charges on insulating material before conducting the tests. This is to prevent objectionable precharging of the test object.

### 6.1.1 Valve base dc voltage test

A dc test voltage $V_{\mathrm{tdb}}$ is applied for the specified time duration between the main dc terminals of the unit connected together and the ground.

$$V_{\mathrm{tdb}} = k_{\mathrm{db}} \times V_{\mathrm{dmb}} \times K_d \tag{4}$$

where

$V_{\mathrm{dmb}}$ is the maximum value of operating direct voltage appearing across the valve base;
$K_{\mathrm{d}}$ is the air density factor;
$k_{\mathrm{db}}$ is 1.6 for 1-min test, and $k_{\mathrm{db}}$ is 1.3 for 3-h test.

Starting from a voltage no higher than 50% of the maximum test voltage, the voltage shall be raised within 10 s to the 1-min test voltage, kept constant for 1 min, and then reduced to the specified 3-h test voltage, kept constant for 3 h, and then reduced to zero.

During the last hour of the specified 3-h test, the number of partial discharges should be recorded. The number of pulses exceeding 300 pC should not exceed 15 pulses/min averaged over the recording period. Of these, no more than 7 pulses/min should exceed 500 pC, no more than 3 pulses/min should exceed 1000 pC, and no more than 1 pulse/min should exceed 2000 pC.

If an increasing trend in the rate of partial discharges is observed, the test duration may be extended by mutual agreement between purchaser and supplier.

The above tests should be conducted for both polarities of voltage.

### 6.1.2 Valve base ac voltage test

An ac test voltage $V_{\mathrm{tab}}$ is applied for the specified duration between the main dc terminals of the unit and ground.

$$V_{\mathrm{tab}} = k_{\mathrm{ab}} \times \left(\frac{V_{\mathrm{mb}}}{\sqrt{2}}\right) \times K_d \tag{5}$$

where

$V_{mb}$ is the peak value of the maximum repetitive operating voltage appearing across the valve base, including temporary overvoltages and commutation overshoot;
$K_d$ is the air density factor.

Following general power industry practices for ac voltage tests on insulation, typical values for $k_{ab}$ are 1.3 for the 1-min test and 1.15 for the 30-min test.

Starting from a voltage no higher than 50% of the maximum test voltage, the voltage should be raised within 10 s to the 1-min test voltage, kept constant for 1 min, and then reduced to the specified 30-min test voltage, kept constant for 30 min, and then reduced to zero.

During the specified 30-min test, the level of partial discharge should be monitored. The value should not exceed 200 pC.

### 6.1.3 Valve base switching impulse test

The switching impulse test voltage is applied between the main dc terminals of the unit connected together and ground.

a) *Peak voltage*. The peak voltage should be the guaranteed switching impulse insulation level of the valve base according to the insulation coordination of the HVDC converter station.
b) *Wave shape*. The test voltage should be applied with a 200- to 300-μ*s* rise time and a 2000- to 3000-μs decay to 50% of the peak voltage.
c) *Minimum number of shots*. The switching impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.

### 6.1.4 Valve base lightning impulse test

The lightning impulse test voltage is applied between the main dc terminals of the unit connected together and ground.

a) *Peak voltage*. The peak voltage should be the guaranteed basic impulse level (BIL) of the valve base according to the insulation coordination of the HVDC converter station.
b) *Wave shape*. The test voltage should be applied with a 1.2-μs rise time and a 50-μs decay to 50% of the peak voltage.
c) *Minimum number of shots*. The lightening impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.

### 6.1.5 Valve base steep-front impulse test

The steep-front impulse test voltage is applied between the main dc terminals of the unit connected together and ground.

a) *Peak voltage*. The peak voltage should be the guaranteed insulation level of the valve base for steep-front impulse voltages according to the insulation coordination of the HVDC converter station.
b) *Wave shape*. The test wave front should be not less than 1200 kV/μs. A longer front time may be acceptable if it can be demonstrated that steep-front impulse voltages with such short fronts cannot occur in service on the valve base.

At low test voltage levels, it may not be practical to obtain such fast-fronted test voltages. For such cases, the test may be modified.

## 6.2 Dielectric tests on an MVU

These tests are intended to verify the design with respect to the dielectric capability of the structure of an MVU. In general, the precise definition of valve structure will depend on the particular valve design. These tests should be carried out unless the dielectric capability of the structure has been demonstrated by other means (e.g., prior test results).

These tests may be carried out at room temperature unless the dielectric properties of the materials are known to exhibit significant temperature dependence over the expected operating temperature range.

Internal components of the MVU may be simulated or omitted from the test if this does not reduce the significance of the results. If any device external to the MVU structure is necessary for proper application of the stress on the structure during tests, it should also be included or simulated in the test.

The tests should be performed on an MVU with appropriate portions of the unit short-circuited as necessary to simulate maximum service stress conditions. Ground shields are to be suitably arranged around the unit to simulate the effects of nearby building steel grounding rods, and any other structure which influences the stray capacitance to ground of the test unit.

There is a potential for spurious triggering of the valve caused by coupling of impulse wave fronts into the thyristor gate circuits. However, any attempt to deduce such effects from the MVU tests may not be practical.

### 6.2.1 MVU dc voltage test

This test is used to demonstrate that the valve structure is free from audible or visible corona and free from disruptive discharge at the dc test voltage level. The partial discharge inception and extinction voltages should be above rated dc voltage to ground of the specific converter unit. The dc test voltage $V_{\mathrm{tds}}$ is applied between the high-voltage dc terminal of the MVU and ground. Care should be taken to suitably terminate the low-voltage dc terminal of the MVU to correctly simulate the voltage on the MVU base.

Tests with one of the polarities may be deleted if it can be established that the MVU will not be subjected to voltage of that polarity. The test voltage, $V_{\mathrm{tds}}$, should be

$V_{\mathrm{tds}} = k_{\mathrm{ds}} \times$ [the rated dc voltage to ground at the high-voltage terminal of the specific converter unit]

For air-insulated valves, $k_{\mathrm{ds}} = 1.3$; test duration = 30 min. For liquid- or gas-insulated valves, the test voltage level and the duration of the test are to be suitably chosen and should consider the characteristics of the insulation medium.

### 6.2.2 MVU switching impulse voltage test

The test voltage is applied between the high-voltage terminal and the low-voltage terminal of the MVU.

a) *Peak voltage*. The peak voltage should be the specified switching impulse insulation level of the MVU as determined by insulation coordination.
b) *Wave shape*. The test voltage should be applied with a 200- to 300-µs rise time and a 2000- to 3000-µs decay to 50% of the peak voltage.
c) *Minimum number of shots*. The switching impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.

### 6.2.3 MVU lightning impulse voltage test

Test conditions are the same as for the MVU switching impulse voltage test, described in 6.2.2.

a) *Peak voltage*. The peak voltage specified should be the specified BIL of the MVU as determined by insulation coordination.
b) *Wave shape*. The test voltage should be applied with a 1.2-µs rise time and a 50-µs decay to 50% of the peak voltage.
a) *Minimum number of shots*. The lightning impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.

### 6.2.4 MVU steep-front impulse voltage test

Test conditions are the same as for the MVU switching impulse voltage test, described in 6.2.2.

a) *Peak voltage.* The peak voltage should be the specified steep-front impulse insulation level of the MVU as determined by insulation coordination.
b) *Wave shape.* The test wave front should not be less than 1200 kV/µs. A longer front time may be used or the test may be omitted if it can be demonstrated to the satisfaction of the purchaser that impulse voltages with such steep fronts cannot occur in service on the MVU. Initial rate of decay is expected to be of the same order as the rate of rise.

## 6.3 Dielectric tests on a valve

These tests are intended to verify the design of the valve regarding its voltage-related characteristics for various types of overvoltages (dc, power frequency, ac, switching impulse, lightning impulse, and steep-front impulse overvoltages). The tests should demonstrate the following:

a) The valve will withstand the specified overvoltages.
b) Any internal overvoltage protective circuits are effective.
c) Partial discharges will not occur under any continuous operating conditions and any such discharges under high overvoltage conditions are within permissible limits.
d) The internal grading and damping circuits have sufficient rating.
e) The voltage distribution within the valve under various types of overvoltages is consistent with the modular concept of the valve design.
f) The gating circuits are immune to interference due to impulse overvoltages, and they function correctly.
g) The valve can be fired from specified high-overvoltage conditions without damage.

The complete “valve” assembly, with all thyristor levels in place but with the surge arresters disconnected, is subjected to the tests. When the valve is mounted, all peripherals required for operation of the valve (e.g., reactors) are included, so that all in-service conditions corresponding to the valve locations are correctly represented. The valve electronics are energized during the tests. All thyristor levels are checked before and after each test sequence. The test is considered successful if it meets the criteria for successful type testing (see 5.6).

Voltage measurements should be made across valve modules within the valve to determine the internal voltage distribution of the valve at power frequency for use in operational test on modules. If the valve sections used for operational tests are not made up of full modules, it will be necessary to determine the voltage distribution among thyristor levels within the modules. These measurements may be made at an appropriate voltage level to provide voltage distribution corresponding to that expected for the full test voltage. A typical level may be 25% of the full test voltage. The ratio of the highest voltage across a module to the average voltage across the modules is designated as the Voltage Distribution Factor.

### 6.3.1 Valve dc voltage test

The magnitude and duration of the maximum direct voltage that a valve can be subjected to in actual service has been a matter of considerable controversy. Early investigations indicated the possibility that a direct voltage of up to 1.8 V per unit might occur in unusual circumstances; but many others doubt that such an overvoltage can be sustained for a long enough time to be classified as a “direct” voltage.

a) *Waveform.* The voltage to which a valve is subjected during converter operation is a composite voltage consisting of an average value dc voltage component plus a superimposed ac voltage component. It is not economically practical to reproduce these voltages with composite ac-dc waveforms in the test laboratories. Therefore, it is necessary to choose a dc test voltage level that will be representative of the actual dc stress on the valve, but, at the same time, will not impose an unreasonable power dissipation requirement on the valve during the test. Consequently, the test value of the dc voltage should be established on a case-by-case basis. In general, however, the test voltages given below will be adequate for most actual situations.

b) *Test voltage.*

$$V_{\mathrm{tdv}} = K_{\mathrm{dv}} \times V_d \tag{6}$$

where

$V_{\mathrm{d}}$ is the rated maximum continuous bridge dc voltage;

$k_{\mathrm{dv}}$ is a factor that takes into account the expected maximum dc voltage on a valve and a reasonable safety margin.

c) *Duration of test.* The duration of the test is 1 min for the higher and 3 h for the lower value of $\mathrm{k}_{\mathrm{dv}}$.

A typical higher value for $k_{\mathrm{dv}}$ is 1.6. However, the value of $k_{\mathrm{dv}}$ should be examined for each application and adjusted as necessary. Similarly, the 1-min test duration should also be examined for relevance to the test. It is known that the dc test voltage may thermally stress the dc grading components of the valve to unrealistic levels during this test. In such cases, a shorter time duration for the test should be considered, except that if the duration of the test is less than 15 s, it may be necessary to increase the test voltage in order to achieve a realistic dielectric stress.

The test voltage $V_{\mathrm{tdv}}$ is applied across the main terminals of the valve. The test is conducted with voltages of both polarities. Starting from a voltage no higher than 50% $V_{\mathrm{tdv}}$, the voltage is raised within 10 s to the test level, kept constant for the test duration period (i.e., 1 min or less as agreed by purchaser and supplier) and then reduced to 0.8 $\mathrm{V}_{\mathrm{d}}$ and held there for 3 h for dry test. If visible or audible corona occurs below or at the specified 1-min test voltage, the inception and extinction voltages shall be recorded.

During the final hour of 3 h of dry test with 0.8 $V_{\mathrm{d}}$, partial discharge measurements should be made. The number of pulses exceeding 300 pC should not exceed 15 pulses/min averaged over the recording period. Of these no more than 7 pulses/min shall exceed 500 pC, no more than 3 pulses/min shall exceed 1000 pC, and no more than 1 pulse/min shall exceed 2000 pC.

If an increasing trend in the rate of partial discharges is observed, the test duration may be extended by mutual agreement between purchaser and supplier.

The tests should be carried out at both polarities of voltage.

The test as described above is conducted on a dry valve first. The test is repeated under wet conditions as described in 5.5. For the wet test, the duration of the test at 0.8 $V_{\mathrm{d}}$ is only for 5 min.

### 6.3.2 Valve ac voltage test

The repetitive voltage stress imposed on an HVDC valve is not symmetrical about zero voltage. Instead, the maximum negative voltage stress occurs when the valve is operating at maximum ac voltage and with a firing angle plus overlap angle at about 90°, whereas the maximum positive voltage occurs during inverter operation when the firing angle plus overlap angle is about 135°. Moreover, the maximum negative commutation spike is always greater than the maximum positive spike. Thus, the problem is to find a suitable ac voltage test that adequately stresses the valve in the reverse direction without overstressing the valve in the forward direction. There are several approaches to this problem. The simplest approach is to apply power frequency ac voltage with a peak magnitude equal to the line-to-line ac valve voltage, including dynamic overvoltages (DOV) plus either 50% of the negative commutation spike or 100% of the positive commutation spike. It is recognized that this test gives a negative peak voltage somewhat less than the actual duty, but the switching surge test will give additional information for this wave shape. Typically, the duration of this test would be 15 s.

Some valve applications may have very high values of DOV for short periods of time. In these cases, an alternative test procedure is appropriate: A long-term (30-min) test at maximum continuous operating conditions (maximum continuous voltage, maximum continuous commutation overshoot, and maximum continuous delay angle without the effect of the DOV) plus a short-term test to last approximately twice the duration of the DOV, with DOV, commutation overshoots, and firing angles appropriate to DOV conditions.

Thus, the test voltage $V_{tav}$ will be

$$V_{tav} = V_{vmax(rms)} \times f_{dov} \times f_{com} \times \{1 + \sqrt{[K^2_{tp} + K^2_{fme} + K^2_{mev} + K^2_{ttv}]}\} \tag{7}$$

where

| | |
|---|---|
| $V_{vmax(rms)}$ | is the rms value of the maximum no-load phase-to-phase voltage on the valve side of the converter transformer; |
| $f_{dov}$ | is the maximum DOV per unit of $V_{vmax(rms)}$ that can occur on the system that leaves the valve conducting; |
| $f_{com}$ | is 50% of the maximum commutation overshoot in the reverse direction based upon the sum of firing angle and overlap angle equal to 90°, i.e., ($a + u = 90°$) and at maximum DOV, but not less than 100% of the commutation overshoot in the forward direction for maximum DOV; |
| $K_{tp}$ | is the allowance for load tap changer position being off by one step, typically, 0.02 or less; |
| $K_{fme}$ | is the margin for field measurement error, typically, 0.05; |
| $K_{mev}$ and $K_{ttv}$ | are as described in 5.4. |

The test voltage is applied across the main terminal of the valve. Starting from a voltage no higher than 50% $V_{tav}$, the voltage is raised steadily to $V_{tav}$ within 10 s, kept constant for twice the time specified for maximum DOV, then reduced to the value of $V_{tav}$ without considering DOV ($f_{dov} = 1.0$) for a period of 30 min, and then reduced to zero.

During the last 10 min of the 30-min test period, partial discharge measurements should be made. See 5.8 for details.

### 6.3.3 Valve switching impulse voltage test

The tests are conducted with the valve in dry conditions and, if the valve is liquid cooled, in wet conditions also. The switching impulse test is carried out with the valve electronics energized. For valve designs where the power supply to the valve electronics is derived from the main power circuit within the valve, the switching impulse test voltages may be applied either on a precharged valve or superimposed on a power frequency voltage of the minimum magnitude at which the valve is required to function properly. The timing of the application of the test voltage with respect to the power frequency voltage is dependent on the valve design and should be agreed upon by purchaser and supplier.

a) *Test voltage.* The impulse test withstand level as described in 5.4 should be used.
b) *Wave shape.* The test voltage should be applied with a 200- to 300-µs rise time and a 2000- to 3000-µs decay to 50% of the peak voltage.
c) *Minimum number of shots*. The switching impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.

Where forced firing in the forward direction is provided to self-protect the valve, this mechanism must be demonstrated during the test. When fired in this manner, the valve must be made to discharge energy equivalent to that imposed in service. If the valve incorporates protective firing against overvoltages in the forward direction, three further applications of positive switching impulses of a specified amplitude, such that the valve does not fire, must be made.

### 6.3.4 Valve lightning impulse voltage test

This test is performed in a manner similar to that for the valve switching impulse voltage test:

a) *Test voltage.* The impulse test withstand as described in 5.4 should be used.
b) *Wave shape.* The test voltage should be applied with a 1.2-µs rise time and a 50-µs decay to 50% of the peak voltage.
c) *Minimum number of shots*. The lightning impulse test should be applied five times with a positive polarity with respect to ground, and five times with a negative polarity with respect to ground.
d) *Valve temperature.* See 5.2.

The lightning impulse test is carried out with the valve electronics energized. Conditions for demonstration of forced firing (if it is expected to occur under lightning impulse overvoltage conditions) are the same as for the switching impulse test described in 6.3.3.

### 6.3.5 Valve steep-front impulse voltage test

This test is performed similarly to the valve lightning impulse voltage test.

a) *Test voltage.*The impulse withstand test withstand level described in 5.4 should be used.
b) *Wave shape.* Front at the rate of 1200 kV/µs unless calculated to be different for the particular system. Initial rate of decay is expected to be of the same order as the rate of rise.

Conditions regarding valve temperature, valve electronics, and demonstration of protective firing in the forward direction are the same as for the valve lightning impulse voltage test described in 6.3.4.

### 6.3.6 Nonperiodic firing test

The main objective of this test is to demonstrate that the thyristors and associated electric circuits are capable of withstanding the voltage and current stresses imposed on them at turn-on, when the thyristors are fired through the normal gating at the highest voltage that occurs in service. The highest voltage on the thyristors generally occurs during switching impulse overvoltages. The nonperiodic firing test is therefore performed with a voltage wave shape as defined in 6.3.3.

The valve voltage at firing shall be the lower of

a) The switching impulse protection level of the arrester
b) The protective firing level of the valve

If the valve is triggered by protective firing, then the test shall be repeated with the redundant thyristor levels operational. If the valve still triggers by protective firing below the switching impulse protective level, the test shall again be repeated with the impulse level reduced to just below the protective firing threshold and the valve triggered by normal firing circuits.

The valve should be fired at the peak of the switching impulse test voltage, or at a voltage level just below the protective firing level if protective firing for switching impulse is provided. Refer to 5.2 regarding the temperature conditions of the valve for the test. The minimum number of shots should be five.

The nonperiodic firing test may also be used to test to a limited extent the immunity of the adjacent valves in an MVU to EMI. In addition to the test valve, an auxiliary valve (or sufficient portion thereof) should be included in the test. This auxiliary valve is the test object as far as the demonstration of immunity to EMI by coupling is concerned. The EMI test object must have operational voltage between its terminals and be forward-biased at the triggering instant of the valve subjected to nonperiodic firing. The electronics of the EMI test object should be energized. Those parts of the valve base electronics that are necessary to the proper exchange of information with the EMI test object should be included.

### 6.3.7 Turn-on stress test

Object of this test is to demonstrate that the valve can withstand without damage the high rate of rise of current that could occur if the current through the valve arrester during arrester operation is transferred to the valve. The magnitude and rate of change of current are determined by insulation coordination study. Digital simulation of the phenomena would be helpful in establishing the current stresses for this test. This test need not be carried out if the nonperiodic firing test discussed in 6.3.6 subjects the valve to turn-on stresses not less than that determined by the insulation coordination study. Otherwise, this test is conducted in one of the following two methods:

a) A capacitor of suitable value is connected across the whole valve, and the valve is fired after the capacitor has been charged to the impulse voltage test levels. The value of the capacitor is so chosen as to provide di/dt stresses not less than those established by the insulation coordination study. The minimum number of shots is 5.
b) The test is conducted on valve sections made up of one or more modules with prorated arrester across them. With the valves blocked, a voltage is applied to make the arrester conduct and then, the valve section is fired to transfer the current to the valve. The minimum number of shots is 3 per valve section.

## 6.4 Operational tests on modules

These tests are intended to verify the design of the valve regarding its performance under normal operating conditions, abnormal operating conditions, and transient fault conditions. As discussed in 5.1, these tests are conducted on valve sections.

The 6-pulse, back-to-back connected converter circuit is the preferred test circuit for operational tests. For those valve designs where this could result in very high testing costs, consideration should be given to alternative proven test circuits. Subject to the approval by the purchaser, a synthetic test circuit that can accurately reproduce the pertinent thyristor stresses can be used in place of the 6-pulse, back-to-back connected circuit.

To get correct voltage waveforms and stresses as are obtained in service, it is important that the total stray capacitance associated with the valve and the inductances contributing to the commutation reactance be properly represented in the test circuit. The cooling conditions (i.e., flow and temperature of the cooling medium) must be identical with the conditions of the complete valve. If the temperature of the cooling medium is different for different modules within the valve, the highest temperature obtained is used.

### 6.4.1 Load test and periodic firing and extinction test

The purpose of this test is to verify the design of the valves by demonstrating the correct operation of the modules in the valve under the worst operating conditions without loss or degradation of the thyristors or auxiliary circuits.

The dc system may have different maximum continuous current ratings for different firing angles. An evaluation should be made of the different angle-dependent current ratings to determine the worst cases in terms of stresses to the thyristors and the snubber circuits. The recommended practice is to carry out the tests at two sets of values of firing angle and direct current—one at the normal firing angle and its corresponding rated current, and another at the maximum firing angle and its corresponding continuous current rating. If the evaluation of different operating conditions shows any other continuous operating condition with higher stresses, additional tests may be carried out for that condition.

In terms of the rated current, $I_\mathrm{d}$ the test direct current $I_\mathrm{dt}$ should be

$$I_\mathrm{dt} = I_d \times \sqrt{[K^2{}_\mathrm{fie} + K^2{}_\mathrm{mei} + K^2{}_\mathrm{tii}]} \tag{8}$$

where

$K_{fie}$ is the margin for field measurement error, typically, 0.05;
$K_{mei}$ is the margin for test measurement error for current similar to $K_{mev}$ for voltage measurement error discussed in 5.4;
$K_{tti}$ is the margin for tolerance for test values for current similar to $K_{ttv}$ for test voltage tolerance discussed in 5.4.

The applied voltage should be the prorated value for the valve section increased upward by the redundancy factor (see 5.3), the Voltage Distribution Factor (see 6.3), the error in tap-changer position (see 6.3.2) and the field measurement error (see 6.3.2).

After the temperature of the cooling medium at the outlet has stabilized at the highest temperature obtained during continuous operation, the test should be conducted for 1 h at specified delay angle and direct current, and then continued at the same direct current but with increased delay angle slightly less than 90° for a period of at least two times the normal permissible operating time for the valve at 90° delay angle.

At the end of the load test, fault tolerance of the valve to continuous operation of the protective firing is demonstrated. One way of doing this is by operation of the valve section under the same test conditions as for the load test, but with firing pulses to one of the thyristor levels suppressed for a specified period of time. Consideration could be given to alternative method(s) of factory testing to demonstrate the continuous operation of protective firing. The duration of the test will depend on valve design and should be agreed upon by the purchaser and the supplier. However, when there is a specific time limit on continuous operation of protective firing, the duration of the test shall not be less than twice the time permitted for continuous protective firing. All necessary observations of voltages, currents, firing angles, temperatures and cooling medium flow are to be made to satisfy the objective of the test. Specifically, the temperatures of the hot spots of the following valve module components should be monitored:

a) Thyristor case (or heat sink, if appropriate)
b) Damping resistor, or its case, if it is jacketed
c) Valve reactor winding

The number of each component to be monitored should be agreed upon by the purchaser and the supplier. At least one component from each module should be monitored.

Furthermore, this test is used to demonstrate the behavior of the valve sections at periodically occurring combined voltage and current stresses at turn-on and turn-off. For this purpose, measurements are to be made as previously agreed upon by the purchaser and the supplier to do the following:

- Check the adequacy of the thyristors and associated electric circuits with regard to the current, voltage, and temperature stresses on the thyristors at turn-on under the worst repetitive stress conditions
- Demonstrate that no commutation failures occur at minimum repetitive voltage and extinction angle, at maximum temperature
- Demonstrate the magnitude of the commutation transients

The test should also be performed at the same applied voltage, 0.95 times the minimum allowable direct current and the maximum normal delay angle.

### 6.4.2 Current sharing test

This test is included in the test program only when the valve design involves parallel connection of thyristors. The purpose of the test is to demonstrate the proper sharing of current between parallel thyristors during steady-state and transient conditions. The test is successful when the imbalance in current sharing between paralleled thyristors does not exceed design values. This test should be performed in a test circuit agreed upon by the purchaser and the supplier.

This test can be omitted when the parallel thyristor assembly is treated as one unit in all respects, including calculation of thyristor failure rate.

### 6.4.3 Minimum alternating voltage

This test is used to demonstrate the proper functioning of the thyristor auxiliary power supply at the specified minimum alternating voltage condition. The test is conducted under the worst conditions of converter loading and firing angle corresponding to the minimum alternating voltage condition.

### 6.4.4 Intermittent dc test

This test is used to demonstrate the proper functioning of the valve firing system and the integrity of the valve when the direct current is discontinuous.

The starting conditions for the test are the same as for the load test. The direct current is adjusted to 1.05 times the maximum rated current initially, and is gradually reduced to the transition current, where the direct current becomes discontinuous, and then to near zero. If a load test is conducted at both the normal delay angle and some other maximum delay angle for continuous operation, this test also should be carried out for those two conditions.

### 6.4.5 Recovery period forward impulse voltage withstand test

This test is intended to demonstrate that the valve is adequately protected if a voltage transient in the forward direction occurs during the critical period of valve recovery immediately after the end of current conduction.

The valve sections are initially operated to provide the maximum steady-state junction temperature. Eight lightning impulses of wave shape as defined for valve lightning impulse test in 6.3.4, varying with point-on-wave, are applied, starting 100 µs after current zero and increasing in steps of 150 *m*s. The amplitude of the impulse voltages shall be such as to verify the following:

a) Up to the values of dV/dt and level specified for protective firing, the valve can withstand the surge or safely self-conduct without protective firing,
b) The protective firing operation is successful. (This would require the test to be conducted with and without protective firing.)

### 6.4.6 Short-circuit current with a subsequent blocking test

The purpose of this test is to demonstrate the maximum fault suppression capability of the thyristor valves. At the maximum temperature of the cooling medium, current is passed through the thyristors until the thyristor junction temperature reaches the maximum permissible value of steady-state current or temporary overload. With the firing angle equal to the minimum delay angle, a fault is applied to pass 1 pulse of maximum fault current with the correct fault wave shape (almost fully offset cosine wave) through the valve section. After the fault, the module must be able to withstand reapplication of forward voltage equal to the maximum overvoltage on load rejection consistent with the short-circuit current. The magnitude of the applied recovery voltage is the prorated valve section voltage adjusted upward by the redundancy factor, Voltage Distribution Factor, and the factors for field measurement error and incorrect transformer tap position.

In the case of ac systems having substantial difference between the minimum and maximum short-circuit levels, there could be a problem selecting the right values for the fault current and recovery voltage. The weak ac system condition gives lower value of fault current, but higher overvoltage on load rejection. The strong ac system gives higher fault current and lower overvoltage on load rejection. A conservative approach is to choose the fault current value corresponding to the strong ac system and the overvoltage value corresponding to the weak ac system. Should this cause unacceptably high stresses on the thyristors, the supplier could have the option to carry out the test on half the number of test valve sections for the weak ac system condition and test the other half of the test valve sections for the strong ac system conditions. If dividing the total number of valve sections into halves results in a fraction, the next higher integer number of valve sections should be tested under each system condition.

In the case of HVDC systems with long cables, the discharge of the cable into the valve in case of inverter faults could result in very high values of fault current. It is necessary to check whether the thyristor stresses for fault current under these conditions are more severe than the stresses due to the converter transformer phase-to-phase or neutral-to-ground fault. The fault current tests should be based on the most severe of these faults.

### 6.4.7 Short-circuit current without subsequent blocking test

The purpose of the test is to demonstrate the capability of the thyristor valve to survive the specified number of maximum surge fault current loops. The number of loops of current should be based on the circuit breaker operation terminating the short-circuit stress on the valve.

The short-circuit current test without subsequent blocking should demonstrate the fault tolerance capability of the valve. For most faults, the conditions for current suppression after the first loop are likely to exist; however, such conditions may not always prevail. For example, during the first loop period or immediately after the fault current has become zero, phase shift or transients in the ac system voltage could prevent the valve from having the required voltage across it to achieve successful current suppression after one loop. Therefore, there is a need for this test.

The presence of these conditions is considered such a rare occurrence that it is not believed necessary to apply the criteria for successful type testing (see 5.6) for this particular test. Instead, a failure rate corresponding to the loss of as many thyristor levels as is permissible for continued operation (e.g., the valve redundancy) is considered adequate. In special cases, the criteria may have to be reestablished, taking into consideration that the fault should not lead to loss of transmission capacity for an extended period.

The initial steady-state junction temperature of the thyristor of the test valve section should be the maximum that can be attained under all permissible loading conditions.

The test consists of applying the specified number of maximum surge fault current pulses. This test is generally considered successful if it is demonstrated to the satisfaction of the purchaser that the valve section withstood the test without degradation other than the thyristor-level failure rate specified above.

## 7. Presentation of test results

A well-presented informative report on the tests conducted on thyristor valves will be of great benefit to the utility purchasing an HVDC power transmission system. It provides the purchaser with a permanent record of the tests performed, and, in cases where some of the tests are not witnessed by the purchaser, the report is the only source of information readily available to the utility regarding the tests performed. To be useful to the purchaser, the test report should include the following:

a) General information (i.e., test title, type and rating of equipment tested, serial number, date of test, name of facility where the test was conducted)
b) Description, in relevant detail, of the major equipment in the test facility used for the test (i.e., impulse voltage generator, dc voltage generator)
c) Detailed information on the arrangement for each test, including a discussion of the instrumentation and monitoring procedures used
d) Tabulated results (i.e., photographs, oscillograms, traces, etc.) of the various tests with detailed remarks regarding all relevant incidents that occurred during the tests
e) Special reports on any equipment or component failure during the tests
f) Conclusions from the test program with recommendations, if any

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