IEEE Guide for the Evaluation of the Reliability of HVDC Converter Stations

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Abstract: This guide is intended to serve high-voltage direct current (HVDC) converter station reliability by suggesting significant objectives, design, operation, monitoring, and specification details. This guide includes the CIGRÉ performance protocol and reliability-related mathematical concepts.
Keywords: availability, converter, HVDC, maintainability, transmission, RAM, reliability

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Introduction

(This introduction is not part of IEEE 1240-2000, IEEE Guide for the Evaluation of the Reliability of HVDC Converter Stations.)

Along with the widely recognized maturity and general acceptance of high-voltage direct current (HVDC) transmission, interest in related reliability concepts is growing. Quantitative reliability requirements and guarantees are found in many HVDC converter specifications and contracts.

This guide covers various aspects of HVDC converter station reliability, put together by a diverse group of experts. The bibliography includes a summary of North American HVDC converter station reliability specifications. The CIGRÉ "Protocol for Reporting the Operational Performance of HVDC Transmission Systems" is included as a set of informative annexes to this guide, reprinted with the permission of CIGRÉ Study Committee 14. A note on the foundations for RAM (Reliability, Availability and Maintainability) calculations is also captured in an annex, and explains some of the underlying mathematical concepts.

The principles and methods presented in this guide apply, at least in part, to other FACTS stations as well.

This guide was prepared by Working Group I7, Reliability of HVDC Converter Stations, in the High Voltage Power Electronics Stations Subcommittee for the IEEE-PES Substations Committee. At the time this guide was completed, the Working Group for Reliability of HVDC Converter Stations had the following membership:

F. John Hormozi, *Chair*
Gerhard Juette, *Vice-Chair*

Jacques Allaire
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Paul Albrecht
Vic Burtnyk
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Claude Durand
William Kramer
Sastry Kuruganty
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The following members of the balloting committee voted on this guide:

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IEEE Guide for the Evaluation of the Reliability of HVDC Converter Stations

1. Overview

1.1 Scope

This document promotes the concepts of reliability, availability, and maintainability (RAM) as applicable to the design, operation, and specification of high-voltage direct current (HVDC) converter stations.

1.2 Purpose

The purpose of this guide is to help improve the reliability of HVDC converter stations through prudent application of RAM concepts to all phases of HVDC projects.

More specifically, this guide intends to provide help in the following areas:

a) Improving HVDC RAM for converter stations already in service.
b) Calculating and comparing RAM of different converter station designs.
c) Calculating and reducing RAM costs of HVDC converter stations.
d) Reducing spare parts requirements of HVDC converter stations.
e) Improving HVDC converter specifications.

Toward these ends, this guide introduces basic RAM theory and calculations; provides guidelines on design, operation, and performance monitoring; and offers considerations for RAM specifications of HVDC converter stations.

2. References

This guide shall be used in conjunction with the following publications: When the following specifications are superseded by an approved revision, the revision shall apply.

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CIGRÉ Study Committee 14—DC Links, #14-97 (WG 04-21), Protocol for Reporting the Operational Performance of HVDC Transmission Systems.[1]

IEC 60633 (1998:12), Terminology for high-voltage direct current (HVDC) transmission.[2]

IEEE Std 352-1987 (Reaff 1999), IEEE Guide for General Principles of Reliability Analysis of Nuclear Power Generating Station Safety Systems.[3]

IEEE Std 493-1997, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*).

IEEE Std 730-1989 (Reaff 1999), IEEE Standard for Software Quality Assurance Plans.

IEEE Std 762-1987 (Reaff 1992), IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity.

IEEE Std 829-1998, IEEE Standard for Software Test Documentation.

IEEE Std 859-1987 (Reaff 1993), IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities.

IEEE Std 982.1-1988, IEEE Standard Dictionary of Measures to Produce Reliable Software.

IEEE Std 982.2-1988, IEEE Guide for the Use of IEEE Standard Dictionary of Measures to Produce Reliable Software.

IEEE Std 1008-1987 (Reaff 1993), IEEE Standard for Software Unit Testing.

IEEE Std 1012-1998, IEEE Standard for Software Verification and Validation.

IEEE Std 1028-1997, IEEE Standard for Software Reviews.

IEEE Std 1058.1-1987, IEEE Standard for Software Project Management.

NOTE—The CIGRÉ Working Group 14-04 reliability definitions and performance reporting system are considered a part of this guide and included in their entirety in Annex B, Annex C, Annex D, and Annex E.

3. Definitions

For this guide, the following terms and definitions apply. *IEEE 100, The Authoritative Dictionary of IEEE Standards Terms* [B11] should be consulted for terms not defined in this clause. Where the use of an expression in this guide differs from that implied in the dictionary or in other published references, the intended meaning is clear from the context.

3.1 actual outage duration (AOD): The elapsed time between the beginning and the end of a power or energy capacity reduction.

[1]CIGRÉ publications are available from CIGRÉ, 21 rue d'Artois, 75 008 Paris, France (http://www.cigre.org).

[2]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). 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.

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3.2 automatic outage: An outage occurrence that results from automatic operation of switching devices.

3.3 bathtub curve: Characteristic graphical representation of failure rate versus time over an item's total economic life; so-called because it resembles the profile of a bathtub.

3.4 bipole availability: The fraction of time that both poles of a high-voltage direct-current (HVDC) bipole are capable of carrying power.

3.5 bipole forced outage: Loss of both poles in a forced outage.

3.6 bipole scheduled outage: The scheduled simultaneous shutdown of both poles.

3.7 corrective maintenance: Work performed without which operation at normal power or energy capacity is impossible or unfeasible; usually, to recover from a forced outage.

3.8 deferred maintenance outage: A scheduled outage that could be postponed until a suitable time (usually at night or on a weekend), but not postponed until the next planned outage.

3.9 derated operation: The intentional reduction of power loading on equipment.

3.10 energy availability: A measure of the energy that could have been transmitted except for capacity limitations due to outages.

3.11 energy unavailability: The complement of energy availability.

3.12 forced outage: An automatic outage, or a manual outage that is not deferrable; defined by CIGRÉ as the state in which an equipment is unavailable for normal operation, but is not in the scheduled outage state.

3.13 human (reliability): Relating to a person or persons as an integral part of the system of interest.

3.14 maintainability: A measure of the ease of keeping an equipment or system able to perform its required functions; expressed, for example, in labor-hours per year.

3.15 manual outage: An outage occurrence that results from intentional or inadvertent operator-controlled opening of switching devices.

3.16 operations related outage: A scheduled outage in which the unit or component is removed from service to improve system operating conditions.

3.17 outage: The state in which the high-voltage direct current (HVDC) system is unavailable for operation at its maximum continuous capacity due to an event directly related to the converter station equipment or dc transmission line.

3.18 partial (forced/scheduled) outage: An outage that results in derated operation.

3.19 permanent forced outage: A forced outage where the component or unit is damaged and is not restorable to service until repair or replacement is completed.

3.20 planned outage: A scheduled outage that is planned well in advance, primarily for preventive maintenance, such as an annual maintenance program.

3.21 pole availability: The fraction of time that at least one pole is able to carry power.

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3.22 pole (forced/scheduled) outage: An outage that involves the loss of up to one pole's power or energy capacity.

3.23 predictive: Warding off a perceived imminent danger of forced outage.

3.24 preventive: Maintaining or improving reliability.

3.25 reliability-centered maintenance (RCM): A maintenance program prioritizing tasks according to their relative impact upon long-term reliability and availability.

3.26 redundant: An extra item (or items) added so that the system continues to meet rated performance with that item, or with another item (or items), out of service.

3.27 reliability block structure: A logic path representing the components, equipment, and/or subsystems needed for system operation.

3.28 scheduled (outage, maintenance, availability, or unavailability): Either planned or deferrable until a suitable time.

3.29 shakedown period: An operational state between the conclusion of commissioning tests and the beginning of the RAM monitoring program; a period during which the equipment or system is placed under service conditions, but is also scrutinized for stable, smooth, and reliable performance; also referred to as "trial operation."

3.30 switching time: A temporal allowance for personnel to configure the system in preparation for maintenance and to reconfigure the system in preparation for the resumption of operation.

3.31 system-related outage: A forced outage that results from system effects or conditions and is not caused by an event directly associated with the component or unit being reported.

3.32 temporary forced outage: A forced outage where the unit or component is undamaged and is restored to service by manual switching operations without repair, but possibly with on-site inspection.

3.33 (thyristor) valve group: An electrically contiguous assembly of solid-state electrical switching apparatus requiring a bias voltage and a gate (i.e., control) signal to switch "on," so that the assembly has two and only two high-voltage direct current (HVDC) terminals.

3.34 transient forced outage: A forced outage where the unit or component is undamaged and is restored to service automatically.

4. RAM objectives

4.1 The role of human reliability

One may incorporate human reliability into any and all of the reliability block structures presented in Annex F. For instance, the correct transition from monopolar metallic return to bipolar operation may require a substantial degree of operator intervention (for protection mode changes and HVDC switching sequences).

The effects of errors in decision-making tend to appear in both the overall failure rate and the overall restoration rate. For example, neglecting to take the proper maintenance action at the proper time may, later on, hamper one's ability to repair a component on the verge of failure. Alternately, the wrong maintenance

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action applied to the component in question may mask an existing condition or make the problem worse. In either event, the reliability of the component may quickly erode; as a result, the component may fail sooner and more often (thus increasing the failure rate). Also, the magnitude of the problem may increase, which may lead to a longer repair time. These cases are analogous to operational errors (such as responding inappropriately to an apparatus overload alarm).

Even when the correct action is taken, variations in response times, impacting individual components and subsystems, may in turn influence system failure rates and restoration rates. Such variations appear on the following two occasions:

— The period during which an operator perceives a problem or operational need, determines the nature of that problem or need, decides on a course of action, and implements it.
— The period during which a technical team prepares for a maintenance activity, arrives on site, is cleared to perform the work, actually does it, and "clears off" (actually releases the subject components back to an operational state). This influence may occur whether the maintenance is "corrective," "preventive," or "predictive" (see 6.2).

In general, one may improve human reliability by one or more of following three methods:

— Redesign the system and processes to make operations and maintenance quick and easy (e.g., by requiring relatively few steps, with clear and complete monitoring, or by refurbishing maintenance facilities).
— Improve the training of personnel to make human decisions more timely and consistently accurate.
— Limit the impact of human decisions upon the long-term functioning of the system as a whole (or, in the extreme, by automating the system and thereby removing the human elements entirely from the system reliability block structure).

4.2 Energy availability

Energy availability, as defined in Clause 3, is the maximum possible energy that could be transmitted (considering outages) divided by the total energy that would have been transmitted at full power in the same period. This concept is valuable when systems are partially derated due to component outages. It relates the simple "in or out" principle (a binary model used in reliability theory) to actual equipment. For example, a typical bipolar converter station (with the two poles electrically in series) has a 50% energy availability when one pole is in service while the other pole is bypassed for maintenance or repair.

4.3 Putting together a total RAM package

An effective RAM design involves integration of the desired RAM parameters in concert with the technical mission of the converter station and with the economic resources available. As a case in point, the design of a back-to-back converter station intended for only intermittent duty would probably emphasize dispatch reliability. On the other hand, a converter station to be used in a heavily loaded, long-distance, overhead HVDC transmission system would feature high energy availability and low outage rates. In yet another scenario, a remotely located terminal of an undersea HVDC cable should, in addition to the previously mentioned requirements, aim for high maintainability (i.e., minimizing the number of labor hours per year needed to keep its operational status). Therefore, in specifying RAM design, performance, and monitoring, one should consider the intended use of the facility.

In spite of the guidelines above, the choice of specification parameters to stress is not always so clear-cut. Specifically, one should beware of second-order effects that may require extra attention to less obvious parameters. The best known example of this phenomenon is that of the double contingency converter transformer failure, in which both of the following occur:

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— One transformer suffers a failure severe enough to require replacement with a spare unit.
— While the first transformer is being repaired off-site or a new one is on order, a second converter transformer fails catastrophically.

The probability of two major converter transformer failures within a relatively short time may seem minuscule. However, if only one spare is available at the outset, the resulting outage time for such an event (i.e., a weighted fraction of the manufacturing and delivery time of a new transformer) may contribute more energy unavailability to the converter station than the sum of all minor transformer failure events. This second-order effect (i.e., of equipment failure rate upon the station's energy unavailability) points to the need for an ever lower transformer failure rate, shorter transformer repair times, the need for multiple spare transformers, or some combination of these options. Such a scenario is but one of the possibilities that could significantly affect the RAM performance and RAM design requirement "package" within the HVDC converter station specifications.

4.4 The ultimate RAM goal

After defining the project's RAM needs (as per 4.3), one should "budget" RAM considerations throughout the project. This step entails identifying the areas permitting the greatest parametric improvements (i.e., the design aspects in which one would expect to find the biggest positive changes in RAM relative to the design features of existing stations) and then "spending" on the associated design enhancements according to the above predetermined RAM goals.

These improvements could arise from the following sources:

— Changes in technology
— Changes in economic feasibility
— An evolving regulatory environment

This big picture of project RAM needs to be translated into specification requirements on design and performance (see Clause 8). Once the contract is in place, its RAM provisions should be enforced with an eye toward accomplishing the RAM goals set via the process described in this clause and in 4.3.

RAM performance should be considered during the entire project lifetime—not only during the RAM performance monitoring program (see Clause 7). In other words, the project needs to be specified, designed, built, and run as if RAM performance is a concern not only while a warranty or guarantee is in force. RAM is a dynamic set of parameters; that is, it may and does change with time. For that reason, continuing a RAM improvement program beyond the end of the contractual RAM performance monitoring period becomes even more important if the project is under consideration for economic life extension.

5. Design and documentation

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

5.1 General design principles

For bipolar converters, the designer should pay special attention to avoiding bipolar forced outages. This effort requires emphasis on such areas as subsystem and system testing, protective relay coordination, proper setting of relays, spare parts, and redundancy and separation of the subsystems of the two poles.

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Except where the user desires even more stringent design requirements, no single failure of equipment under rated operating conditions should ever cause 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.

Subject to the user's operating policy, no more than one pole at a time should need de-energization as a pre-condition to any scheduled maintenance task. Furthermore, the converter station design should require no more than one annual planned outage for routine maintenance of any individual piece of equipment.

The converters should be designed to prevent, wherever possible, false power reversals due to equipment failure, malfunction, or operator error.

All control and protection systems should be designed so that no single failure in any of these systems causes a reduction in HVDC power transfer capacity.

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 ac system(s).

Throughout the design of the converter station, and particularly in the valve halls, care should be taken to identify and to prevent possible causes of fire. Where the possibility of fires may not be eliminated entirely, provision should be made for the following conditions:

a) Fire detection and alarming.
b) Human verification to avoid false tripping and unnecessary initiation of suppression measures.
c) Suppression methods that emphasize, first, human safety and, second, equipment and structural preservation.

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 HVDC power transfer capacity. Redundant cooling pumps, cooling fans, and heat exchangers would be one approach to meeting this requirement.

5.2 More detailed design principles

The following features should be 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 well 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.

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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.

5.3 Software design principles

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

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.

All of the general design principles mentioned in 5.1, and most of the specific principles listed under 5.2, 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.

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. Adequate software documentation (i.e., function blocks, structures, block diagrams, files, lists, etc., but not code) and training are essential.

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; and again, adequate software documentation and training.

Certain practices have been found helpful toward these goals. Some are reflected in IEEE guideline standards, which include software quality assurance plans, software verification and validation plans, software management plans, software test plans and documentation, and software reviews and audits. They are included in the four-volume IEEE Software Engineering Standards Collection, which is available from the IEEE.[4]

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

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5.4 Operation and maintenance manuals

Operation and maintenance manuals should include a description and principles of operation of the converter station, as well as detailed instructions for operation and maintenance. Table 1 suggests typical contents for an operation and maintenance instruction manual.

Table 1—DC station operation and maintenance instruction manual

Section	Title
1.	Introduction to manual
2.	Description of the dc scheme
3.	Schedule of main system equipment rating data and drawing references
4.	Interlocking and safety
5.	Fire prevention, detection, and suppression
6.	Ac protection
7.	Converter valves
8.	Converter transformers
9.	Ac harmonic filters and reactive power banks
10.	Dc filters and smoothing reactor (where applicable)
11.	High-frequency filters (e.g., power line carrier, radio, television)
12.	Ac and dc switchgear (indoor and outdoor)
13.	Surge arresters
14.	Ac auxiliary supplies
15.	Dc auxiliary supplies
16.	Voltage and current measurement
17.	Converter controls
18.	Control desk
19.	Valve cooling system
20.	Valve cooling control
21.	Valve hall air conditioning
22.	Recording systems
23.	Operating instructions
24.	Maintenance and test equipment; special tools
25.	Spare parts
26.	Troubleshooting (a guide to the speedy solution of problems, listed by the titles of status alarms)

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The manuals should include clear, easily read drawings with sufficient details and cross-references to facilitate repair, inspection, and maintenance. They should also contain files of the commissioning measurement data for comparison with annual and post-fault testing.

The manuals should include instruction books supplied for all the constituent items of equipment in the stations. A complete set should be available at each station, and the relevant sections should also be provided at each remote operations center.

5.5 RAM records

Prior to commissioning, the user should establish a procedure to document all RAM-related events (see Clause 7). 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.

6. Operation

6.1 Training

6.1.1 The role of training in HVDC converter station RAM

At the earliest stage (tender and contract preparation), the staffing requirements of a station should be outlined. The size and qualifications of that staff should be as follows:

a) Defined by the tender or contract

b) Allocated by the operating utility

c) Trained by the manufacturer

d) Backed up by a performance warranty

6.1.2 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 should start with a classroom orientation, which is completed in time for the start of equipment precommissioning. Because construction activities may disrupt classroom training, personnel should receive this orientation before major equipment installation begins.

A training course has 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. The user may want to consider making a video recording of lectures for later training. The operation and maintenance manuals themselves should be used as lecture course notes.

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c) Experience gained from participation in installation, testing, precommissioning, and commissioning, after these lectures have been assimilated. If possible, the testing of converter valves and of controls should be witnessed by trainees. 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.

6.2 Maintenance programs affecting reliability

6.2.1 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 if the system design includes redundancy. These tasks may be planned and executed as (system) 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) on-line 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.

6.2.2 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. This recalculation, in turn, would have an impact on design, equipment specification, and maintenance planning.

6.2.3 Planning maintenance programs

Maintenance planning should 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 vendor’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.

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— 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.

— The tutorials, reports, and other types of literature on RCM that are available.

After the RCM analysis, the 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 systems that are able to transmit 50% (or more) energy on either pole and 100% energy on both 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, despite the design goals of 5.1).

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.

6.3 Spare parts

The manufacturer’s RAM spare parts calculations tend to focus on the warranty period (see 8.3.1.2.2). As an aid to long-term spare parts procurement, the specifier could also have the manufacturer consider the life-time of the project in the RAM calculations.

6.3.1 Types of spare parts

6.3.1.1 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.

6.3.1.2 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.

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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.

6.3.2 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.

6.3.3 A typical spare parts list

This list is intended to give the user some examples of what other HVDC projects have kept in stock.

Spare parts may include the following:

a) Converter transformers—especially when single-phase transformers are used
b) Converter transformer components
    1) Bushings
    2) Pumps with motor
    3) Fans with motor
c) Reactors
    1) Smoothing reactor (if the smoothing reactor is oil-filled, then there may be a need for components similar to those for the transformer)
    2) Shunt (power factor) reactor
    3) Filter reactor
    4) Electrode line reactor
d) Converter valves
    1) Thyristors
    2) Components of the snubber circuit, damper circuit, and voltage divider (e.g., capacitors, resistors)
    3) Transient current-limiting reactor for the valve
    4) Electronic circuit boards and valve-base electronics
    5) Fiber-optic cables
e) Dc wall bushings
f) Ac and dc arresters

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g) Ac circuit breaker and load-break switch accessories
   1) Closing and tripping coils
   2) Closing and tripping mechanisms
   3) Control rods
   4) Arcing contacts (for tripping and closing)
h) Voltage and current measurement devices
   1) Capacitive voltage transformers
   2) Dc voltage dividers
   3) Potential transformers
   4) Current transformers
   5) Dc current transducers
i) Power factor bank and harmonic filter equipment (besides reactors)
   1) Shunt capacitors
   2) Resistors
j) Other dc-side equipment
   1) Dc switchgear
   2) Neutral bus capacitors
   3) Electrode line capacitors
k) Control, protection, and metering equipment
   1) Valve control (electronic boards)
   2) Dc control (electronic boards)
   3) Fault monitoring
l) Station service and auxiliary power equipment
   1) Low-voltage circuit breakers and transfer switches
   2) Fuses
   3) Low-voltage arresters
   4) Batteries
   5) Uninterruptible power supply accessories
m) Valve cooling equipment
   1) Fan with motor
   2) Pump with motor
   3) Heat exchanger
   4) Mechanical valves
   5) Filters for cooling medium

7. RAM performance monitoring

To verify the compliance of an HVDC converter station with contractual energy availability requirements, the measurement and demonstration procedure in this clause is suggested. In addition to general considerations, these suggestions reflect the format of the CIGRE “Survey of the Reliability of HVDC Systems Throughout the World” (see Christofersen, Elahi, and Bennett [B4][B5]) and protocol for reporting the operational performance of HVDC transmission systems (see Annex B, Annex C, Annex D, and Annex E).

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7.1 Monitoring and evaluation periods

The monitoring and evaluation times for energy availability should be specified in accordance with the related requirements, guarantees, liquidated damage clauses, etc., for energy availability.

The period (after commissioning) for monitoring the energy availability of HVDC converters may be identical with, or different from, the contractual warranty period. For example, a “burn-in” period of some months may be allowed after commissioning ends, but before the monitoring period begins. The evaluation period may be identical with, or shorter than, the monitoring period. For example, the best two years within three years after acceptance (or the best four years out of five) could be counted for evaluation. This approach eliminates some of the anomalous statistical variations that could occur in annual energy availability (by excluding major, one-time events such as a converter transformer failure).

Any calculated energy availability should be understood in statistical terms. For example, a calculated energy availability of 98% means that the expected (most probable) energy availability is 98% (equivalent to 100% energy availability for nearly 358 days out of a standard year). The actual energy availability in any single year is below or above this expected (most probable) number. Consequently, if energy availability guarantees are requested, it is reasonable for the supplier to guarantee a somewhat lower energy availability than calculated and/or for the user to specify a flexible evaluation time window.

7.2 Monitoring procedures

The principles in this subclause, in conjunction with the definitions provided in Clause 3, should be applied to RAM-related specifications, as well as to actual procedures mutually agreed upon between the user and the supplier before the beginning of the actual monitoring and evaluation period. Lines of communication, forms of reporting, verification and acknowledgment of events, sources of parts and support, and other details should be agreed upon to meet the requirements of the case at hand and the parties involved.

a) If different ends of one dc system are owned by different entities and/or were supplied by different suppliers, the principles offered here may have to be applied in slightly different ways according to differing needs and practices. RAM monitoring should distinguish among the causes of events and attribute them accordingly. For example, the outage of one converter should not be counted against the second converter, as long as the second converter remains available (i.e., ready to operate).

b) During the monitoring period for energy availability, precise logging of converter operation and outages is essential. In addition to obvious parameters, such as power direction and magnitude, all events reducing converter energy availability should be recorded. The records should include sufficient details on the causes of events, outages, or reduced energy availability, in particular. Data from sequence-of-events recorders and fault recorders should be stored for this purpose. Distinction between scheduled and forced outages, based on applicable definitions per contract, is essential. During outages (forced outages in particular) allocation of time spent for different activities (e.g., travel of maintenance personnel to the station, clearing procedures, switching time, diagnosis, getting spare parts to the station, repair time, work breaks, restarting) should also be recorded. Such record keeping facilitates allocation of outage time to the responsible parties (i.e., owner versus supplier, in most cases).

c) Depending on contractual specifics, one may need to log the availability of spare parts and repair equipment within the user’s organization, as well as the time elapsed for delivery of spare parts by the supplier or other sources. The presence and use of the user’s trained maintenance personnel is also noteworthy.

d) Records should be produced during periods of operation as well as during minimum-load or no-load periods. Even during no-load periods, (i.e., when the converter is actually not needed), the energy availability and energy unavailability of the converters should be determined and recorded.

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e) Causes and locations of forced outages should be categorized, including the categories listed in the CIGRÉ protocol (see Annex B, Annex C, Annex D, and Annex E). Such categories include ac and auxiliary equipment, valves, control and protection, dc equipment, transmission line or cable, and others. The protocol should also be considered when establishing a monitoring and evaluation routine so that the resulting statistics may assist others in their assessment of dc link performance.

f) Proper recording of operational and environmental parameters should be assured at any time to help diagnose the causes of any outages.

g) Outages of specific components (i.e., thyristors, thyristor levels, capacitor cans, others with failure rates subject to contractual guarantees) and subsystems should be recorded together with sufficient supporting information to establish in-service failure rates and to check them against calculated outage rates and applicable guarantees. In addition to the contractual aspects of monitoring such component and subsystem availability, it may help to detect and identify

   — Latent defects and design errors

   — Improper maintenance procedures

h) A formal, reliable, and practical procedure for deciding on event causes and responsibilities (for the record) should be established and maintained by the parties involved.

i) The use of recording forms and computer programs for compiling and evaluating the data is advisable.

7.3 Evaluation procedures

Periodic (e.g., monthly, quarterly, annual) evaluation and reporting of converter availability should follow the principles established under 7.2 above. Preparation of inputs to the CIGRÉ survey (see Annex B, Annex C, Annex D, and Annex E) should be included, (i.e., the CIGRÉ protocol should be completed).

In addition, reasonable efforts should be made to correlate failures with operational or environmental parameters.

All outages and unavailability periods should be interpreted, categorized, added, translated into contractual availability terms, and reported per contract requirements.

Definitions and formulae as per Clause 3 and Annex F (as well as per Annex B Annex C, Annex D, and Annex E) should be used to determine the actual energy availability, energy utilization, forced energy unavailability, scheduled energy availability, and/or other contractually significant performance measures.

Contractual availability clauses often identify certain responsibilities of the user. Such responsibilities may include assumed maintenance personnel work hours and time to get to the site, as well as ready access to the proper tools, spare parts, etc. For actual outages, these conditions may be different. Therefore, actual recorded outage durations may need to be converted to contractually equivalent outage durations. The user and supplier should agree on such corrections on a case-by-case basis and apply them as suggested by the contract. In other words, for example, for a certain actual outage duration (AOD), a corrected outage duration (AOD*) may be used to measure the supplier's performance:

AOD* is AOD – Corr., where
Corr. is time correction for longer than assumed maintenance personnel travel time, unavailability of tools or spares, etc.

To detect and identify latent defects and design errors, even more detailed performance analysis is advisable. This analysis would include detection of chronic, cascading, or catastrophic component outages; comparison of actual with calculated subsystem outage rates; and monitoring of the use of spares and maintenance

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supplies. Such monitoring should include even those components and supplies that normally have no impact on overall station availability. The cost of replacing such components and supplies could be significant. Also, unexpected consumption of spares may cause excessive station outages and waiting periods.

8. Considerations for RAM specifications

The intended mission of the stations may influence both the RAM design goals and the desire for some form of warranty program during the first few years of field service. For example, HVDC converter stations located at remote generating stations are a different application from back-to-back HVDC converter stations in the middle of an ac transmission system, which may be considered an integral part of the ac transmission system.

The simplest RAM requirements may be written for a single pole HVDC converter station. Bipolar HVDC terminals may require additional RAM specifications. Additional RAM specifications may also be needed if part of one pole may be switched out of service while the rest of the pole remains in service. In any event, and throughout the discussion in this clause, specifying a requirement for energy availability is highly recommended because this Aiparameter facilitates standardized RAM performance data reporting (see Annex B, Annex C, Annex D, and Annex E).

8.1 HVDC converter stations located at remote generating stations

HVDC converter stations that are located at remote generating stations may have RAM specifications similar to specifications for a generating unit (see IEEE Std 762-1987). These HVDC applications involve transmitting power from a remote source to distant load centers. In many cases, a single RAM specification would cover the HVDC converter stations at both ends of the line. In such applications, the amount of energy that is capable of being transmitted might be considered in the RAM specifications, and the term “energy availability” is a logical parameter to consider specifying. (The term “energy availability” is analogous to the term “equivalent availability factor” used for a generating unit in IEEE Std 762-1987, and it conveniently treats systems that are partially derated due to equipment outages. For example, a bipolar converter station has 50% energy availability when one pole is in service while the other pole is bypassed for maintenance or repair.)

HVDC converter specifications should also include outage requirements such as the following:

a) The number of “planned outages per year”
b) The guaranteed maximum number of “forced outages per year”
c) The maximum acceptable number of “deferred maintenance outages per year”
d) The maximum acceptable annual number of “failures to start, per start attempt”

All of these types of outages are defined in IEEE Std 762-1987. In Annex B.3.1.2, CIGRÉ defines a “deferred maintenance outage” as an outage for work which could be postponed at least one week but which cannot be postponed until the next “planned outage.” Most specifications permit one “planned outage” per year. The number of “forced outages” per year is probably the most important requirement. The operator of the HVDC system may control the timing of “planned outages” and “deferred maintenance outages” and thus have them occur when the power system has made preparations for the event.

HVDC converter specifications normally include both “forced energy unavailability” and “scheduled energy unavailability” where a “scheduled outage” includes both “planned outages” and “deferred maintenance outages.” The “fail to start” outages affect the “forced energy unavailability” if a valve group does not restart after a scheduled outage or if it does not restart properly after a dc line fault has been cleared.

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8.2 Back-to-back HVDC converter stations

Back-to-back HVDC converter stations are integrated within ac transmission links and play a role similar to that of transmission tie stations (or substations) on an ac transmission system. Often, the back-to-back HVDC converters are permitting power interchange between two weak and/or unsynchronized ac systems. In some applications, the back-to-back tie is used for only a few hours per day, and power may flow either way.

In these cases, the "availability" is a logical RAM parameter to specify as one of the design goals, and the specification should treat the entire back-to-back tie as a single system. Other RAM specification terms should be similar to the terms used in IEEE Std 859-1987.

In other applications, it might be desirable to transmit the maximum amount of energy possible at all times and in only one direction. In such cases, one may treat the HVDC converter station as a generator, and "energy availability" may be a better parameter to specify than "availability."

One may still employ the four outage categories described in 8.1, but deferred maintenance and planned outages may be combined and called "scheduled outages." However, the RAM specification should not count "scheduled outages" that are called "operations related outages" in IEEE Std 859-1987. An "operations related outage" is when the unit is removed from service to improve system operating conditions. The RAM specification also needs to define whether "scheduled outages" for equipment modifications to the HVDC converter station are to be counted.

IEEE Std 859-1987 defines four types of "forced outage," as follows:

a) *Transient forced outage:* A forced outage where the unit is undamaged and is restored to service automatically.

b) *Temporary forced outage:* A forced outage where the unit is undamaged and is restored to service by manual switching without repair, but possibly with on-site inspection.

c) *Permanent forced outage:* A forced outage where the unit is damaged and is not restorable to service until repair or replacement is completed.

d) *System-related outage:* A forced outage that results from system effects or conditions and is not caused by an event directly associated with the unit.

RAM specifications for HVDC converter stations should count only the "permanent" and "temporary" forced outages.

IEEE Std 859-1987 also divides "outage initiation" into two categories: "automatic outages" and "manual outages." A "manual outage" may be either a "forced outage" or a "scheduled outage."

8.3 Parameters to consider for energy availability and reliability

RAM specifications based upon "energy availability" should also specify forced energy unavailability and the number of forced outages per year. Some HVDC converter stations operate above "maximum continuous capacity" with the help of redundant equipment; the failure of such equipment, with the station still capable of maximum continuous capacity, does not generally constitute a forced outage (see Annex B.3.1).

This Clause considers only the parameters that a user might write into the RAM specification for a "turnkey" HVDC converter station from a manufacturer. Only outages chargeable to the "turnkey" manufacturer should be considered when comparing field performance with the RAM. It is assumed that the electric utility properly operates and maintains the equipment in accordance with the manufacturer's instructions and that

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outages are not counted if they are caused by user-supplied equipment or by “out of range” operating conditions of the power system.

8.3.1 Single pole system

8.3.1.1 Number of forced outages

The RAM specification should include the maximum allowable number of pole forced outages per year.

8.3.1.2 Forced energy unavailability

The RAM specification should include the maximum acceptable forced energy unavailability. This limit depends upon the number and severity of forced outages, as well as the average downtime needed for restoration. This average downtime per outage depends upon the following:

a) Travel time to the site if the outage occurs during unattended operation

b) Urgency for repair

c) Availability of necessary spare parts

8.3.1.2.1 Unattended operation and urgency for repair

The specification should indicate the average number of hours per week of unattended operation and the “travel time to the site” during unattended operations. The manufacturer should not be charged for “travel time to site” that is longer than the time given in the specification. Urgency for repair depends upon the relative importance (i.e., high, normal, low) of the HVDC converter station to the operation of the power system. RAM specifications are usually written only for the cases of high or normal urgency for repair, where “high urgency for repair” implies an “around-the-clock, all-out effort.” “Normal urgency” involves “repair during normal work days with some overtime.”

8.3.1.2.2 Availability of spare parts

The availability of spare parts depends on what parts the user has already decided to purchase with the converter station, as well as upon the estimated failure rate (or consumption rate) and the anticipated lead time for delivery of each type of spare part. The manufacturer should include such data with a list of recommended spare parts, regardless of whether the user ultimately decides to purchase certain spares. In rare cases, when the user refuses to purchase a spare, the manufacturer may carry the spare during the warranty period that includes the demonstration program for reliability and availability.

In particular, the “time for repair and return to site” of a failed transformer is an important factor when estimating the need for one or more spare transformers. If a spare transformer is provided, the “time to replace” a failed transformer may significantly influence the forced energy unavailability (see 4.3). The utility may wish to specify that the transformer may be replaced without being required to drain and refill the oil; this feature may reduce the estimated downtime from about seven days to one.

8.3.1.3 Scheduled energy unavailability

The specification should state the maximum acceptable scheduled energy unavailability. This quantity usually includes downtime for one planned outage per year for normal scheduled maintenance and the downtime caused by other necessary outages for “deferred maintenance” to repair equipment problems in the HVDC converter station. The downtime for the planned annual maintenance depends upon the factors given in 8.3.1.5.

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The specification should indicate whether scheduled downtime is counted for HVDC equipment modifications. The user should also indicate whether downtime is counted when the HVDC converter station is not needed; for example, if the entire generating source at a remote station is down for maintenance, then the HVDC converter station is not needed.

Downtime caused by factors external to the HVDC converter should not be counted.

8.3.1.4 Total energy unavailability

Total energy unavailability equals forced energy unavailability plus scheduled energy unavailability. Some specifications include total energy unavailability instead of specifying scheduled energy unavailability.

8.3.1.5 Labor hours per year for planned maintenance

The specification often asks the manufacturer to indicate what labor resources are required during the planned annual maintenance shutdown, for example:

a) The number of people required

b) The specialties required

c) The assumed work schedule (e.g., an eight-hour work day, or two 10-hour shifts)

8.3.1.6 Prediction of energy availability and reliability

Many specifications for HVDC converter stations have required that the manufacturer make two documented predictions of energy availability and reliability: an estimate during the bid phase and a more detailed prediction during the design phase. Each report should show that the manufacturer predicts that the specified design requirements for energy availability and reliability are achievable. Examples of design areas that may be influenced are the following:

a) The need for a spare converter transformer
b) The need for redundancy in the valve cooling system

8.3.1.7 Demonstration program for energy availability and reliability

Some HVDC converter specifications have required demonstration programs for energy availability and reliability during the warranty period (see 7.1). These programs have usually been for periods of three years to five years. The HVDC converter station is usually run for a “shakedown” period (typically three months) before the formal demonstration program starts.

Such demonstration programs need to stipulate the following:

a) What is an “outage” in the context of the demonstration?

b) May a poor year be dropped if the other years are good?

c) May past periods be dropped if an unexpected problem has been corrected?

d) May the warranty program be extended in order to get another chance to pass?

e) What are the consequences of failing to pass? (see 8.4.)

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8.3.2 Additional parameters for energy availability and reliability in bipolar stations

Most of the specifications for energy availability and reliability for a bipole may be the same as if two separate poles were supplied. Additional specifications are required to cover when both poles are out at the same time. Specifications may be needed for the following outage cases:

a) A single failure causes a forced outage of both poles (bipole forced outage).
b) Both poles are on forced outage (but not from a single failure incident).
c) One pole has a forced outage while the other pole is on scheduled outage.
d) Both poles are scheduled out at the same time.

The case in a) is often considered the most important because of the large impact that it may have on the power system. Some specifications contain a requirement for scheduled energy availability for the case in d) so that the simultaneous scheduled downtime of both poles is minimized or eliminated.

Some specifications have required simply that no single failure cause a bipole forced outage. This requirement forces the two poles to be completely independent of each other.

Other specifications have contained one energy availability requirement covering all of the cases in a) through d), of which the case in c) usually has the highest predicted energy unavailability.

Most users plan annual maintenance on each pole so that one pole is shut down for the planned maintenance while the other pole is kept in operation. Sometimes the manufacturer is given some bonus or credit if the remaining pole in operation has overload capability (see 8.4). In some of these cases this overload capability may need to use some of the redundancy normally designed into cooling systems for the valves and converter transformers. Credit for this overload capability is more easily handled in specifications where “energy availability” is used instead of “availability of rated power.”

8.4 Contract administration for energy availability and reliability

The user should estimate, in advance, the costs of outages and downtime. If these costs are significant, the user may choose to incorporate incentives, penalties, and/or bonuses into specifications for RAM performance. These methods include “share the savings” and “share the cost” programs, and the user may begin employing them (e.g., as quantitative merit points) as early as the bid evaluation stage of the project.

8.4.1 Bid phase RAM evaluation

During the bid evaluation phase of the project, the user would normally concentrate on the following RAM-related aspects of a manufacturer’s proposal:

a) The field record of reliability and energy availability on systems built by the manufacturer (particularly important if the proposed HVDC system has essentially the same design as the design of a system already in service).
b) The manufacturer’s preliminary RAM prediction (especially useful if the proposal includes new or different features not previously supplied by the manufacturer).
c) The manufacturer’s RAM guarantees (needed when the cost of outages is high or when transmission continuity is critical).
d) The manufacturer’s approach to prevention, detection, and suppression of valve hall fires (typically found in proposals for new converter stations).

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8.4.2 Design phase RAM evaluation

Part of the manufacturer's design process should include a detailed prediction of energy availability and reliability. It is important to receive and to review this report before the design is "frozen" so that design weaknesses may be identified and resolved. This prediction should include a detailed review of spare part recommendations.

8.4.3 In-service RAM evaluation

The user may specify that actual RAM performance shall be assessed by the following two programs, both of which are described in Clause 7:

a) A "burn-in" or "shakedown" period immediately following the converter station commissioning tests.
b) A longer term monitoring period to assure compliance with equipment guarantees and converter station RAM performance warranties.

The first program may be particularly effective in identifying and resolving problems that would otherwise have endangered the success of the second program. Similarly, the user may structure the second program to provide incentives for active and continuous RAM improvement throughout the operating life of the converter station (see 4.4).

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Annex A

(informative)

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[B14] Vancers, I., Hormozi, F. J., et al, "A summary of North American HVDC converter station reliability specifications," *IEEE Transactions on Power Delivery*, vol. 8, no. 3, pp. 1114–1122, July 1993.

[5]ISO publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iso.ch/). ISO 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 (http://www.ansi.org/).

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Annex B

(informative)

CIGRÉ's "Protocol for Reporting the Operational Performance of HVDC Transmission Systems"[6]

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Recognising that the experience gained on HVDC transmission systems could be of value throughout the industry, CIGRÉ Study Committee 14 established Working Group 04, Performance of DC Schemes, with terms of reference which included an obligation to collect information on all systems in commercial service. It was considered that such information could be useful in the planning, design, construction and operation of new projects. It was also envisaged that the sharing of operational performance data could be of benefit to those concerned with the operation of existing HVDC links or those planning new HVDC links. It was clear that such reports were best prepared in accordance with a standardized procedure so that, with time, the accumulated data from several systems would establish a basis against which performance could be judged.

General information collected includes a system description, main circuit data and a simplified one-line diagram for each scheme. This descriptive information is compiled in a Compendium. The Compendium is revised biennially with the pages distributed to Regular Members of SC14. The Regular Members may be contacted to obtain the latest copy of the Compendium or revised pages as required. The Compendium or revised pages may also be obtained through the Chair or Secretary of WG 14.04. Furthermore, operational performance data is collected annually from each scheme in commercial operation. Performance data include reliability, availability and maintenance statistics. Reliability data are confined to failures or events which result in loss of transfer capability. Statistic are categorized in order to indicate which type of equipment caused the reduction in the transmission capacity. With the exception of recording thyristor failures, data on component failures not causing a loss of transmission capacity are not recorded. Reliability data on individual components such as capacitors, relays or circuit breakers is more appropriately kept by groups directly involved with each respective apparatus. Working Group 04 summarizes the performance statistics for all reporting schemes every two year in a CIGRÉ paper entitled "A Survey of the Reliability of HVDC Systems Throughout the World."

As the equipment and techniques of HVDC transmission developed, for example, the replacement of mercury-arc valves by thyristor valves in new projects; it has been necessary to revise or supplement the procedure from time to time. This revision of the Protocol will provide more accurate data on scheduled or planned outages, reporting of system capacity and commutation failures summarized as follows:

a) Outages taken for major reconfiguration shall not be reported.

b) Scheduled outages will include work that may be postponed until a suitable time during light load periods—usually night or weekend. Outages of this type will include work on redundant systems such as the controls where there is the philosophy of the owner to schedule an outage for this activity.

c) Maximum capacity has been clarified to include capacity available through utilizing redundant equipment when system may be loaded over normal conditions.

d) Inverter end commutation failures during ac faults will be reported when ac bus voltage drops below 90 percent rather than 85 percent. Another category has been added to commutation failures related to control problems.

[6]The CIGRÉ protocol document comprises Annex B, Annex C, Annex D, and Annex E of this guide.

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Scheduled equipment unavailability (SEU) has less significance than forced equipment unavailability (FEU) in comparing different systems since scheduled outages may be taken during reduced system loading conditions or when some reduction in power transfer capability is acceptable. Discretionary outages for maintaining redundant equipment are also considered within the SEU category. Accordingly, SEU is intended to be used mainly by owners over a long period of time for general comparison or for comparisons of their own needs, and not intended to be used for evaluating reliability of availability performance in RAM design or under RAM warranties.

This revised Protocol has been distributed to SC14 members for ballot last quarter, 1996 and was approved in March 1997. The Protocol will supersede the earlier issues and should be used for reporting 1996 performance and beyond.

NOTE—General terms relevant to HVDC transmission with explanatory figures are to be found in the International Electrotechnical Commission publication 633, "Terminology for High-voltage Direct Current Transmission" to which reference should be made.

Please observe that the time should be given in "decimal hours" i.e., 6 h:30 min = 6.5 hours.

B.1 Scope of reporting scheme

A separate report on the operational performance of each HVDC power transmission system or back-to-back interconnection in commercial service is to be prepared each year. These reports are to be made in accordance with this Protocol to ensure uniformity and comparability of the data. For an established system, the reporting period shall be from January to December. For a system in its initial calendar year of commercial operation, the report is to cover the period from the start of commercial operation to December of that year.

This protocol covers point-to-point transmission systems, back-to-back interconnections and multiterminal transmission systems. For point-to-point systems and back-to back interconnections, i.e. two-terminal systems, statistics are to be reported based on the total transmission capability from the sending end to the receiving end measured at a given point. If, however, the two terminals are operated by different companies, are composed of equipment of different vintage or of equipment from different suppliers, statistics can be reported on an individual station basis if so desired by those responsible for reporting. In such a case the outage should only be charged to the originating station taking care not to report the same event twice. For distributed multiterminal systems, i.e. systems with more than two terminals, statistics are to be reported separately for each station based on its own individual capability. Multiterminal systems, incorporating parallel converters but having only two terminals on the dc line, e.g., the Pacific Intertie with the parallel Expansion, can be considered as either point-to-point systems or as multiterminal systems for purpose of reporting. Therefore, statistics for this special type of multiterminal system can be reported based on either total transmission capability or on individual station capability. If the convertors at one station use different technology, station statistics can be reported separately for each different type of capacity if desired. Multiple bipoles are to be reported individually. Special mention should be given in the text and in the tabulations to any common events resulting in bipolar outages.

From time to time older systems, for which further data is judged to be of only marginal value, will be specifically excluded from the reporting scheme.

B.2 Preparation and distribution of reports

The preparation and submission of reports on national systems is the responsibility of the individual HVDC System Correspondents nominated by the Regular Member of Study Committee 14 for the country in question. For systems having different stations with different owners/operators, it is preferred that the Corre-

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spondents integrate their statistics into a joint report for that system before submission. In the case of international connections, the responsibility rests jointly with the separately nominated Correspondents.

One copy of each report is to be sent to the Convenor of Working Group 14 (WG)04 by the end of March in the year following the period covered by the report. These reports will be collected by the Convenor, copied and distributed to all Correspondents for their mutual information and to Working Group Members.

The Working Group will prepare each year, or as required, a paper summarizing the performance data from all the systems for presentation to the Study Committee at its meeting each year. To assist the proper interpretation of these data the Working Group will make available a Compendium of the main particulars of all HVDC systems.

Furthermore, the Working Group will from time to time, acting in accordance with the directions of the Committee, prepare a coordinating paper giving an analysis of the performance data collected for presentation to the CIGRÉ Conference in the name of the Study Committee.

B.3 Definitions

B.3.1 Outage Terms

B.3.1.1 outage: The state in which the HVDC System is unavailable for operation at its maximum continuous capacity due to an event directly related to the converter station equipment or dc transmission line is referred to as an outage. Failure of equipment not needed for power transmission shall not be considered as an outage for purposes of this report. AC system related outages will be recorded but not included in HVDC system reliability calculations. For purposes of this report, outages taken for major reconfiguration or upgrading such as addition of converters shall not be reported.

B.3.1.2 scheduled outage: An outage, which is either planned or which can be deferred until a suitable time, is called a scheduled outage.

Scheduled outages can be planned well in advance, primarily for preventive maintenance purposes such as annual maintenance program. During such planned maintenance outage, it is usual to work on several different equipment, or systems concurrently. It is not necessary to allocate such outage time to individual equipment categories. Only the elapsed time should be reported in Table E.2 SS as “PM.”

Classified under the scheduled outage category are also outages for work which could be postponed until a suitable time (usually night or weekend) but cannot be postponed until the next planned outage. Equipment category code in Table E.2 SS should be used to identify the affected equipment. This includes discretionary outages based on operating policies, owner’s preference and maintenance of redundant equipment.

NOTE—If the scheduled outage is extended due to additional work which would otherwise have necessitated a forced outage, the excess period is counted as a forced outage.

B.3.1.3 forced outage: The state in which an equipment is unavailable for normal operation but is not in the scheduled outage state is referred to as a forced outage.

B.3.1.4 trips: Sudden interruption in transmission by automatic protective action or manual emergency shutdown.

B.3.1.5 other forced outages: In general other forced outages are unexpected HVDC equipment problems that force immediate reduction in capacity of HVDC stations or system but do not cause or require a trip. Also in this category are outages caused by start-up or de-block delays.

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NOTE—In some cases the opportunity exists during forced outages to perform some of the repairs or maintenance that would otherwise be performed during the next scheduled outage. See B.5.2, rule (f)

B.3.2 capacity Terms

B.3.2.1 maximum continuous capacity Pm: The maximum capacity (MW), excluding the added capacity available through means of redundant equipment, for which continuous operation under normal conditions is possible is referred to as the maximum continuous capacity.

For two-terminal systems reporting jointly, the maximum continuous capacity is referred to a particular point in the system, usually at one or the other convertor station. For multiterminal systems or two-terminal systems reporting separately, the maximum continuous capacity refers to the rating of the individual convertor station.

NOTE—When the maximum continuous capacity varies according to seasonal conditions, the highest value shall be used as the capacity for the purpose of reports prepared according to this Protocol.

B.3.2.2 outage capacity Po: The capacity reduction (MW) which the outage would have caused if the system were operating at its maximum continuous capacity (Pm) at the time of the outage is called the outage capacity.

For two-terminal systems reporting jointly, the outage capacity is referred to the same point in the system used for determining Pm. For multiterminal systems or two-terminal systems reporting separately, the outage capacity refers only to the individual convertor station.

B.3.2.3 outage derating factor ODF: The ratio of outage capacity to maximum continuous capacity is called the outage derating factor.

$$ODF = Po/Pm$$

B.3.3 Outage duration Terms

B.3.3.1 actual outage duration AOD: The time elapsed in decimal hours between the start and the end of an outage is the actual outage duration. The start of an outage is typically the first switching action related to the outage. The end of an outage is typically the last switching action related to return of the equipment to operational readiness.

B.3.3.2 equivalent outage duration EOD: The actual outage duration (AOD) in decimal hours, multiplied by the outage derating factor (ODF), so as to take account of partial loss of capacity, is called the equivalent outage duration.

$$EOD = AOD \times ODF$$

Each equivalent outage duration (EOD) may be classified according to the type of outage involved:

— Equivalent forced outage duration (EFOD) and,
— Equivalent scheduled outage duration (ESOD).

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B.3.4 Time Categories

B.3.4.1 period hours PH: The number of calendar hours in the reporting period is referred to as the period hours. In a full year the period hours are 8760, or 8784 in leap years. If the equipment is commissioned part way through a year the period hours will be proportionately less.

B.3.4.2 actual outage hours AOH: The sum of actual outage durations within the reporting period is referred to as the actual outage hours.

$$AOH = \Sigma\ AOD$$

The actual outage hour (AOH) may be classified according to the type of outage involved:

— Actual forced outage hours (AFOH) and,
— Actual scheduled outage hours (ASOH).

$$AFOH = \Sigma\ AFOD$$

$$ASOH = \Sigma\ ASOD$$

B.3.4.3 equivalent outage hours EOH: The sum of equivalent outage durations within the reporting period is referred to as the equivalent outage hours.

$$EOH = \Sigma\ EOD$$

The equivalent outage hours (EOH) may be classified according to the type of outage involved:

— Equivalent forced outage hours (EFOH) and,
— Equivalent scheduled outage hours (ESOH).

$$EFOH = \Sigma\ EFOD$$

$$ESOH = \Sigma\ ESOD$$

B.3.5 Availability and Utilization Terms

B.3.5.1 energy unavailability EU: A measure of the energy which could not have been transmitted due to outages is referred to as the energy unavailability.

For two-terminal systems reporting jointly, the energy unavailability is calculated based on the same point in the system used for determining Pm. For multiterminal systems or two terminal systems reporting separately, the energy unavailability is calculated separately for each individual convertor station.

$$\text{Energy unavailability \% } EU = (EOH / PH) \times 100$$

$$\text{Forced energy unavailability \% } FEU = (EFOH / PH) \times 100$$

$$\text{Scheduled energy unavailability \% } SEU = (ESOH / PH) \times 100$$

B.3.5.2 energy availability EA: A measure of the energy which could have been transmitted except for limitations of capacity due to outages is referred to as energy availability.

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For two-terminal systems reporting jointly, the energy availability is calculated based on the same point in the system used for determining Pm. For multiterminal systems or for two-terminal systems reporting separately, the energy availability is calculated separately for each individual convertor station.

Energy Availability % EA = 100 – EU

B.3.5.3 energy utilization U: A factor giving a measure of the energy actually transmitted over the system.

For two-terminal systems, the energy utilization is calculated based on the same point in the system used for determining Pm. For multiterminal systems, the energy utilization is calculated separately for each individual convertor station.

Energy Utilization % U = [(total energy transmitted)/(Pm × PH)] × 100

Total energy transmitted = energy exported + energy imported (expressed in MWh) both referred to the point at which Pm is defined.

Pm: Maximum continuous capacity in MW
PH: Period hours

B.3.6 commutation failure performance terms

B.3.6.1 recordable A.C. system fault: In this context, an a.c. system fault is one which causes one or more of the inverter a.c. bus phase voltages, referred to the terminals of the harmonic filter, to drop immediately following the fault initiation below 90 per cent of the voltage prior to the fault. Note also that in this context, ac system faults at, or near, the rectifier are not relevant and should not be included in this reporting. An exception to this rule is a special case where the network topology dictates that an ac fault near the rectifier also produces a simultaneous recordable fault at the inverter.

B.3.6.2 commutation failure start CFS(A): The initiation or onset of commutation failure(s) in any valve group immediately following the occurrence of an ac system fault, regardless of whether the ac fault is “recordable” as defined in B.3.6.1 above. Do not include in here commutation failures as a result of control problems or switching events.

B.3.6.3 commutation failure start CFS(B): The initiation or onset of commutation failure(s) in any valve group as a result of control problems, switching events or other causes, but excluding those initiated by ac system faults under B.3.6.2 above.

B.4 Equipment and fault category terms

Convertor station equipment is classified into major categories for the purpose of reporting cause of capacity reduction or convertor outages. Failure of equipment resulting in an outage or loss of convertor capacity is charged to the category to which the failed equipment belongs. Failures or outages of redundant equipment which do not result in a loss of converter capacity are not reported in this Protocol. The outage may be forced as a direct consequence of the failure or misoperation, or the outage may be scheduled due to maintenance requirements. Only scheduled outages classified as deferred are categorized according to equipment type. The major categories listed in the following sections are standard for CIGRÉ performance reports. In the interest of providing information which can be used to further describe problem areas and help improve designs, major categories are divided into subcategories. These subcategories are described in the following subsections and are summarized in Appendix D. System correspondents are to utilize these subcategories by appending the respective subcode to the major outage code when maintaining the outage log and in completing Table E.2.

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B.4.1 A.C. and auxiliary equipment AC-E

This major category covers all ac main circuit equipment at the station. This includes everything from the incoming ac connection to the external connecting clamp on the valve winding bushing of the convertor transformer. This category also covers low voltage auxiliary power, auxiliary valve cooling equipment and ac control and protection. This category does not apply to capacity outages resulting from events in the ac network external to the convertor station. The following subsections give the different subcategories of equipment included in this category and contain examples of each type of equipment.

B.4.1.1 A.C. Filter and shunt bank AC-E.F

Loss of station capacity due to failure of passive and active ac filters, shunt compensation or PLC filters is assigned to this subcategory. Types of components included in this subcategory would be capacitors, reactors, and resistors which comprise the ac filtering or shunt compensation of the converter station.

B.4.1.2 A.C. Control and protection AC-E.CP

Loss of station capacity due to failure of ac protections, ac controls, or ac current and voltage transformers is assigned to this subcategory. AC protections or control could be for the main circuit equipment, for the auxiliary power equipment or for the valve cooling equipment.

B.4.1.3 Converter transformer AC-E.TX

Loss of station capacity due to failure of a converter transformer is assigned to this subcategory. Included in this subcategory is any equipment integral with the converter transformer such as tap changers, bushings or transformer cooling equipment.

B.4.1.4 Synchronous compensator AC-E.SC

Loss of station capacity due to failure of a synchronous compensator is charged to this subcategory. Included in this subcategory is anything integral or directly related to the synchronous machine such as its cooling system or exciter.

B.4.1.5 Auxiliary equipment & auxiliary power AC-E.AX

Loss of station capacity due to failure or misoperation of auxiliary equipment. Such equipment includes auxiliary transformers, pumps, battery chargers, heat exchangers, cooling system process instrumentation, low voltage switchgear, motor control centers, fire protection and civil works.

B.4.1.6 Other A.C. switchyard equipment AC-E.SW

Loss of station capacity due to failure of ac circuit breakers, disconnect switches, isolating switches or grounding switches is assigned to this subcategory. Also included are other ac switchyard equipment such as ac surge arresters, buswork or insulators.

B.4.2 Valves V

This major category covers all parts of the valve itself. The valve is the complete operative array forming an arm, or part of an arm of the convertor bridge. It includes all auxiliaries and components integral with the valve and forming part of the operative array. The valve category is divided into two subcategories.

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B.4.2.1 Valve electrical V.E.

Loss of station capacity due to any failure of the valve except for those related to that part of the valve cooling system integral with the valve is assigned to this subcategory.

B.4.2.2 Valve, valve cooling V.VC

Loss of station capacity due to any failure of the valve related to that part of the valve cooling system at high potential integral with the valve is assigned to this subcategory.

B.4.3 DC control and protection equipment C-P

This major category covers the equipment used for control of the overall HVDC system and for the control, monitoring and protection of each HVDC substation excluding control and protection of a conventional type which is included in "a.c. and auxiliary equipment." The equipment provided for the coding of control and indication information to be sent over a telecommunication circuit and the circuit itself is included. Devices such as disconnectors, circuit-breakers and transformer tap changers which may actually perform the control or protection action are excluded. The following subsections give the different subcategories of equipment included in this category and contain examples of each type of equipment.

B.4.3.1 Local control and protection C-P.L

Loss of station capacity due to any failure of the control, protection or monitoring equipment of the local HVDC station is charged to this subcategory. Examples would include failures of the convertor firing control, current and voltage regulators, convertor and dc yard protections, valve control and protection, and local control sequences.

B.4.3.2 Master control and protection C-P.M

Loss of station capacity due to any failure of the master control equipment is charged to this subcategory. The master control equipment is that used for interstation coordination of current and voltage orders, interstation sequences, auxiliary controls such as damping controls or higher level controls such as power control or frequency control.

B.4.3.3 Control and protection telecommunications C-P.T

Loss of station capacity due to any failure of the equipment provided for the coding of control and indication information to be sent over a telecommunication circuit as well as the telecommunication circuit itself, e.g., microwave or PLC, is included in this subcategory.

B.4.4 Primary D.C. equipment DC-E

This major category covers all equipment at the HVDC substations except for that in the three categories "a.c. and auxiliary equipment," "valves" and "control and protection equipment." The following subsections give the different subcategories of equipment included in this category and contain examples of each type of equipment.

B.4.4.1 D.C. filters DC-E.F

Loss of station capacity due to failure to active and passive dc filters or dc-side PLC filters is assigned to this subcategory. Types of components included in this subcategory would be capacitors, reactors, and resistors which comprise the dc filtering of the converter station.

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B.4.4.2 DC smoothing reactor DC-E.SR

Loss of station capacity due to failure of the dc smoothing reactor is charged to this category.

B.4.4.3 DC Switching equipment DC-E.SW

Loss of station capacity due to failure of dc circuit breakers, dc commutating switches, dc disconnect switches, isolating switches or grounding switches is assigned to this subcategory.

B.4.4.4 DC ground electrode DC-E.GE

Loss of station capacity due to problems with or failure of the ground electrode and its local termination or connecting equipment is charged to this subcategory.

B.4.4.5 DC ground electrode line DC-E.EL

Loss of station capacity due to failure of the ground electrode line or cable is charged to this subcategory.

B.4.4.6 Other DC switchyard and valve hall equipment DC-E.O

Loss of station capacity due to failure of other dc switchyard and valve hall equipment is assigned to this subcategory. This subcategory includes valve and dc-side surge arresters, overcurrent diverters, buswork insulators, wall bushings and direct current and voltage measuring transducers.

B.4.5 Other O

Loss of station capacity or extension of outage duration due to human error or unknown causes is assigned to this category. If, after an outage due to an event in another category, the outage duration is extended due to human error in maintenance or operation, the consequential extension in outage time is charged to this category.

B.4.6 DC transmission line TL

Loss of transmission capacity due to faults on the dc transmission line, underground or submarine cable or cable terminal is charged to this category. This category covers auxiliaries associated with oil-filled cables but does not cover outages related to false operation of line protection. Only permanent dc line faults are classified as forced outages and coded as TL in Table E.1. Information about all dc line protection operations is included in Table E.3. Reference is also made to B.6.3.

B.4.7 External AC system EXT

Loss of transmission capacity due to faults or events in the ac network external to the converter station is charged to this category. Examples would include ac network instability, ac overvoltage in excess of the convertor protective rating, short circuit level lower than the minimum design level, loss of ac outlet line(s) or loss of generation.

B.4.8 Severity code

Each forced outage is to be classified according to an outage severity code as follows:

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BP Bipolar Total Outage
P Monopolar Total Outage
C Convertor Total Outage
RP Other Capacity Reduction

For reporting purposes, bipolar outage is one in which both poles are lost as a direct or immediate consequence of a single event. Since such bipole outages are of special significance, it is requested that a narrative discussion of every bipole outage be included in the discussion section of the report. The discussion should indicate whether both poles tripped simultaneously, and if not, the sequence of events involved. Overlapping pole outages due to different events or with a prior outage of the other pole should be reported as separate pole outages, not as a bipole outage. A convertor or valve group is the smallest switchable operating unit of capacity in the station. Overlapping convertor outages on the same pole due to different events or with prior outages of another convertor should be reported as two separate convertor outages rather than a pole outage. For stations not having series connected convertors, the convertor category does not apply. For stations having only a single dc circuit or monopole, the bipole category does not apply. If an outage affects multiple bipoles, each bipole should be reported separately but the event should be described in the annual report.

B.4.9 Restoration code

Each outage is classified according to a restoration code as follows:

R Equipment causing outage is repaired or adjusted
S Failed equipment is replaced by spare
M No equipment failure, manual restart

B.5 Instructions for compilation of report

B.5.1 General instructions

The blank tables given in Appendix E, completed in accordance with these instructions, will form the basis of each annual report. It is recognized that these blank tables may not suit exactly each and every system, but since the comparison of performance of different HVDC systems is a central purpose of the reporting scheme, it has been determined that the standard blank tables must be used throughout. The effect is that the normalization of data in accordance with the Protocol is left with the HVDC System Correspondent who having the supporting information available is best able to carry out this task.

Also, it is appropriate to give information on innovative technical solutions which may be helpful to other HVDC System Correspondents.

The tables are to be augmented with an explanation of the major contributions of unavailability. The presentation of information or clarification of the data in the tables should be considered under the following topics:

B.5.1.1 Utilization

State the reason for exceptionally high or low figures, e.g., low generator availability.

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B.5.1.2 Availability

Elaborate on major or abnormal factors influencing availability, e.g., special maintenance requirements, expansion or upgrade of equipment.

B.5.1.3 Reliability

Give reasons behind exceptionally high outage rate, e.g., repetitive outage due to an intermittent control problem difficult to find and not initially corrected.

B.5.1.4 Severity of outage

Comment on the relative frequency of valve group, pole or bipole outages. Elaborate on major outages especially bipolar outages.

When changes are made to a system, the details must be reported so that the Compendium of system particulars can be revised by the Working Group.

To ensure good reproduction of reports by the Convenor, original or clear masters should be submitted.

B.5.2 Instructions for Table E.1 and Table E.1 M/S

B.5.2.1 Section 1

For back-to-back and for two-terminal systems reporting in the preferred manner as a combined system, complete lines 1.1 and 1.2 with the substation names so as to indicate the direction of the energy flow and give the total energy in each direction in GWh. In the case of an HVDC back-to-back system, identify the direction of energy flow by using the names of the a.c. systems so connected. In the case of convertors operating in a multiterminal system or in a two-terminal system which is reporting separately, record station energy for both rectifier and inverter operation by completing one Table E.1 M/S for each station.

B.5.2.2 Section 2

Calculate the Energy Utilization per cent in accordance with B.3.5.3 and complete the line. For two-terminal systems, the preferred method of Energy Utilization is calculation based on a system basis whereas for multiterminal systems, Energy Utilization is calculated and reported separately for each station.

B.5.2.3 Sections 3, 4 and 5

In order to calculate the availability and unavailabilities for these sections, it is necessary to maintain a log of outages through the year. The system log can most conveniently be prepared by first preparing separate logs for each substation and for the transmission line. For two-terminal systems, these separate logs can then be merged into a single combined log for the system which eliminates the effects of concurrent outages. For multiterminal systems or two-terminal systems reporting separately, no combination of station outages is to be made. Care must be taken, however, that outages due to the other stations are so charged. The form of the log used is for the HVDC System Correspondent to determine but an example of a typical log is given as Appendix C for information only. The completed log is not to be submitted as part of the annual report.

The rules set out here must be applied when preparing the log and subsequently calculating the availability and unavailabilities:

a) Record all outages in the log that cause a reduction in system capacity below the maximum continuous capacity.

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b) Indicate if the outage involves a total convertor (valve group), a total pole, or a total bipole or other capacity reduction by supplying the appropriate severity code as described in B.4.8.

c) Classify each outage as either a scheduled or a forced outage. For each scheduled outage record if the outage is scheduled according to the definitions given in B.3.1.2.

d) For each forced outage or scheduled outage, determine the primary cause of the outage and select the one most appropriate category from the seven major equipment and fault categories and associated subcategories given in Clause B.4, “Equipment and Fault Category Terms.” All equipment in the HVDC system is included uniquely in one of these categories and subcategories.

e) For each outage determine the outage derating factor, ODF. Calculate the equivalent outage duration (EOD) of each outage (B.3.3.2).

f) If during a forced outage the opportunity is taken to carry out some repair or maintenance that would otherwise be done during the next scheduled outage, record this as a scheduled outage with its own outage reference number. Record the equivalent outage duration (EOD) as zero, however, unless this scheduled outage increases the outage derating factor above that caused by the forced outage, or extends in time beyond the end of the forced outage. Should either of these events occur, calculate the outage derating factor and equivalent outage duration attributable to the scheduled outage.

g) If during a forced outage a further forced outage occurs, record the new outage also. When determining the equivalent outage duration (EOD) of the new outage take into account only the extent to which the new outage increases the outage derating factor or extends in time the pre-existing outage.

At the end of the year when the outage log is complete, proceed as follows to calculate the numerical data required to complete Sections 3, 4 and 5 of Table E.1:

— *Step 1:* Group the outages into scheduled and forced. Group the forced outages according to the major outage categories and severity code.

— *Step 2:* Total the equivalent scheduled outage durations (ESOD) to obtain the equivalent scheduled outage hours (ESOH). Calculate the energy unavailability due to scheduled outages (B.3.5.1) and complete line 4.1.

— *Step 3:* Total the equivalent forced outage durations (EFOD) to obtain the equivalent forced outage hours (EFOH). Calculate the energy unavailability due to forced outages (B.3.5.1) and complete line 4.2. Break down the equivalent forced outage hours and forced energy unavailability into those due to substations and those due to the DC transmission line and complete lines 4.21 and 4.22.

— *Step 4:* Add the energy unavailability percent due to scheduled outages (line 4.1) to that for forced outages (line 4.2) and subtract from 100 to obtain the energy availability percent and complete line 3.

— *Step 5:* Record the number of forced outage events in each of the seven equipment and fault categories. Likewise total the equivalent forced outage durations (EFOD) for each of the seven categories to obtain the equivalent forced outage hours (EFOH) for each category. Record values in lines 5.11 to 5.15 and lines 5.2 and 5.3.

— *Step 6:* Total the number of events and equivalent outage hours for categories AC-E, V, C-P, DC-E and O (lines 5.11 to 5.15) to obtain the number of events and equivalent outage hours for line 5.1 substations.

B.5.2.4 Section 6

Transfer the number of commutation failure starts CFS(A) and recordable ac faults from Table E.4 to complete line 6.

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B.5.2.5 Section 7

Record the number of forced outage events in each of the four severity codes. Compute the forced energy unavailabilities (FEUC, FEUP, FEUBP, and FEURP) for each of the severity codes. The forced energy unavailabilities are calculated in accordance with B.3.5.1 using the equivalent forced outage hours in Table E.6 for each of the severity codes. Only the outage time due to the substations and dc line are to be used. Outages due to the external ac system are to be excluded. Total the number of events and the forced energy unavailabilities to complete Section 7. The total FEU should equal the value on line 4.2.

B.5.3 Instructions for Table E.2 FS and Table E.2 SS

B.5.3.1 Forced outages Table E.2 FS

Record details of all forced outages that cause a reduction in system capacity. The log used to compile Table E.1 data can additionally provide the input for Table E.2 FS. Appendix C gives an example of this. For two-terminal systems, either a common Table for both stations or separate Tables for each station can be provided as long as the same outage is not reported twice. For multiterminal systems, separate Tables are to be provided for each station.

— *Step 1:* For each forced outage determine which of the five equipment and fault category codes and subcodes applies. Record code and subcode in first column. Record severity code and percent capacity reduction.

— *Step 2:* Identify the failed equipment by a brief description, e.g. the code and subcode may be AC-E.AX while the description could be auxiliary power transformer. Record the forced outage type after the description (e.g. (DD) - delayed deblock).

— *Step 3:* Record actual outage duration and whether the corrective measure was repair (R) or replacement by a spare (S).

B.5.3.2 Scheduled outages Table E.2 SS

Record details of all scheduled outages that cause a reduction in system capacity. The log used to compile Table E.1 data can additionally provide the input for Table E.2 SS. If the scheduled outage can be attributed to a certain category of equipment, supply the appropriate outage code. For two-terminal systems, either a common Table for both stations or separate Tables for each station can be provided as long as the same outage is not reported twice. For multiterminal systems, separate Tables are to be provided for each station.

— *Step 1:* Record code in first column.

— *Step 2:* Identify the maintained equipment by a brief description, e.g. the code may be AC-E.TX, while the description could be convertor transformer failed bushing. If the outage is for planned maintenance program use the code “PM.”

— *Step 3:* Record actual outage duration and whether the corrective measure was repair (R) or replacement by a spare (S).

B.5.4 Instructions for Table E.3

If the HVDC system includes one or more HVDC overhead line sections, and line protection is arranged to initiate auto-restart, perhaps at a lower pole operating voltage, for occurrences such as pollution or lightning induced flashovers, complete Table E.3 as follows:

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— *Step 1:* Give each line protection event a unique number and record this together with the date and time using the 24 hour clock. Treat repeated operations of the protection within the reset time, usually some tens of seconds, as one event.

— *Step 2:* Record the actual steady operating voltage and polarity, disregarding transients, of the affected pole immediately prior to the protection operation.

— *Step 3:* Complete the event entry with the number of automatically attempted restart sequences, and whether or not the final automatic restart is successful. If the restart is unsuccessful, record the actual outage time. Give in a note any available information relevant to the cause of the protection operation and subsequent restoration if successful. If the dc system is multiterminal, indicate any automatic sectionalizing that takes place.

B.5.5 Instructions for Table E.4

In order to complete Table E.4 it is necessary to keep a log at each inverter substation to record information about a.c. system faults and any associated commutation failure starts. The rules set out here must be applied in the preparation of this log:

Determine if the a.c. system fault is recordable or not at the inverter as defined in B.3.6.2. In order to decide if an a.c. system fault is recordable it is necessary to have at each inverter substation a fault recorder, with a prefault memory, initiated by a fall in a.c. bus voltage. When determining whether or not the voltage drops to or below 90 percent of the pre-existing voltage, consider only the fundamental voltage, i.e. disregard distortion. Take into account only reductions in voltage caused by phase-to-phase or phase-to-earth faults on the a.c. system.

Exclude the cases of temporary voltage reduction caused by other means such as normal switching of lines, transformers or reactive compensation, or faulty a.c. voltage regulating equipment.

At the end of the year proceed to complete tables as follows:

— *Step 1:* Complete the first column of lines 1.1 and 1.2 with the substation names. In the case of an HVDC coupling system identify the two sides of the coupling by the names of the a.c. systems so coupled. For a multiterminal system, record data for each station.

— *Step 2:* Count the number of recordable a.c. system faults during inverter operation at each substation and record the separate totals.

— *Step 3:* Count the number of commutation failure starts, CFS(A), as defined in B.3.6.2. A CFS may be determined by automatic recording for each converter unit or by inspection of the oscillographic records, but no more than one CFS(A) shall be attributed to each ac system fault.

— *Step 4:* Count the number of commutation failure starts, CFS(B), as defined in B.3.6.3.

B.5.6 Instructions for Table E.5

Omit this table from reports on wholly mercury-arc valve systems.

— *Step 1:* Complete the first column by listing separately the converter units at both substations or both sides in the case of coupling systems, e.g. 1,2,3 and 4, or Pole 1 Norway, Pole 2 Norway, Pole 1 Denmark, Pole 2 Denmark.

— *Step 2:* For each converter unit record whether it is a 6 or 12 pulse converter unit.

— *Step 3:* Record the hours each converter unit is available, whether transmitting power or not.

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— *Step 4:* Record the number of thyristors failed in each converter unit. To provide uniformity in reporting, the short circuiting of a thyristor due to any cause shall be recorded as a thyristor failure. If two or more thyristors are used in parallel in a valve, record the short circuiting of the parallel connected thyristors as a single failure, e.g. When 2 or more thyristors are used in parallel within a valve, record the short circuiting of the parallel thyristors as a single failure even though it might be known that 2 or more of the thyristors have in fact failed.

B.5.7 Instructions for Table E.6

Table E.6 summarizes the information contained in Table E.2 FS. All forced outages are summed by outage classification and by subclassification as well as by severity code. Completion of Table E.6 is an intermediate step in preparation for filling out Table E.1.

B.6 Guidelines for interpretation of events

B.6.1 Calculation of outage duration

Reported outage time should be the calendar time that the dc system or station is not available. The maintenance or forced outages often span several working days, possibly including weekends. The purpose of recording scheduled outage time is to develop a data base indicating the actual maintenance time. Therefore, clarification is needed on how “non-working” time is to be considered. If the system is made available but not operated during a portion of the non-working time, e.g. on a weekend, then such time should be excluded from the scheduled outage time. The key to computation of chargeable scheduled outage time is not whether or not work is performed, but whether or not the system is available for operation.

In some cases, outage duration may be longer than would normally be required. For example, there may be a period of low demand during which there is no economic loss due to unavailability of the dc link. This may permit the annual maintenance to be conducted on a more leisurely basis. Such extenuating circumstances should be noted in the discussion section of the report.

Similarly, lack of dc transmission resulting from scheduled outage of a generating plant which supplies the dc link should not be recorded as an outage of the dc system, provided that the dc system remains available for service. If maintenance is conducted on the dc link during such times, then the maintenance time should be reported as scheduled outage time.

B.6.2 External events

Events external to the HVDC system which result in interruption of HVDC power transmission are not to be considered as outages of the dc system as long as the dc system operates as designed and is available for service after the event is over. For example, if the ac lines feeding the dc link open due to faults or if the ac system hosting the dc link goes unstable, the outage time is not recordable.

B.6.3 Protective operation

Transient faults which are successfully cleared by correct operation of protection equipment do not constitute outages and should not be recorded in Table E.2 FS. Incorrect operation of protection equipment, either operation when not intended (false trip) or failure to automatically restart, would be reported as an outage, regardless of duration. Interruptions which require manual restart should be counted as forced outages if the system is designed to recover from such events.

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B.7 Performance of special controls

A number of dc systems are equipped with special supplementary controls, such as frequency control, damping control or runback, to help support the ac system. It is encouraged to include narrative comments regarding any significant positive or negative system aspects due to operation of such controls.

Operations of special controls when those operate to support the AC system shall not be counted as dc forced outages but shall be recorded as forced external AC outages.

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Annex C

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CIGRÉ's "Protocol for Reporting the Operational Performance of HVDC Transmission Systems"—An example of an outage log

Care must be taken to not report the same outage twice. Therefore, only record an outage code for outages caused by the respective station. If the outage is caused by a remote station and leads to a consequential outage of the local station, the outage should be charged to the remote station. Exclude outages caused by remote stations in the preparation of Table E.2 for the local station.

Table C.1—Outage log form

System: _____ **Station:** _____ **Year:** _____

Outage due to faulty equipment	Outage code[a] Forced	Scheduled
A.C. and auxiliary equipment	F.AC-E	S.AC-E
Valves	F.V	S.V
Control & protection equipment	F.C-P	S.C-P
Primary D.C. equipment	F.DC-E	S.DC-E
Other	F.O	S.O
Transmission line	F.TL	S.TL
External A.C. system	F.EXT	
Scheduled outage for planned maintenance		S.PM

Outage reference number	Date & time		Actual outage duration AOD	Outage derating factor ODF	Equiv. outage duration EOD	Outage code	Severity code BP, P, C	Description of event, equipment or component causing outage	Repaired -R Spare-S Man restart-M
	Start	Finish							

[a]See Clause B.4 or Appendix D for outage code subclassification for forced or for deferred scheduled outages.

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For single non-overlapping outages having a constant outage derating factor complete the log as follows:

— *Step 1:* Assign the Outage Reference Number. This is a unique number given to each outage event at the start of the outage.

— *Step 2:* Record the date and time at the start of the outage and subsequently the date and time at the end of the outage.

Record times to the nearest minute using the 24 hour clock.

— *Step 3:* Determine and record the main cause of the outage using only one of the outage codes given at the head of the form. For forced outages and for deferred scheduled outages extend the outage code by appending the outage subclassification from Appendix D. For example, the primary cause of the outage can be indicated by “F.AC-E.AX” indicating a forced outage caused by AC equipment in the station auxiliaries.

— *Step 4:* Calculate and record the Actual Outage Duration (AOD) which is the time elapsed between the start and end of the outage in accordance with B.3.3.1.

— *Step 5:* Describe the event, equipment or component causing the outage.

— *Step 6:* Determine and record the restoration code to indicate if the restoration required equipment repair (R), replacement by spare (S) or just a manual restart (M).

— *Step 7:* Determine and record the Outage Derating Factor (ODF) in accordance with B.3.2.

— *Step 8:* Calculate and record the Equivalent Outage Duration (EOD) which is the product AOD x ODF.

For single non-overlapping outages having a variable outage derating factor and for overlapping outages, additional information must be recorded in order to calculate the correct EOD.

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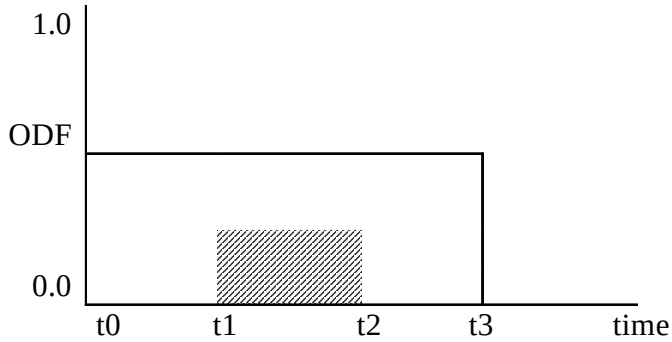
Examples of application of Rule (d) of B.5.2

Scheduled Outage during a Forced Outage.

Case 1—Scheduled outage does not increase ODF or extend outage duration.



t0 - forced outage due to AC-E starts ODF = 0.5
t1 - scheduled outage starts ODF = 0.25
t2 - scheduled outage ends
t3 - forced outage ends

AOD = t3 - t0
ODF = 0.5
EOD due to AC-E = 0.5 (t3 - t0)

Scheduled outage does not contribute to unavailability.

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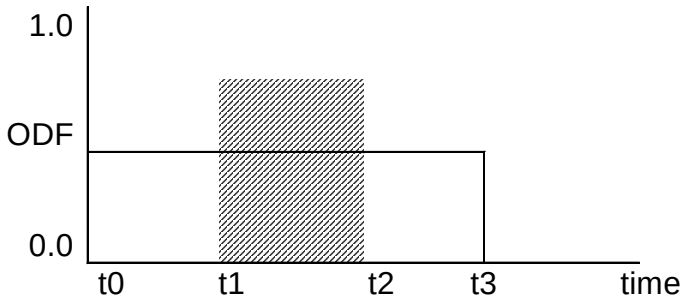
Case 2—Scheduled outage increases ODF.



t0 - forced outage due to TL starts ODF = 0.5
t1 - scheduled outage starts ODF = 0.75
t2 - scheduled outage ends
t3 - forced outage ends

AOD due to TL = t3 - t0
ODF due to TL = 0.5
EOD due to TL = 0.5 (t3 - t0)

AOD due to scheduled outage = t2 - t1
Excess ODF due to scheduled outage = 0.75 - 0.5 = 0.25
EOD due to scheduled outage = 0.25 (t2 - t1)

Scheduled outage contributes to unavailability.

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Examples of application of Rule (e) of B.5.2

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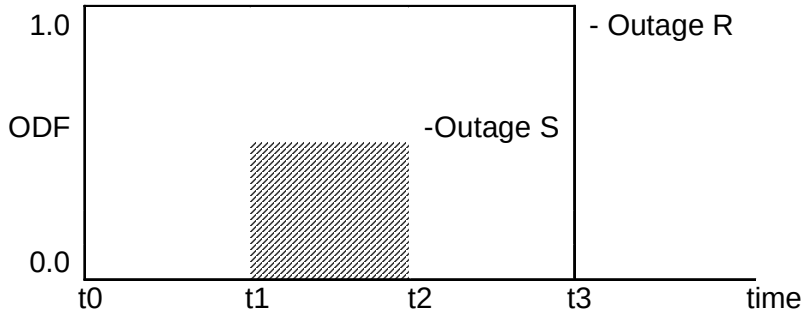
Case 1—Second outage does not increase ODF or extend outage duration.



t0 - forced outage due to TL starts - outage ref. R ODF = 1.0
t1 - forced outage due to DC-E starts - outage ref. S ODF = 0.5
t2 - forced outage due to DC-E ends
t3 - forced outage due to TL ends

AOD due to TL = t3 - t0
ODF due to TL = 1.0
EOD due to TL = 1.0 (t3 - t0) - outage ref. R is counted in the total number of events attributable to TL.
Outage due to DC-E does not increase ODF and so the EOD = 0. Since EOD is zero, outage ref. S is not counted in the total number of events attributable to DC-E.

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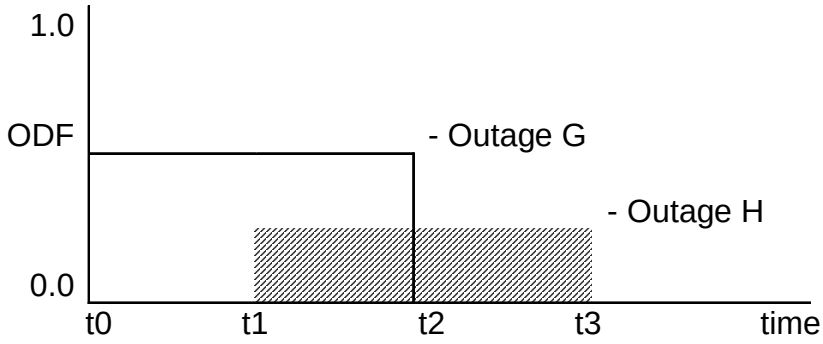
Case 2—Second outage extends duration.



t0 - forced outage due to AC-E starts - outage ref. G ODF = 0.5
t1 - forced outage due to another event AC-E starts - outage ref. H ODF = 0.25
t2 - forced outage - ref. G ends
t3 - forced outage - ref. H ends

AOD due to AC-E ref. G = t2 - t0
ODF for outage ref. G = 0.5
EOD due to AC-E ref. G = 0.5 (t2 - t0)
AOD due to AC-E ref. H = t3 - t1, but period t1 to t2 already accounted for so effectively it is taken as = t3 - t2.
ODF due to outage ref. H = 0.25
EOD due to AC-E ref. H = 0.25 (t3 - t2)

Since both outages are category AC-E and both EOD are non-zero, 2 is added to the total number of AC-E events by these two outages.

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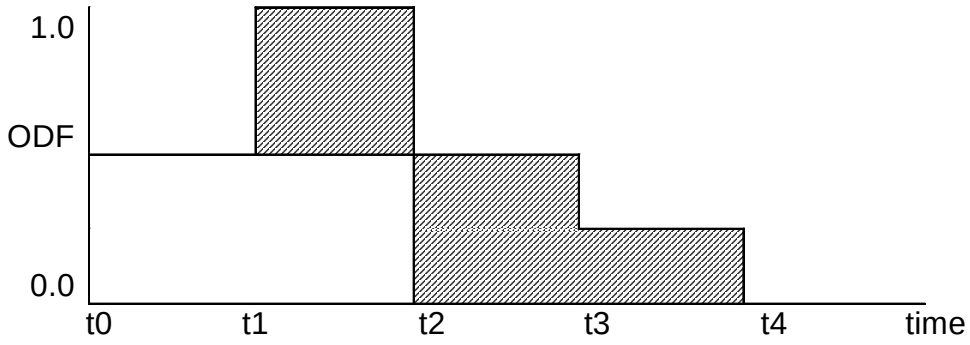
Case 3—Second outage with variable ODF.



t0 - forced outage due to V starts ODF = 0.5
t1 - forced outage due to AC-E starts ODF = 0.5
t2 - forced outage due to V ends
t3 - forced outage due to AC-E changes ODF ODF = 0.25
t4 - forced outage due to AC-E ends

This type of outage diagram occurs when the second outage takes out of service equipment not affected by the first outage.

EOD due to V = 0.5 (t2 - t0)
EOD due to AC-E = 0.5 (t3 - t1) + 0.25 (t4 - t3)

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Annex D

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CIGRÉ's "Protocol for Reporting the Operational Performance of HVDC Transmission Systems"—Fault classification codes

Category and subcategory	Code
A.C. and Auxiliary Equipment	AC-E.
AC Filter And Shunt Bank	AC-E.F
AC Control And Protection	AC-E.CP
Convertor Transformer	AC-E.TX
Synchronous compensator	AC-E.SC
Auxiliary Equipment & Auxiliary Power	AC-E.AX
Other AC Switchyard Equipment	AC-E.SW
Valves	V.
Valve Electrical	V.E
Valve, Valve Cooling (integral to valve)	V.VC
HVDC Control and Protection Equipment	C-P.
Local HVDC Control & Protection	C-P.L
Master HVDC Control & Protection	C-P.M
Telecommunication Interface/Coding Equipment	C-P.T
Primary D.C. Equipment	DC-E.
DC Filters	DC-E.F
DC Smoothing Reactor	DC-E.SR
DC Switching Equipment	DC-E.SW
DC Ground Electrode	DC-E.GE
DC Ground Electrode Line	DC-E.EL
Other DC Yard and Valve Hall Equipment	DC-E.O
Other	O
DC Transmission Line	TL
External AC System	EXT

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Annex E

(informative)

CIGRÉ's "Protocol for Reporting the Operational Performance of HVDC Transmission Systems"—Tables

Table E.1 through Table E.6 should be used to comply with the requirements of Annex B.

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Table E.1—DC system performance for back-to-back systems and for two-terminal systems reporting jointly

System: _____ **Year:** _____										
1. Energy transmitted GWh										
1.1 From _____ To _____										
1.2 From _____ To _____										
1.3 Total										
2. Energy utilization % Pm = MW / U										
3. Energy availability % EA										
4. ENERGY UNAVAILABILITY % due to:										
4.1 Scheduled Outages SEU										
4.2 Forced Outages FEU										
4.21 Substations FEUSS										
4.22 DC Transmission Line* FEUTL										
5. Forced outages due to:									**Number of events**	**Equiv. outage hours**
5.1 Substations SS										
5.11 A.C. and Auxiliary Equipment AC-E										
5.12 Valves V										
5.13 Control and Protection Equipment C-P										
5.14 Primary D.C. Equipment DC-E										
5.15 Other O										
5.2 DC Transmission Line[a] TL										
5.3 External AC System[b] EXT										
6. Commutation failure starts CFS(A)/recordable AC faults										
7. Forced outage severity	Capacity reduction		Convertor		Pole		Bipole		Total	
	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.

[a]Not applicable for back-to-back systems.
[b]Not included in unavailability.

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Table E.1 M/S—DC system performance for multiterminal systems and for stations reporting separately as part of two-terminal systems

System: _____ **Station:** _____ **Year:** _____										
1. Energy transmitted GWh										
1.1 As rectifier										
1.2 As inverter										
1.3 Total										
2. Energy utilization % Pm = MW / U										
3. Energy availability % EA										
4. ENERGY UNAVAILABILITY % due to:										
4.1 Scheduled Outages SEU										
4.2 Forced Outages FEU										
4.21 Substations FEUSS										
4.22 DC Transmission Line[a] FEUTL										
5. Forced outages due to:									**Number of events**	**Equiv outage hours**
5.1 Substations SS										
5.11 A.C. and Auxiliary Equipment AC-E										
5.12 Valves V										
5.13 Control and Protection Equipment C-P										
5.14 Primary D.C. Equipment DC-E										
5.15 Other O										
5.2 DC Transmission Line[a] TL										
5.3 External AC System[b] EXT										
6. Commutation failure starts CFS(A)/recordable AC faults										
7. Forced outage severity	Capacity reduction		Convertor		Pole		Bipole		Total	
	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.	Number of events	Forced energy unavail.

[a]Not applicable for back-to-back systems.
[b]Not included in unavailability.

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Table E.2 SS—Scheduled outages substation

System: _____ **Station:** _____ **Year:** _____					
Scheduled outages due to[a]		**Outage Code**[a]		**Severity Code**	
A.C. and auxiliary equipment		AC-E.X		Bipolar: BP	
Valves		V.X		Monopolar: P	
Control & Protection		C-P.X		Converter: C	
Primary D.C. Equipment		DC-E.X		Capacity Reduction:	
Capacity Reduction		RP			
Other		O.X			
Planned Maintenance: PM					
Outage code	Event or equipment failure description	Severity code	Repaired (R), replaced by Spare (S) or Manually restarted (M)	Actual outage duration AOD h	Reduction of capacity %

[a]See B.4 or Annex D for outage code subclassification for deferred outages.

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Table E.2 FS—Forced outages substation

System: _____	**Station:** _____	**Year:** _____
Forced outages due to	**Outage Code[a]**	**Severity Code**
A.C. and auxiliary equipment	AC-E.X	Bipolar: BP
Valves	V.X	Monopolar: P
Control & Protection	C-P.X	Convertor:
Convertor	C	
Primary D.C. Equipment	DC-E.X	Capacity Reduction:
Other	O.X	

Outage code	Event or equipment failure description (outage type)	Severity code	Repaired (R) replaced by Spare (S) or Manually restarted (M)	Actual outage duration AOD h	Reduction of capacity %

NOTES—Outage Type:
DD—delayed deblock
RB—ramped down and blocked
RE—reduction in MW
SR—stopped ramp
TR—automatic trip

[a]See B.4 or Annex D for outage code subclassification.

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Table E.3—HVDC overhead line protection operations

System: _____ **Year:** _____							
Event no.	**Date**	**Time of day**	**Pole voltage & polarity**	**Number of attempted restarts**	**Final restart successful/ unsuccess-ful**	**Actual outage duration if unsuccess-ful**	**Notes** (e.g. say if restart is at reduced voltage, which line section is affected or if automatic sectionalizing occurs)

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Table E.4—AC system faults & commutation failure starts back-to-back, two terminal or multiterminal systems

System: _____ Year: _____			
	Number of a.c. recordable system faults at inverter	**Number of CFS(A)**	**Number of CFS(B)**
1.1 Substation A:			
1.2 Substation B:			
1.3 Substation C:			
1.4 Substation D:			
1.5 Substation E:			
2. Complete HVDC System			
NOTES CFS(A)—Commutation failure starts by ac system faults. CFS(B)—Commutation failure starts initiated by control problems, switching events or other causes.			

Table E.5—Converter unit hours & thyristors failed

System: _____ Year: _____			
Convertor unit reference[a]	**6 or 12 pulse**	**Hours energized**	**Number of thyristors failed[b]**
	Totals:		

[a]Convertor unit reference refers to station, pole or convertor designator per B.5.6.
[b]See B.5.6, Step 4.

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Table E.6—Forced outage summary

System: _____ Station: _____ Year: _____															
Forced outages due to:	**Outage code**	**Capacity reduction**			**Convertor**			**Pole**			**Bipole**			**Total**	
		No. of events	**Actual outage events**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Equiv. outage hours**
AC Filter and Shunt Bank	AC-E.F														
AC Switchyard Equipment	AC-E.SW														
AC Control and Protection	AC-E.CP														
Convertor Transformer	AC-E.TX														
Synchronous Compensator	AC-E.SC														
Auxiliary Equipment	AC-E.AX														
Total AC and Aux. Equipment	AC-E														
Valve Electrical	V.E														
Valve Cooling (integral with valve)	V.VC														
Total Valves	V														
Local HVDC C&P	C-P.L														
Master HVDC C&P	C-P.M														
Telecommunication	C-P.T														
Total HVDC C&P	C-P														

Table E.6—Forced outage summary *(continued)*

System: _____ Station: _____ Year: _____															
Forced outages due to:	**Outage code**	**Capacity reduction**			**Convertor**			**Pole**			**Bipole**			**Total**	
		No. of events	**Actual outage events**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Actual outage hours**	**Equiv. outage hours**	**No. of events**	**Equiv. outage hours**
DC Filters	DC-E.F														
DC Smoothing Reactor	DC-E.SR														
DC Switching Equipment	DC-E.SW														
DC Ground Electrode	DC-E.GE														
DC Ground Electrode Line	DC-E.EL														
Other DC Yard and Valve Hall Equip.	DC-E.O														
Total DC Equipment	DC-E														
Other	O														
Total Substations	SS														
DC Transmission Line[a]	TL														
External AC System[b]	EXT														

[a]Not applicable for back-to-back systems.
[b]Not included in unavailability.

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Annex F

(informative)

Foundations for RAM calculations

F.1 System modeling

Any engineered system may be modeled as a combination of three basic reliability block structures (i.e., structures of components or subsystems in which any continuous left-to-right path is associated with a valid operating condition). These three canonical forms are shown in Figure F.1.

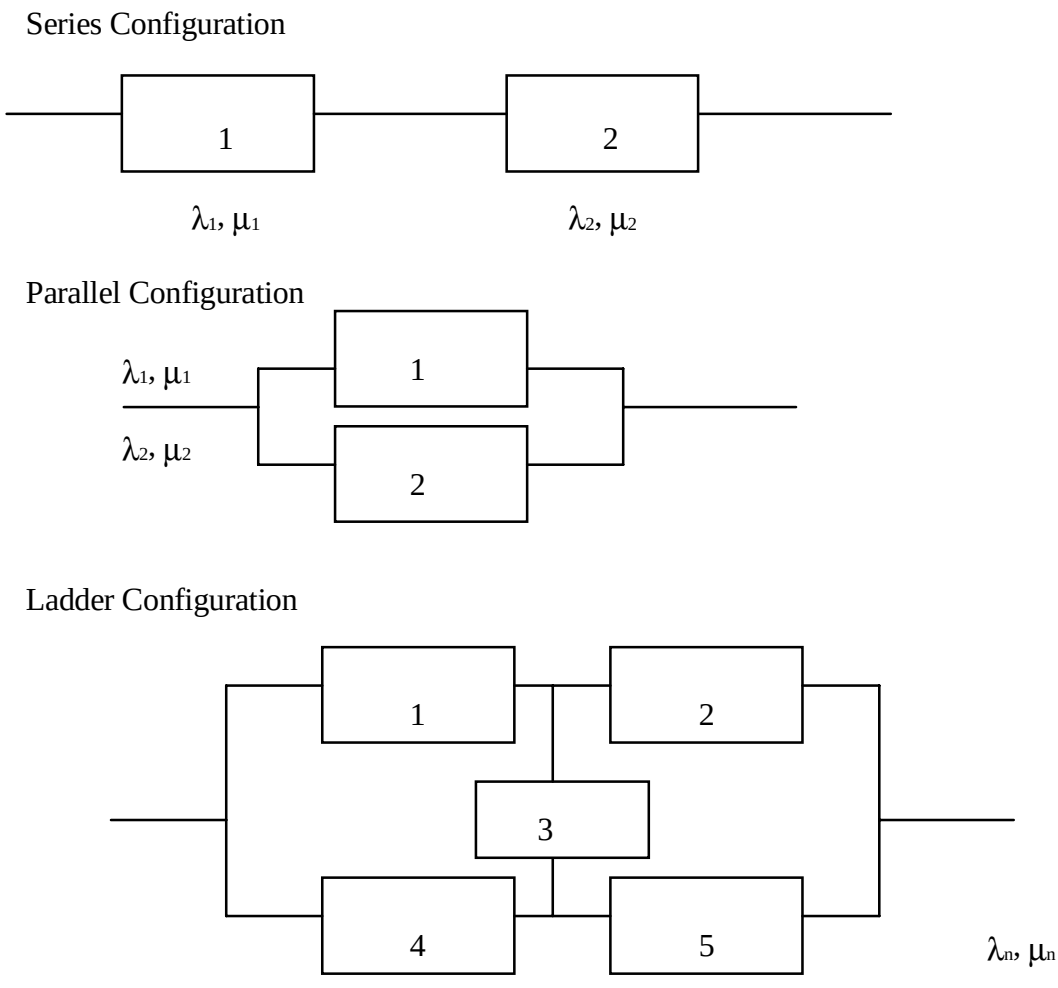

Figure F.1—Basic reliability block structures

Given a failure rate (λ) and restoration rate (μ) for each of the components in Figure F.1, each of these three configurations is associated with a specific pair of equations representing the net failure rate and net restoration rate of the respective configuration. These expressions, in turn, may be used in ever-growing combinations of these configurations until the system of interest is completely modeled. At any point in this

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"building block" process, one may convert the net failure rates and restoration rates into outage rates, availabilities, loss of energy expectations (LOEE), loss of load probabilities (LOLP), etc. The derivation of these equations, along with alternate analytical methods, is beyond the scope of this guide, but is provided at length in Lloyd and Lipow [B10], and in Billinton and Allan [B2].

NOTE—"Availability" and "unavailability," as described in this annex, are different from "energy availability" and "energy unavailability" as used by CIGRE for operational performance reporting (see Annex B). For full details on the qualitative and quantitative definitions of "energy availability" and "energy unavailability," refer to Annex B.

F.2 Fundamental RAM equations

To treat every potential calculation (including, for example, the effects of varying quantities of spares, reordering periods, and maintenance intervals) would require a text many times the length of this guide. Such texts already exist (Lloyd and Lipow [B10], along with Billinton and Allan [B2], among them); see them for details on how to calculate RAM parameters for any specific case of interest.

For simplicity, the following equations assume that

— The failure rate (or "hazard rate," λ, expressed as a number of failures per unit time) and the repair rate (or "restoration rate," μ, expressed as a number of repairs per unit time) are exponentially distributed for a given population of the same component, and

— These two rates are constant with time.

Lloyd and Lipow [B10], and Billinton and Allan [B2], treat the relatively few cases where these assumptions do not hold.

NOTE—Generally, 1% should be a small enough error for a good approximation, but prudence should be used for the particular application involved.

Then, the probability of survival to time t (i.e., the component's reliability) is

$$R(t) = e^{-\lambda t}$$

and the probability of failure by time t (i.e., the component's unreliability) is

$$Q(t) = 1 - R(t) = 1 - e^{-\lambda t}$$

If the component's failure rate is such that its expected lifetime is far greater than the time period of interest, then to a good approximation

$$Q(t) \cong \lambda t$$

and

$$R(t) = 1 - Q(t) \cong 1 - \lambda t$$

The mean time to failure is

$$\text{MTTF} = 1/\lambda$$

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the mean time to repair is

$$\text{MTTR} = 1/\mu$$

and the mean time between failures (i.e., “cycle time”) is

$$\text{MTBF} = \text{MTTF} + \text{MTTR} = \frac{\lambda + \mu}{\lambda\mu}$$

For simplicity

call $R_n(t) \rightarrow \boldsymbol{R_n}$, $Q_n(t) \rightarrow \boldsymbol{Q_n}$, and so forth

As a result

$$Q_n = \lambda_n t \text{ and so on}$$

F.2.1 Series systems

For the series configuration of F.1

$$R_{\text{total}} = R_1 R_2$$

$$Q_{\text{total}} = 1 - R_{\text{total}} = 1 - R_1 R_2$$

$$\lambda_{\text{total}} = \lambda_1 + \lambda_2$$

$$\text{MTTR}_{\text{total}} = \frac{(\lambda_1/\mu_1) + (\lambda_2/\mu_2) + (\lambda_1\lambda_2/\mu_1\mu_2)}{\lambda_1 + \lambda_2}$$

As a result, if

$$\frac{\lambda_1\lambda_2}{\mu_1\mu_2} \ll \frac{\lambda_1}{\mu_1} \text{ and } \frac{\lambda_2}{\mu_2}$$

then

$$\text{MTTR}_{\text{total}} \cong \frac{(\lambda_1/\mu_1) + (\lambda_2/\mu_2)}{\lambda_1 + \lambda_2}$$

and, in turn

$$\mu_{\text{total}} = \frac{1}{\text{MTTR}_{\text{total}}} \cong \frac{\lambda_1 + \lambda_2}{(\lambda_1/\mu_1) + (\lambda_2/\mu_2)}$$

Net unavailability is (if MTTF ≅ MTBF)

$$U_{\text{total}} = \frac{\lambda_{\text{total}}}{\mu_{\text{total}}} \cong \frac{\lambda_1}{\mu_2} + \frac{\lambda_2}{\mu_2}$$

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and, as a result, net availability is

$$A_{\text{total}} = 1 - U_{\text{total}} \cong 1 - (\lambda_1/\mu_1 + \lambda_2/\mu_2)$$

F.2.2 Parallel systems

For the parallel configuration of F.1

$$Q_{\text{total}} = Q_1 Q_2 = (1 - R_1)(1 - R_2)$$

$$R_{\text{total}} = 1 - Q_{\text{total}} = R_1 + R_2 - R_1 R_2$$

$$\mu_{\text{total}} = \mu_1 = \mu_2$$

$$\text{MTTR}_{\text{total}} = \frac{1}{\mu_{\text{total}}} = \frac{1}{\mu_1 + \mu_2}$$

$$\lambda_{\text{total}} = \frac{\lambda_1 \lambda_2 (1/\mu_1 + 1/\mu_2)}{1 + (\lambda_1/\mu_1) + (\lambda_2/\mu_2)}$$

As a result, if

$$\frac{\lambda_1}{\mu_1} \text{ and } \frac{\lambda_2}{\mu_2} \ll 1$$

then

$$\lambda_{\text{total}} \cong \lambda_1 \lambda_2 (1/\mu_1 + 1/\mu_2)$$

Net unavailability becomes

$$U_{\text{total}} = \frac{\lambda_{\text{total}}}{\mu_{\text{total}}} \cong \lambda_1 \lambda_2 (1/\mu_1)(1/\mu_2)$$

and, as a result, net availability is

$$A_{\text{total}} = 1 - U_{\text{total}} \cong 1 - \lambda_1 \lambda_2 (1/\mu_1)(1/\mu_2)$$

For "*m* out of *n*" parallel systems, in which at least *m* out of a population of *n* components are needed for the system to function, see Lloyd and Lipow [B10].

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F.2.3 Ladder systems

For the ladder configuration of Section F.1

$$R_{total} = [1 - Q_1Q_4][1 - Q_2Q_5]R_3 + [1 - (1 - R_1R_2)(1 - R_4R_5)]Q_3$$

$$= R_1R_2 + R_4R_5 + R_1R_3R_5 + R_2R_3R_4 - R_1R_2R_4R_5 - R_1R_2R_3R_5 - R_1R_2R_3R_4 - R_2R_3R_4R_5 + 2R_1R_2R_3R_4R_5$$

Billinton and Allan [B2], show how λ_{total}, μ_{total}, U_{total}, and A_{total} might be derived for such a system. Also, see their work for a representation of forced outages overlapping scheduled maintenance.

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