

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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3 Park Avenue, New York, NY 10016-5997, USA

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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:

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Sastry Kuruganty

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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.

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.

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

²IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, 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.

³IEEE 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/>).

- 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.

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

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:

- 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.

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.

- 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

⁴IEEE 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/>).

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)

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.

- 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.

- 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.

- 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

- 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).

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.