

TECHNICAL REPORT

AMENDMENT 1

**Performance of high-voltage direct current (HVDC) systems with line-commutated converters –
Part 1: Steady-state conditions**



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**Performance of high-voltage direct current (HVDC) systems with line-commutated converters –
Part 1: Steady-state conditions**

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FOREWORD

This amendment has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this amendment is based on the following documents:

DTR	Report on voting
22F/277/DTR	22F/286A/RVC

Full information on the voting for the approval of this amendment can be found in the report on voting indicated in the above table.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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Replace, the titles of Clause 19 and its subclauses as follows:

- 19 Radio frequency interference
 - 19.1 General
 - 19.2 RFI from HVDC systems
 - 19.2.1 RFI sources
 - 19.2.2 RFI propagation
 - 19.2.3 RFI characteristics
 - 19.3 RFI performance specification
 - 19.3.1 RFI risk assessment
 - 19.3.2 Specification RFI limit and its verification
 - 19.3.3 Design aspects

Add the title of Annex A as follows:

Annex A (informative) Factors affecting reliability and availability of converter stations

Replace, in the list of figures, the title for Figure 23 as follows:

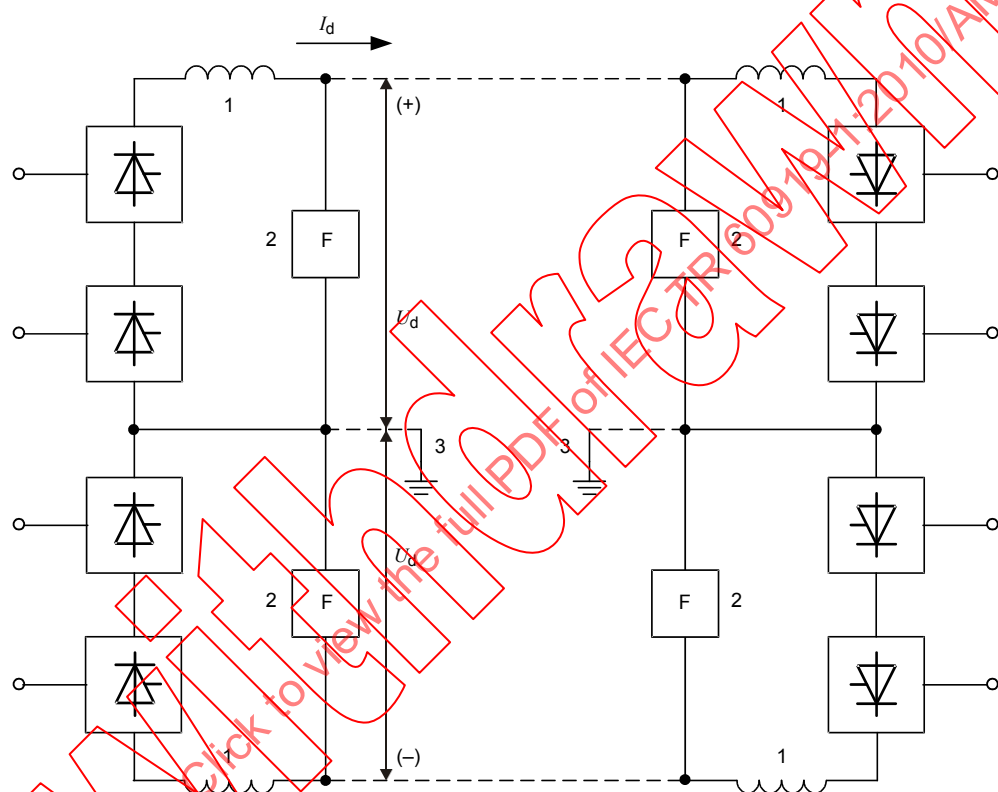
Figure 23 – RY COM noise meter results averaged – Typical plot of converter noise levels on the d.c. line corrected and normalized to 3 kHz bandwidth – 0 dBm = 1 mW corresponding to 0,775 V at a pole-to-pole surge impedance of 600 Ω

Add, in the list of figures, the title for Figure 25 as follows:

Figure 25 – Recommended measurement procedure with definition of measuring point

Figure 7 – Bipolar system

Replace Figure 7 by the following new figure:



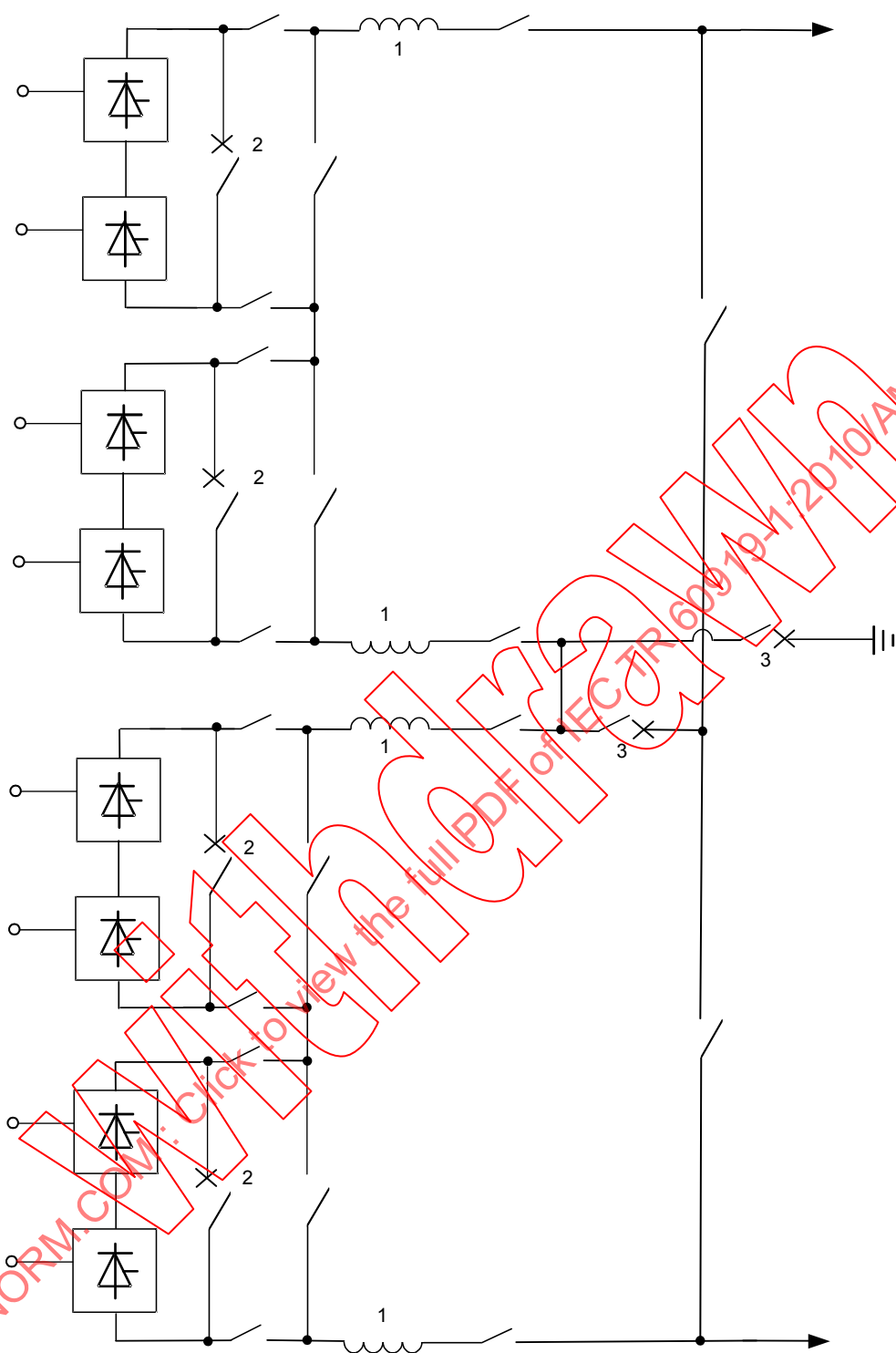
Key

- 1 DC reactor
- 2 DC filter
- 3 Earth electrodes

Figure 7 – Bipolar system

Figure 10 – Bipolar system with two 12-pulse units in series per pole

Replace Figure 10 by the following new figure:



IEC 808/13

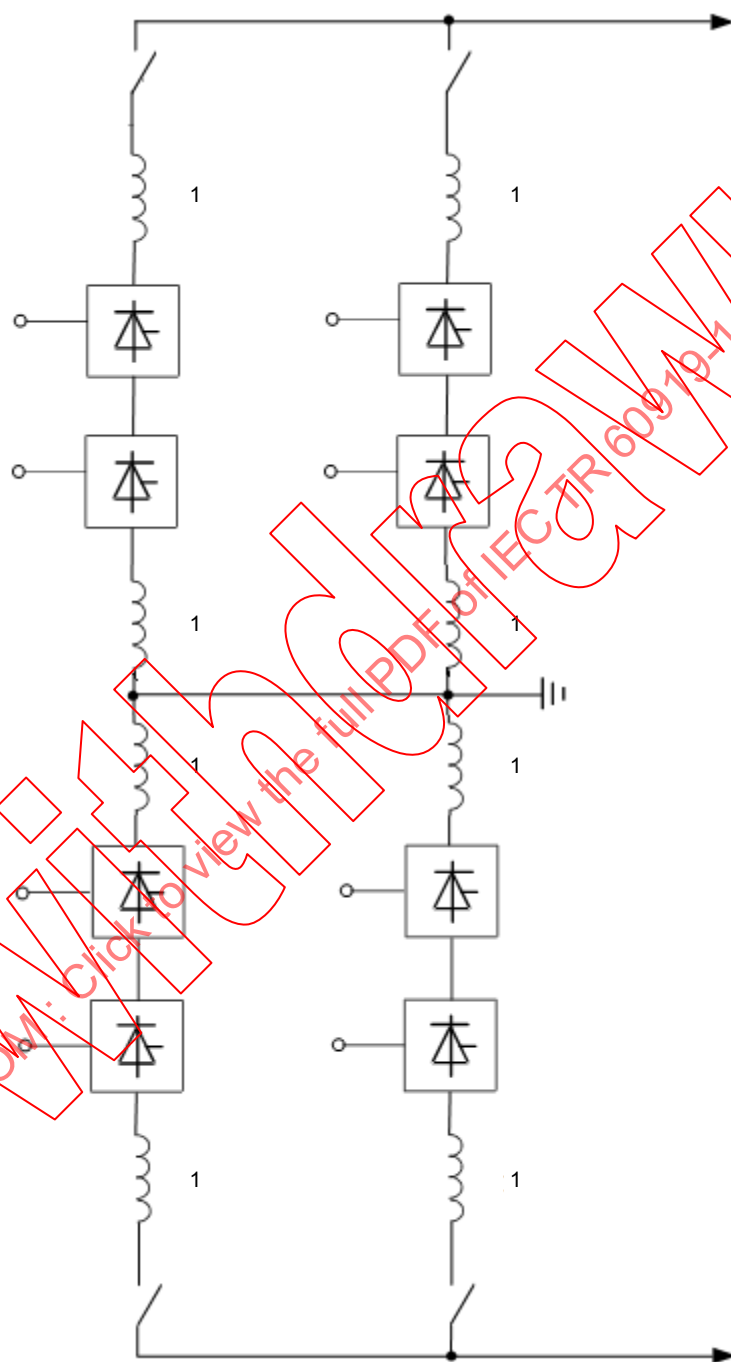
Key

- 1 DC reactor
- 2 By-pass switch
- 3 DC switch

Figure 10 – Bipolar system with two 12-pulse units in series per pole

Figure 11 – Bipolar system with two 12-pulse units in parallel per pole

Replace Figure 11 by the following new figure:



IEC 809/13

Key

1 DC reactor

Figure 11 – Bipolar system with two 12-pulse units in parallel per pole

10.2.2 Electrical parameters

Replace, in item 1) the words “100 Hz” by “two times of the fundamental frequency”.

Replace, in item 3) the words “100 kHz” by “two times of the fundamental frequency”.

11.1 General

Add, in the second paragraph after the second sentence ending “.... during the acceptance period of an HVDC system.” the following new sentence:

Please refer to Annex A for more information on factors affecting reliability and availability of converter stations.

13.6 Optical fibre telecommunication

Add the following new sentence at the end of the third paragraph:

Use of OPGW (optical ground wire) as one of shielding wire is another typical arrangement used in many overhead lines schemes.

18.1 General

Replace the third paragraph by the following new paragraph:

Field experience shows that thyristor valves generate about 10 dB to 15 dB less conducted noise interference than mercury arc valves.

18.2 Performance specification

Replace the fifth paragraph by the following new paragraph:

Where dBm is defined as a means of interference measurement in which 0 dB is specified to 1,0 mW, which corresponds to 0,775 V pole-to-pole interference voltage assuming a line to-line surge impedance of 600 Ω. In a 50 Ω cable on the low voltage side, 0 dBm and 1 mW corresponds to 0,224 V.

Add the following new sentence at the end of the sixth paragraph after “...should be evaluated”:

It should be considered that the cost for a broad band PLC filter is significantly higher than the cost for a narrow band PLC filter. Especially, filters for the lower frequencies 20 kHz to 50 kHz cost significantly more than PLC filters for higher frequencies.

Figure 23 – RY COM noise meter results averaged – Typical plot of converter noise levels on the d.c. line corrected and normalized to 3 kHz bandwidth – 0 dBm = 0,775 V

Replace the existing title of Figure 23 by the following new title:

Figure 23 – RY COM noise meter results averaged – Typical plot of converter noise levels on the d.c. line corrected and normalized to 3 kHz bandwidth – 0 dBm = 1 mW corresponding to 0,775 V at a pole-to-pole surge impedance of 600 Ω

19 Radio interference

Replace the title and text of Clause 19 by the following:

19 Radio frequency interference

19.1 General

Historically Radio Frequency Interference (RFI) from high voltage electric power installations has been related to interference with AM broadcast distribution due to high voltage a.c. line corona. Consequently, this aspect is covered well in the literature and in relevant standards, i.e. the CISPR 18 series. RFI from substations has been of minor practical concern. Therefore very little has been documented regarding RFI from HV and MV substations. However, CIGRÉ Technical Brochure No. 391, provides a thorough analysis of the aspect related to RFI from substations, including HVDC substations. The analysis is based on both theory and measurement results.

One important aspect that is treated in the Technical Brochure (TB) is the attenuation of the RFI versus distance, including how the attenuation depends on the frequency.

RFI relates to a quite wide frequency range. According to CISPR 11 frequencies between 9 kHz and 400 GHz may be used for wireless communication and are therefore covered by the International Telecommunication Union (ITU) current international table of frequency allocations. Consequently, electromagnetic interference in this frequency range is defined as Radio Frequency Interference (RFI). However, the frequencies below 150 kHz are nowadays sparsely used and the standards for frequencies above 1 GHz are under development.

19.2 RFI from HVDC systems

19.2.1 RFI sources

RFI energy at the HVDC substation is produced by the turn-on and turn-off sequences in the valves, from corona on the high voltage switchgear and lines, and from sparking and gap discharge activities within the switchyard.

The RFI noise from the valve operation is predominantly produced by the fast voltage collapse during the turn-on sequence. These transients excite localized resonance circuits formed by stray capacitance and inductive elements in the bus structures, bushings, reactors, converter transformers, etc.

RFI generated by the a.c. corona in the high voltage a.c. switchyard of the HVDC substation varies significantly with the weather conditions and is highest at bad weather. RFI generated by d.c. corona is highest near the positive conductor and decreases with the radial distance from the conductor. DC corona does not vary very much with the weather conditions and is somewhat higher at fair weather.

Recent measurements have indicated that there may be a significant high frequency RFI from the a.c. part of a substation, especially at dry weather conditions if the substation is old. This high frequency RFI noise is considered to be generated by gap discharge and/or sparking activities. For more information reference is made to CIGRÉ TB No. 391.

19.2.2 RFI propagation

RFI generated in the HVDC substations may propagate as:

- a) a guided wave transmission propagating along the HVDC transmission line;
- b) a guided wave transmission propagating along the a.c. transmission lines;

c) direct wave radiation from the HVDC substation.

The attenuation of the RFI versus distance varies with the frequency as follows.

- a) The attenuation for the line-to-earth mode of RFI propagating along the lines is in the order of $3f^{0.8}$ dB/km with f in MHz. The attenuation varies with line design parameters and the soil resistivity.
- b) The attenuation for the line-to-line mode of RFI propagating along the lines is in the order of $0,3f^{0.8}$ dB/km with f in MHz. The attenuation varies with line design parameters and the soil resistivity.
- c) The physics for attenuation of the direct wave RFI with distance is quite complex. As an approximation, at a distance from a substation shorter than $\lambda/2\pi$ or longer at a certain distance $d(\text{SA})$ the attenuation of the field strength decreases as $1/r^2$ (where λ is the wavelength of the EM radiation and r is the distance to the installation). For intermediate distances, the attenuation is proportional to $1/r$. The distance $d(\text{SA})$ depends on the frequency, the height of the antennas and the soil properties. For more information reference is made to CIGRÉ TB No 391. For a realistic example in the TB, the distance $d(\text{SA})$ is in the order of 25 m at 50 MHz and increases linearly with the frequency for higher frequencies. For lower frequencies than 50 MHz, the distance $d(\text{SA})$ varies as $1/f$.

The implication of the above is that for RFI propagating along the lines, the high frequency RFI vanishes after a few kilometres, especially the line-to-earth component that is dominating. However, low frequency RFI will propagate quite a long distance, especially the line-to-line component.

Within a few hundred meters from the substation, the direct wave RFI can have a quite broad frequency range. However, when normal design is applied, the RFI has diminished to the background RFI level after 0,5 km to 1 km.

19.2.3 RFI characteristics

The general characteristic of the RFI noise from an HVDC substation is repeated transients regardless that the noise is produced by the commutation process, corona, sparking or gap discharge. Due to the different sources the frequency characteristics of the broad band RFI from a converter station can be quite complex and very irregular. To some extent this is valid for any high voltage substation.

RFI noise generated by the commutation process of the HVDC converter has the following characteristics.

- a) Interference energy is directly proportional to the magnitude of the voltage jumps produced during the turn-on sequences of the valves and also depends on circuit parameters. The voltage jumps at turn-off has less impact as the rise time at turn-on is much shorter than the rise time at turn-off.
- b) As the RFI due to the converter commutation process depends on the circuit resonances, the frequency spectrum is quite irregular.
- c) Due to the defined rise time for the voltage jumps at turn-on, the RFI due to the commutation process decays for frequencies above 1 MHz and is negligible for frequencies above 10 MHz.
- d) The noise that comes out from the valve hall is predominantly the noise conducted through the wall or transformer bushings if the valve hall is designed with good RF shielding.
- e) The noise level is essentially independent of the operating current.
- f) The number of converters has minor impact on the noise level.

The dominant mode for all RFI generated in a substation is the line-to-earth mode.

19.3 RFI performance specification

19.3.1 RFI risk assessment

The process for the specification should start with an RFI risk assessment regarding any local conditions requiring specific precautions regarding RFI. It should be noted that the risk for interference is related to nearby radio receivers, not to nearby radio transmitter. A nearby airport may imply an extra risk for RFI with the airplanes approaching the airport for landing.

Of special concern is interference related to the non-directional beacons (NDB) as their operating frequency is coincident with the frequency range for the converter RFI emission.

Also local communication centres with dual communication such as fire brigade stations should be considered in the risk assessment.

The important factors are: Frequencies used, the bandwidth, the signal level, the noise to signal requirement and the distance to and the location of the antenna of the radio receivers.

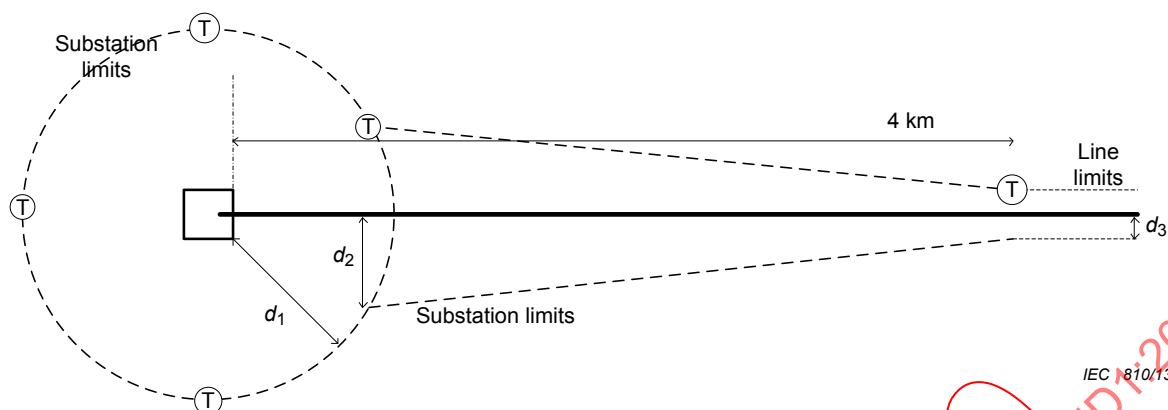
19.3.2 Specification RFI limit and its verification

The specified RFI requirement should include all sources related to the relevant delivery. The specification shall define all steady state operation modes and conditions and weather conditions during which the criteria shall be met.

Basically a single basic criterion shall be specified to be applied to all steady state operation modes, at any load up to and including the full load rated value, and within the design range of firing angle and all weather conditions is recommended. The performance criterion should cover the normal a.c. and d.c. operating voltage ranges. For practical reasons, then overall verification of the RFI performance by measurements shall be performed under fair weather conditions while the RFI emission due to a.c. corona under bad weather conditions shall be verified by calculation.

The requirement shall be specified as a graph of the maximum E-field in dB[μ V/m] versus frequency for the entire frequency band 0.9 kHz to 1 GHz. There should be one graph for the substation limit and one graph for line limits. Suitable limits for the normal cases are given in CIGRÉ TB No. 391, with justifications.

The recommended procedure for verification by measurements is shown in Figure 25. The recommendations are detailed in CIGRÉ TB No. 391.



Key

- d_1 measuring distance for substations, normally 200 m for an HVDC substation
- d_3 measuring distance for lines that is 30 m up to 600 kV a.c. and 50 m for higher voltages
- d_2 one third of d_1
- T most relevant positions for measurement

Figure 25 – Recommended measurement procedure with definition of measuring point

The limits for substations in accordance with Table D.2 in CIGRÉ TB No.391:2009 is applicable both for the contour around the active parts of substations and the closest part of the contour along the line. After a distance of 4 km, the limits for the line in accordance with Table D.3 in CIGRÉ TB No.391:2009 apply.

The measurement shall be performed as a frequency scan over the entire RFI frequency range as the frequency characteristic may be very irregular. It is not sufficient to measure the RFI level at 0,5 MHz only, as often done for RFI due to a.c. line corona.

19.3.3 Design aspects

The valve-hall building design should incorporate necessary shielding to meet the RFI requirement without any external switchyard screening. Special attention should be given to minimizing the antenna area for loops with high frequency transients conducted through the valve and the transformer bushings.

The specification should require a statement on the proposed method of limiting RFI within the specified limits. There should also be a statement regarding estimation of the expected RFI level by calculation during the design stage, within the entire frequency range. This estimation shall cover both the RFI from the substation and the RFI from the line, as defined in Figure 25. In this estimation also bad weather a.c. corona within the substation should be considered.

Add the following Annex:

Annex A (informative)

Factors affecting reliability and availability of converter stations

This annex explains various factors affecting reliability and availability of an HVDC substation itself and not the evaluation of reliability and availability. It may be noted that all may not be applicable to every HVDC substation and/or HVDC user.

NOTE The owner/user should specify specifically such reliability & availability requirements, as deemed applicable for the HVDC project. Without a mutual specific agreement between the supplier/manufacturer and the user/owner; this annex is only for information and guidance.

A.1 Design and documentation

A.1.1 General

The following subclauses are a compilation of suggested RAM-driven design principles that have been specified for previous HVDC substation projects. The user may consider these in future converter station designs/specifications, as appropriate, in light of the operational mission, the surrounding electrical system, and the economics of the project.

A.1.2 General design principles

- a) For bipolar converters, the designer should pay special attention to avoid bipolar forced outages and keep such duration to a minimum. This effort requires emphasis on such areas as subsystem and system testing, protection coordination, proper setting of protections, spare parts, and redundancy and separation of the subsystems of the two poles.
- b) Except where the user desires even more stringent design requirements, no single failure of equipment under rated operating conditions shall lead to more than a pole forced outage, and no combination of equipment failures within an HVDC converter pole should ever cause a forced outage extending beyond that pole. It may be noted that under some operating configuration (e.g. bipolar balanced operation with station earth), this may not be avoidable.
- c) Subject to the user's operating policy, no more than one pole at a time should need de-energisation as a precondition to any scheduled maintenance task. Furthermore, the HVDC substation design should require no more than one annual planned outage for routine maintenance of any individual piece of equipment.
- d) The converters should be designed to prevent, wherever possible, false power reversals due to equipment failure, malfunction, or operator error.
- e) All control and protection systems should be designed so that no single failure in any of these systems causes a reduction in rated HVDC power transfer capacity.
- f) The control and protection equipment should be designed to cause no more than a defined number of discrete transient disturbances (with a minimum duration defined by the user) per pole per year; but excluding transient disturbances occurring while the HVDC controls and protections are responding, as designed, to problems originating in the adjacent a.c. system(s).
- g) Throughout the design of the HVDC substation, and particularly in the valve halls, care should be taken to identify and to prevent possible causes of fire for example by use of fire retardant material. Where the possibility of fires may not be eliminated entirely, provision should be made for the following conditions.
 - Fire detection and alarming.
 - Human verification to avoid false tripping and unnecessary initiation of suppression measures, if applicable.

- h) The user may specify that the design and placement of auxiliary equipment (including their associated controls and protection) be such that a single equipment failure does not reduce rated HVDC power transfer capacity. Redundant cooling pumps, cooling fans, and heat exchangers would be one approach to meeting this requirement.

A.1.3 More detailed design principles

The following features would improve performance when designed into the controls, protections, and similarly organized equipment.

- a) The least complex design capable of performing a required function.
- b) Components that are applied within their individual ratings and that have been proven in service or have undergone applicable accelerated life stress tests before commissioning.
- c) Pre-aged components (a burn-in period should be applied to all electronic components within the valve groups, and within the control and protection equipment, before their incorporation into larger assemblies).
- d) Circuits using common components (to reduce the number of specific spares to stock).
- e) Design practices (such as surge protection, filtering, and interface buffers) to render sensitive components and circuits immune to damage and interference by induced voltages and currents in external cabling and cubicle wiring.
- f) Fail-safe and self-diagnostic designs.
- g) Redundant equipment and control cables, with automatic transfer facilities as appropriate.
- h) Physical separation of redundant cables and circuits to minimize the effect of fire, floods, and other such hazards.
- i) Designs that, in the event of component failures, transfer to a less complex operating mode.
- j) Equipment that may be maintained, repaired, and operated at the converter stations without the need for special operating and maintenance environments, test equipment, special tools, or complex operating sequences.
- k) Modular construction to permit rapid replacement of modules with failed components or subassemblies.
- l) Identification and separation of control switches for each converter and associated equipment to minimize operator errors.
- m) Designs that do not rely upon immediate operator actions to avoid equipment damage.

A.1.4 Software design principles

Typically, all control and protection functions in HVDC substations are implemented as software. The overall reliability of a HVDC substation is directly impacted by the quality of this software.

- a) As with hardware, general quality assurance methods, principles, and organizations should be employed for software design and application. Organizational methods, audits, and certifications, as defined, for example, in the ISO 9000 family (see 4.5, 4.9, 4.10, 4.11, and 4.12 of ISO 9001:1994 [B12], and ISO 9000-3:1997 [B13] in particular) and the ISO 10000 family, apply here.
- b) Most of the general design principles mentioned in A.1.2, and most of the specific principles listed under A.1.3, are applicable to software as well. For example, the principle of minimum complexity should be observed to minimize the possibility of errors and to ease maintenance and repair. Use of proven standard function blocks (for control, logic, and communication) is recommended. These proven standard function blocks are configured (i.e. parameterized and combined) to provide the HVDC control and protection structure as needed. In order not to achieve robustness at the expense of jeopardizing performance, this "function block" approach should be used only by well-trained, experienced personnel employing adequate hardware and software of familiar design.

- c) Software offers fundamental reliability-related advantages over hardware. These advantages should be used in all HVDC converter applications. For example, self-monitoring, self-diagnostics and fail-safe software should be applied prudently. Automatic documentation features should be used for diagrams, test reports, and manuals. All major control and protection functions should be included in the simulation tools used for the overall control and protection system design. The identical software combination should then be implemented and tested as part of the actual control and protection equipment.
- d) Awareness of the specific software-related problems and risks is necessary as well. potential computer failures, auxiliary power outages, risk of unauthorized access, vulnerability to viruses, as well as the inevitable existence of (hidden) software faults should all be taken into consideration. Some of the remedies to be applied are use of proven and reliable computer, processor, and interface hardware; uninterruptible power supply; limited access; safely stored back-up software etc.

A.1.5 RAM records

Prior to commissioning, the user should establish a procedure to document all RAM-related events. Each event, whether scheduled or unpredicted, should be recorded with reference to all data relevant to its cause and to its effect on RAM performance.

A.2 Operation

A.2.1 Training

A.2.1.1 The role of training in HVDC substation RAM

Trained staff does make a difference to the total reliability/availability of an HVDC substation. At the earliest stage (tender and contract preparation), the staffing requirements of a station should be outlined.

A.2.1.2 Training courses

In general, training should be given to operation and maintenance personnel and should start, if possible, before the factory acceptance tests begin for the control and protection system.

A training program may start with a classroom orientation, which is then completed in time for the start of equipment pre-commissioning. A training course may be divided in four parts. They are as follows.

- a) General lectures on the system and the equipment – their purposes, functions, methods of use, and control and protection principles – with appropriate texts.
- b) Specific lectures on operation and maintenance, given separately, even if attended by the same personnel. All items of equipment, whether special or conventional, should be covered by both courses.
- c) Experience gained from participation in installation, testing, pre-commissioning, and commissioning, after these lectures have been assimilated. If possible, the testing of converter valves and of controls should be witnessed by some trainees.

NOTE Here, too, video recording is highly advisable – particularly for relatively uncommon events such as the replacement of a converter transformer, smoothing reactor, or thyristor.

- d) Practical exercises to ensure that trainees are able to operate the station in a safe and efficient manner.

A.2.2 Maintenance programs affecting reliability

A.2.2.1 Basics

The goal of maintenance planning is to reach an optimum balance between the total expense of scheduled outages and the frequency of forced outages. Maintenance may be as follows:

- a) preventive: to maintain or improve the equipment ability to operate;
- b) predictive: to ward off a perceived imminent danger of forced outage;
- c) corrective: to clear a forced outage.

Maintenance tasks, having intervals less than one year, may be on-line tasks, specially when the system design includes redundancy. These tasks may be planned and executed as on-line maintenance throughout the year.

Most, but not all, maintenance tasks having intervals equal to or longer than one year are (subsystem or component) off-line tasks. Depending on whether a redundant subsystem or component exists and on whether it is accessible when the system is on-line, its maintenance is either made part of the (system) online maintenance or declared a (system) off-line task. These off-line tasks are grouped on an annual basis and performed during an annual scheduled outage.

A.2.2.2 Designing systems and specifying equipment for optimum maintainability

A predictive RAM calculation should, among other goals, include design targets related to maintenance. As the design and maintenance planning progresses, the RAM calculation might have to be repeated.

A.2.2.3 Planning maintenance programs

Maintenance planning may be based on the methodology of reliability-centered maintenance (RCM).

RCM focuses on the prioritization of the tasks according to their perceived necessity, instead of just performing the work according to, for instance, the manufacturer's maintenance manuals. As a typical result, identical components in different locations might have different maintenance schedules, after considering criteria such as the following:

- function within the system as a whole;
- probability of failure, also considering the stress conditions;
- availability of early failure warning;
- impact of failure on system performance [failure mode and effect analysis (FMEA) is often used to analyze this impact];
- redundancy;
- measurable aging and wear on equipment;
- identifying which maintenance tasks are indispensable;
- determining which further maintenance activities would improve reliability by reducing the exposure to failures, delaying their occurrence, facilitating their detection, etc;
- tutorials, reports, and other types of literature on RCM that are available.

After the RCM analysis, the HVDC user should consider further factors in order to refine the overall maintenance plan. These factors are as follows:

- vendor warranty requirements;
- applicable standards requirements;
- other contractual requirements;
- liability and insurance requirements;
- economics.

A special feature of HVDC bipole systems that are able to transmit 50 % (or more) energy on either pole and 100 % energy on both poles is that one pole may undergo a scheduled outage while the other pole is in operation (provided the equipment layout and the power network

allow this option). In such cases, the user might divide the annual scheduled outage into three parts: one pole outage for each pole, and a scheduled bipole outage (for any equipment common to both poles, irrespective of the design goals of A.1.2).

Finally, planning off-line maintenance on an annual basis does not mean that all annual scheduled outage plans are identical, even if the equipment list remains unchanged, for the following two main reasons.

- a) Tasks with prescribed intervals equal to or longer than two years are not carried out year by year.
- b) Although constant component failure rates are assumed, failure rates tend to change with time according to the “bathtub curve,” and as a function of the mechanical and/or electrical stresses to which the components are subjected.

A.2.3 Spare parts

A.2.3.1 Types of spare parts

A.2.3.1.1 Consumables

Consumables are used continuously, so small numbers are kept on hand or ordered just before scheduled maintenance periods. They are easily replaced, sources are plentiful, and they are not usually included in the original contractual inventory.

A.2.3.1.2 Long-term spares

Long-term spares are needed for the entire life of the converter station. They may be classified into two groups, as follows.

- a) Parts needed only at long intervals (e.g., once in five years). The user should check the availability of these items frequently, and they may have to be included in the station's inventory if they become difficult to procure.
- b) Emergency items needed to recover from a forced outage. There is no way to guarantee the failure rate or the availability of the replacement part at the time of the failure.

Early in the life of the project, the user should identify long lead-time items available from relatively few sources.

A.2.3.2 Evaluation

Consumables and maintenance items are not much of a problem, in that the replacement rate is known. The real issue in spare parts inventory is the emergency item. To have every possible needed emergency part would require having almost a complete spare converter station in the inventory. In general, the amount of spare parts kept in the station's inventory is proportional to the cost of the station's downtime and is based upon field experience with similar equipment or apparatus. The user should, therefore, decide what items need to be kept on hand and what may be supplied by the manufacturer by considering the following:

- a) items with an expected high failure rate,
- b) items with a long lead time for replacement,
- c) items critical to the operation of the station,
- d) items not readily available from the manufacturer or no longer in production,
- e) procurement and warehousing costs.

Redundancy is, in effect, an “in-service” spare part and also affects the spare part strategy.