



BSI Standards Publication

Life extension guidelines for HVDC converter stations

National foreword

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TECHNICAL REPORT



Life extension guidelines for HVDC converter stations

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020; 29.240.10

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

LIFE EXTENSION GUIDELINES FOR HVDC CONVERTER STATIONS

FOREWORD

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INTRODUCTION

In today's complex environment, energy players face growing demands to improve energy efficiency while reducing costs. Energy shortages and increased ecological awareness have resulted in great expectations for grid stability and reliability. Utilities and industries are supposed to find eco-efficient solutions to maintain secure, safe and uninterrupted operations. A number of regulatory changes in the electricity market have led to increased efforts by utilities and grid operators for optimized utilization of their existing networks with respect to technical and economic aspects. As the electric power transmission system ages, the topics of life assessment and life extension have become predominant concerns. At the same time, cost pressures have increased the desire to minimize maintenance. The goals of minimum maintenance and extended life are often diametrically opposed.

The concept of simple replacement of power equipment in the system, considering it as weak or a potential source of trouble, is no longer valid in the present scenario of financial constraints. Today the paradigm has changed and efforts are being directed to explore new approaches and techniques of monitoring, diagnosis, life assessment and condition evaluation, and possibility of extending the life of existing assets.

A major challenge for grid operators worldwide is to ensure sufficient power with quality and reliability. In this regard high voltage direct current (HVDC) systems play a major role in bulk power transmission, system stability, integrating remote renewables and ride through of disturbances. Therefore, HVDC systems represent an indispensable part of the electricity grid in the countries where they are installed.

HVDC has been in commercial use since 1954, and most of the systems are still in operation. However, the early mercury arc valve systems have been phased out and replaced by thyristor valves. This has extended the life of many of the early systems, but the thyristor based systems are also approaching an age where the thyristor valves are likely to require replacement or refurbishment. Operation and maintenance issues of these ageing systems have become a challenge. The situation is further complicated by the fact that all of the HVDC systems are custom built by a relatively small number of original equipment manufacturers (OEM). The HVDC manufacturers have supplied several different generations of equipment and these differences are considered in any life extension assessment.

One major challenge in any refurbishment project is proprietary equipment. Most of the HVDC equipment is composed of unique devices for which replacement/refurbishment by other manufacturers is very difficult. For example, when planning to replace components of a thyristor valve, it is more likely to be only supplied by the original manufacturer which will drive the cost up for such replacement. However, this is still preferred if other component life is much longer, as the alternative would be to replace the entire thyristor valves which will be costlier. Proprietary equipment also causes difficulties in sharing details of equipment to other prospective suppliers for the refurbishment projects.

It is assumed that regular maintenance of HVDC system/component/equipment is being done by the owner as per the OEM recommendation as well as their maintenance practices. Further it is assumed that they are familiar with equipment details and records of equipment failure. They have knowledge of equipment behaviour, its characteristics and its impact on system performance based on international standards. This document deals with life extension of the HVDC converter station.

With the ageing of the equipment, measures to extend the equipment's life is considered by utilities and grid operators. Renovation, modernization and life extension of HVDC stations is usually one of the most cost-effective options for maintaining continuity and reliability of the power supply to the consumers. Implementation of these life extension measures is implemented with minimum impact on the HVDC system and the associated networks whilst maintaining an acceptable level of reliability and availability. If life extension is not economical, the systems are disposed of in an environmentally acceptable way. Also, consideration of environmental issues is made prior to a life extension project to avoid any inadvertent environmental damage.

The cost of outages to carry out a refurbishment is considered as part of the overall cost. This then dictates a greenfield option where a new converter station can be built and only short switch overtime is required. An example of this is the Oklaunion Converter Station (CS) in the USA, where the outage costs tipped the scale towards a greenfield versus a brownfield option for refurbishment. The definition of the interfaces in the case of a brownfield project is critical and more complicated than in a greenfield project.

Most utilities are interested in better understanding and projecting service life of HVDC equipment to help manage risk; however, generic reliability data is inadequate for current decision support needs. It is important to establish industry-wide equipment performance databases to establish a broad-based repository of equipment performance data. With proper care and analysis, this data can provide information about the past performance of equipment groups and subgroups, and the factors that influence that performance. With enough data, projections can be made about future performance. Both past and future performance information can be useful for operations, maintenance, and asset management decisions.

However, for some components it is more difficult than most to determine the useful life and the actual end of life failure modes. The thyristors themselves are an example, as they have been around for some 35 or more years and yet are showing little sign of reaching end of life, except where some design or quality issues have been uncovered.

Life-extension involves any of the following actions:

- Refurbishing the systems or subsystems,
- Selectively replacing ageing components,
- Combination of the above.

In some cases where life extension is not economically feasible, a greenfield replacement can be considered.

The following steps can be taken to arrive at a decision:

- Review the past performance of the major HVDC equipment and systems.
- Identify the future performance issues associated with the ageing of special components of the HVDC systems. The equipment that has not shown performance issues in the past but is still required during life extension, is also considered.
- Determine economic life of various components in the converter station and for making replacement versus life extension decisions. The consideration of economic life will include capital cost, reliability and availability, cost of maintenance and the cost of outages and power losses.
- The usable life of a refurbishment is likely in the average of 15 to 20 year range whereas a greenfield option is likely 30 to 40 years and this can be factored into the evaluation but it is recognized that some components can have a different year range.

One way of going about this activity could be to develop criteria, weightings and methodology for determining near-term action and forecasting the technical and financial effect due to system ageing. This follows an approach based on condition replacement cost and importance of the equipment and components. Assessment of condition parameters could be in terms of equipment age, technology, service experience (e.g. after sales service quality, maintenance costs) and future performance, individual failure rates, and so on. A viable duration for the life extension is determined and usually 15 to 20 years is achievable. Longer durations are more difficult to assess with any degree of accuracy.

Evaluation of the possibility of extending the service life of electrical equipment is a techno-economic compromise which can lead to "run-refurbish-replace" decisions. Once the expected service life period has expired, refurbishment of such equipment falls within the life extension program.

The investment at initial stage is very capital intensive to the utility concerned, as the devices to be installed in the system for residual life assessment (RLA) and condition evaluation purpose, are very costly. However, the decision to refurbish or to replace are generally done based on the study of comparable costs and benefits over the same potential life time of the asset.

Therefore, it can be concluded that the need for life extension and replacement of equipment in HVDC system arises due to:

- Arresting the deterioration in performance,
- Improving the availability, reliability, maintainability, efficiency and safety of the equipment,
- Regaining lost capacity,
- Extending the useful life beyond originally designed life of 30 to 40 years,
- Saving investment on new equipment,
- Not having availability of new spares due to obsolescence.

These objectives help utilities as follows:

- design refurbishment strategies for their existing HVDC systems to extend equipment life,
- evaluate O&M and reliability performance improvement strategies for their existing HVDC systems,
- provide a guideline for determining economic life of various components in the converter station and for making replacement versus life extension decisions. The consideration of economic life are generally capital cost, reliability and availability, cost of maintenance and the cost of power losses.

In order to achieve above objectives this document covers primarily following aspects:

- Key factors/reasons driving need for replacement work e.g.: system concerns such as relevance of link. Technical and commercial feasibility efficiency of the refurbishment planned.
- Failure or life degradation of equipment in the HVDC station.
- Critical equipment or critical interface points in the HVDC station.
- Planning of replacement work: Procurement – utility approach for procurement (OEM/multiple vendor) and reasons for adoption based on type of equipment.
- Plan of execution – scope definition, preparation of technical specification, existing system data requirement, etc.
- Outage planning.
- Performance guarantees
- World-wide experience of system operators.
- This document provides guidelines for the general procedure for performing life assessment (Clause 4). Following this, a more detailed description of performance issues of the thyristor based HVDC systems (Clause 5) is given and the life assessment measures of equipment (Clause 6) and guidelines for accessing the techno-economic life of equipment (Clause 7). Clause 8 deals with the recommendation for specification of refurbishing HVDC system and Clause 9 follows with the testing of the refurbished and replaced equipment. Further, this document will outline environmental issues (Clause 10) and regulatory issues (Clause 8) involved in the life assessment and finalize with a financial analysis of the refurbishment options (Clause 9).

This document is about life extension of HVDC converter stations only. Upgrading the converter stations or operating them beyond their design specifications is out of the scope of this document. However, for both of these OEM can be consulted as these are complex and a custom-built installation and the normal design rules will likely not apply.

LIFE EXTENSION GUIDELINES FOR HVDC CONVERTER STATIONS

1 Scope

This document provides guidelines for the general procedure for performing life assessment for an HVDC converter station. Following this, a more detailed description of performance issues of the thyristor based HVDC systems is given and the life assessment measures of equipment and guidelines for accessing the techno-economic life of equipment are given. This document also deals with information for specification of refurbishing HVDC system and the testing of the refurbished and replaced equipment. Lastly, this document outlines environmental issues and regulatory issues involved in the life assessment and concludes with a financial analysis of the refurbishment options.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

life extension

life assessment of the HVDC and the final result being beyond its original designed life time

Note 1 to entry: As a result of the life assessment, the output could be not to extend the life and this would be outside the scope of this document.

3.2

design lifetime

time for which the component has been designed to be commercially available or is commercially viable in its original supplied form

3.3

independent expert

person having an expert knowledge of a part or many parts of a HVDC link and is permitted to be a consultant or not

3.4

maintenance spare

spare component to replace a component within the system that is expected to wear out or have a limited lifetime, either in terms of operational (or storage) time or usage

Note 1 to entry: These components, known as maintenance spares, can be replaced at predictable and specified intervals.

3.5**strategic spare**

spare component to replace a component that has failed where failure and replacement cannot be predicated and quantified on a yearly basis and be random in nature

3.6**vendor-specific spare**

spare component that is available from the original equipment manufacturer only and for a limited period of time (typically about 15 years)

Note 1 to entry: For example, an HVDC control system has a life of approximately 15 years before a new generation is developed.

Note 2 to entry: If a spare component is purchased at the end of one generation and the spares are not available for the overall lifetime of the control system, a strategic spare parts management is required to ensure the availability of the system.

Note 3 to entry: Thus, the number of spares has a direct influence on the usable life of the equipment.

3.7**resin impregnated paper****RIP**

condenser paper in a bushing which is impregnated with an epoxy resin compound

3.8**refurbishment**

replacement, renovation or overhauling of components or equipment or parts of a system in response to wear or end of life

3.9**upgrade**

modification or replacement of parts of an HVDC link to add functionality such as AC system stabilization, overload capabilities, better dynamic performance, increased reliability and availability, lower maintenance, etc.

Note 1 to entry: An upgrade also includes increasing the rated transmission capacity of the HVDC link.

3.10**extension**

HVDC link that is extended to adapt to growing demands, involving additional converters or additional filters, etc.

3.11**greenfield**

developing a brand new HVDC link on a previously free and undeveloped area using all new equipment

3.12**brownfield**

developing an essentially new HVDC link or refurbishing part of HVDC link on an existing site

3.13**refurbishment outage time**

time during which the HVDC project being refurbished is kept out of service and not able to transmit energy

Note 1 to entry: Depending on conditions, the outage time requirement excludes system tests, and post-refurbishment.

3.14**insulated gate bipolar transistor****IGBT**

turn-off semiconductor device with three terminals: a gate terminal (G) and two load terminals, emitter (E) and collector (C)

Note 1 to entry: This kind of device is used in voltage-sourced convertor (VSC) HVDC application.

Note 2 to entry: Bi-mode insulated gate transistor (BIGT) and injection-enhanced gate transistor (IEGT) are variants of IGBT. There are several types of turn-off semiconductor devices which can be used in VSC converters for HVDC, too.

Note 3 to entry: For convenience, the term IGBT is used throughout this document to refer to the main turn-off semiconductor device.

4 General procedure for performing a life assessment**4.1 General**

A typical HVDC system consists of the following main equipment and sub-systems integrated for power transmission of the HVDC link:

1) Converter transformer and its associated bushings:

Primary side AC bushing is rated for system voltages. Secondary or valve side bushings are rated for AC-DC stresses. Further, depending on the connection to the thyristor valve bridge, bushings are used to compose the circuit of star or delta configuration.

2) Valve hall and its equipment:

This mainly consists of a thyristor valve along with its electronics, optical fiber and valve arresters. It also consists of DC current and voltage measurement devices and other surge arresters inside or outside depending on layout of system.

There is a valve cooling system either with or without piping and tubing of the valve cooling.

3) HVDC Control and Protection (C&P) system.

4) AC filters and associated AC switchyards:

Typically, AC circuit breakers feeding the AC filter and converter become critical from a transient recovery voltage (TRV) point of view. Other equipment such as AC surge arrester, AC CT and VT also require replacement during the course of life of the system.

5) DC switchyard and associated equipment:

In the case of point-to-point transmission with DC line/cable, the DC switchyard consists of DC filters, smoothing reactor, high speed pole isolating/connecting switches, commutating switches with commutating circuits, DC disconnectors, DC current and voltage measurement equipment, etc.

As indicated in list items 2) and 3), depending on the age of the project, thyristor failure rate statistics and the availability of spares (both with owner and OEM) justifies necessary validation. The owner reviews and judiciously decides whether valve replacement (along with all its electronic components within the valve hall considering ageing and performance) is required or not. If needed the same can be done with an integrated approach along with HVDC C&P. This approach with a larger scope provides the advantage of competitive pricing with an incremental cost to the owner. It is noted that in back-to-back HVDC, number of thyristor levels are generally lower as compared to bipolar HVDC scheme. HVDC C&P is vendor-specific firmware, software and hardware and as well as their valve design. Hence, replacement of HVDC C&P and the valve as a package could bring an optimal technical and commercial solution through multi-vendor competitive bidding.

The electrical equipment is stressed during operation, which causes ageing and degradation of equipment affecting equipment performance. The ageing mechanism and cause of failure differs for each class of equipment.

The plan to refurbish an old HVDC plant culminates from the life assessment of the above equipment in station (refer to Annex A). This is critical as it paves the path for prioritizing the equipment replacement, packaging and tendering of the scope of work. This document outlines the failures and ageing pattern of various types of equipment.

Each assessment will be slightly different depending on the needs and expectations of the owner as well as the information available. In many cases, only high-level information will be available, in some cases detailed information will be available. In most cases, only a technical evaluation is required but in others a commercial justification is also required. This document is intended to describe the technical procedure only.

Only the HVDC equipment will be considered in this document, as the AC equipment is outside the scope of this procedure and there are several sources of existing literature already covering this topic. This excludes AC and DC filters and synchronous condenser and SVCs or STATCOM.

4.2 Preparation

In preparation for performing the life assessment, it is critical to define the needs and expectations of the owner as much as possible. The next step is to produce a written proposal detailing the scope of work, information available and to be provided by the owner, deliverables and estimated cost. The proposal needs to be discussed with the owner and modified as required and agreed upon. It is also critical to determine the amount of time that a life assessment is good for. It is expected that a life assessment would be conducted shortly before the end of recommended lifetime is reached to evaluate if the system can be used for more years than expected. Taking into consideration the project and scope definition time, it is recommended to conduct life assessments for C&P systems after 15 years, for main components in a more regular basis, starting with the life assessment of C&P systems and then every 5 years.

4.3 Team

A team can be established which typically consists of the owners' staff, suppliers' staff and independent experts, or any combination thereof. The team structure is different if only one piece of equipment is being evaluated or if the entire HVDC station is being considered. Formal communication is expected to be through a leader on both the independent experts' and owners' sides only. Formal communication is anything that affects price, schedule or quality. Informal communications are still encouraged.

In general, a specialist or expert is employed for each of the areas, but some areas are critical because of the importance, complexity, or cost:

- Converter transformers and smoothing reactors – Critical because they are normally the highest cost item in a life assessment endeavour and are very complex.
- Thyristor valves – Critical as they are the next highest cost and a very specialized area.
- HVDC control and protection – Critical as they are very complex.
- Valve cooling systems – not as critical but still need proper evaluation.
- Air conditioning for control rooms and converter plant areas.
- Auxiliary systems – Critical, these are usually a source of many operating problems.
- Other DC equipment – includes DC current transformer (DCCT), DC voltage transformer (DCVD), disconnectors and breakers and switches.
- Civil – Ageing of structures and foundations.
- Miscellaneous – Wiring, fire protection, security buildings and ground grid. These items are usually overlooked in an assessment, but consideration of the same items is to be given.

4.4 Assessment process

A kick-off meeting with the team is recommended to obtain the information and discuss the format in which it is provided, as well as any software required to open the files and interpret the results. These are provided in a standard format such as using common word processing software wherever possible.

Several visits to the station(s) are carried out for discussions with the maintenance staff. Also, discussions are carried out with the operating staff to determine if the equipment is meeting their expectations. It is also determined whether there are any additional requirements that the existing equipment cannot provide and possible benefits.

The following are part of the analysis:

- Operating problems or changes in the mode of operation,
- Maintenance records for the last 5 years,
- Any modifications performed and why,
- Any failures and failure reports,
- Original quality or design issues,
- Any equipment replaced and when,
- Spare or replacement parts or obsolescence for major or critical equipment. An example is the number of thyristor failures per year, spares on hand and whether they are still available from a supplier.
- Status of spares – questions to consider are whether they are usable? Have they been maintained? Have they been in service and removed because they were of technical issue such as gassing of the converter transformer which were then repaired and returned to the replacement stock inventory? Have they never been in service?
- Technical skills of staff to continue operating and maintaining the equipment. Is additional training required?
- Normal life of each piece of equipment.
- Drill down to the smallest subsystem or components possible to check if it is possible to replace only some components and not the larger equipment subsystem or system. This could save a lot of cost but requires that detailed information be available.
- Criticality of the HVDC link to the system and consequences if it is unreliable or out of service.
- Risk assessment – is there a way to prevent or mitigate a risk? What needs to be done if the risk occurs?
- Some equipment does not have a history of problems and failures, but consideration is given that such issues will occur if the life assessment is long enough and is considered as a contingency.
- Replacement costs, wherever possible, are obtained from a supplier. Where this is not possible, estimated costs based on previous experience are required.
- An implementation schedule will also likely be required. Wherever possible the schedule is obtained from a supplier. Where this is not possible, a rough schedule based on previous experience is required.
- Environmental effects of the terminal and the surrounding site is considered.

As equipment is costly it is beneficial to use an independent expert to review an assessment provided by a supplier.

Regular status update meetings between the owner and the involved parties are generally held to ensure everyone is on track and to disseminate any new information, if available.

In order to make a future failure estimation, the asset owner could also use mathematical tools to analyse the historical records of the failure rate data of the existing high voltage equipment. Statistics and statistical tools could be applied to describe and analyse the failures for the decision-making process. Cigre TB 706, guidelines for the use of statistics and statistical tools on life data, provides more details on this topic.

Additionally, in general for the new system, a condition-based maintenance database is established to have a clear picture of the system at any time. In the case of replacement of components or refurbishment of systems, necessary sensors are built to facilitate such condition-based maintenance. Furthermore, with this database it would be possible to calculate the future failure probability of the equipment. As a result, it will be possible to get a clear picture of which equipment is expected to be renewed in what timeframe.

4.5 Deliverable

The deliverable is usually a report with a range of options for comparison, recommendations and conclusions. A preliminary copy of the report is reviewed with the owner incorporating any comments or concerns. In some cases, the owner will request additional work in a specific area requiring additional analysis, modifying the report and another preliminary meeting.

Eventually a final report will be issued. The owner will then combine this with the commercial analysis and make a final recommendation for brownfield or greenfield.

In the event that the owner also wants a commercial analysis, it is necessary to understand these requirements and follow the standard way or format in which the company produces the information and if the project is to be financed by a bank what is necessary for the bank to carry out its risk assessments.

4.6 Life assessment timetable

Life assessment generally begins 5 years (refer to Figure 1) before the time indicated in Table 1¹ or if there are high failure rates or maintenance issues.

The reality is that there is no piece of equipment where a firm number is accurate. The idea of coming up with a number is that if this piece of equipment has not caused any major problems up to the relevant point in time, a life assessment is generally done to determine the remaining life, refurbishment and replacement of that piece of equipment, subsystem or system, or if replacement is done, then the entire HVDC project is sometimes the best option. Only major items are considered in this document, and not subcomponents.

¹ Reproduced from CIGRE Technical Brochure No. 649 with the permission of CIGRE.

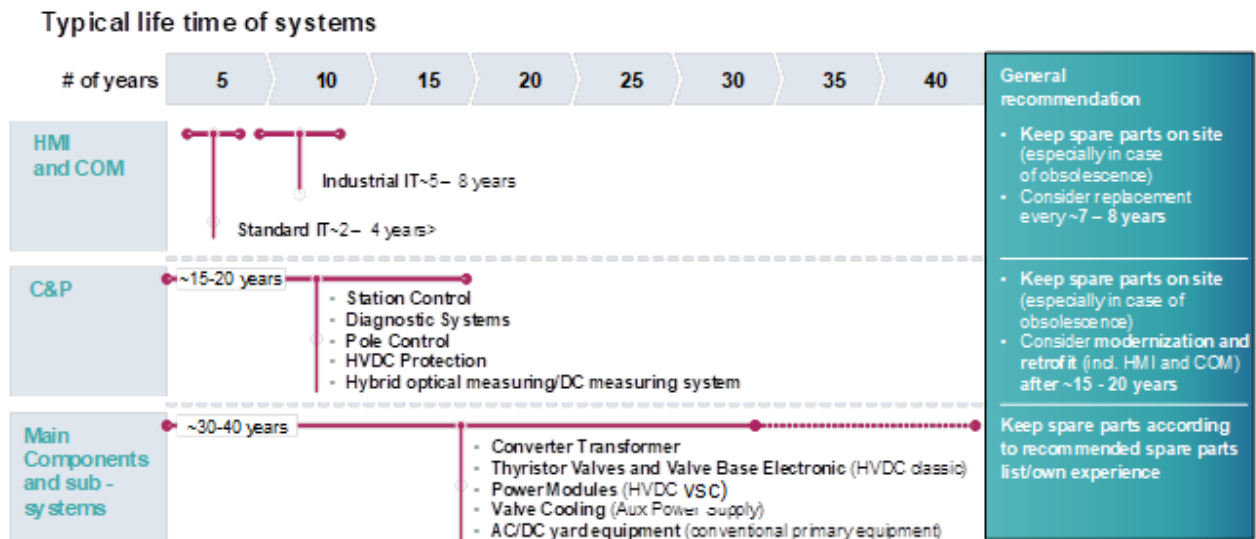


Figure 1 – Typical lifetime of systems/equipment in HVDC stations

The necessity to renew the different systems of an HVDC can be generally divided into four stages of the complete lifetime.

- 1) SCADA / HMI: 8 to 10 years
- 2) Control and protection: 15 to 20 years
- 3) Auxiliary system (heating, ventilation and air conditioning, cooling water control, auxiliary power etc.): 10 to 20 years
- 4) Main components: 30 to 40 years

As it can be seen that Stage 2 and Stage 3 are overlapping, it would make economic sense to combine the replacement of the control and protection system and the subsystems.

Table 1 – HVDC equipment lifetimes (typical)

HVDC equipment lifetimes		
NOTE Excludes design and production run quality issues		
HVDC station design life 30 to 40 years		
Equipment	Lifetime (years)	Comments
Converter transformer	40	Depending on load factor
AC Bushings	25 to 30	
DC Bushings	30 to 35	
Tap changer	30	Vacuum type tap changers generally have longer life span with higher number of operations as compared to oil filled tap changers. A refurbishment decision can be judiciously taken by the owner based upon the actual condition of tap changers.
Coolers	25	
Thyristor valves	35	
Thyristors	35	
Valve reactors	30	
Tubing	25	
Fiber optics	35	
Damping capacitor	30	
Damping resistor	30	
Electronic cards	25 to 30	
Coolers	25	The efficiency of the cooling system to be evaluated after 15 years.
Control & Protection		
HVDC Controls (digital)	15 to 20	
HMI	7	
Other major equipment		
DC smoothing reactor (oil)	35	Bushings have a shorter life
DC smoothing reactor (dry type air core)	35	Dry type air core reactor is simply called air core reactor
Optical DCCT	30	Electronics have a shorter life
DC voltage divider	30	
DC surge arrestors	35	
DC insulators	35	
DC wall bushings	30 to 35	30 OIP, 35 RIP – DC bushings have more insulation
DC switching equipment	35	
DC Bus work, structures	50	
Ground electrode	40 to 50	Normal design life
Civil work	50	
Communications systems	15	

Source: CIGRE Technical Brochure No. 649.

5 Thyristor based HVDC systems performance issues

5.1 General

HVDC technology has experienced enormous growth worldwide in the past 50 or more years, and many HVDC systems are currently in operation. As these systems age, asset management questions of what to refurbish, what to replace and the scope of equipment repair and replacement is becoming increasingly important to extend the life of all HVDC links.

An HVDC system will likely have a computerized maintenance management system (CMMS) which will contain more detailed records than that which is necessary for reporting to CIGRE or internally to high level management within an organization. It is important that the root cause analysis reports from the field experts can be stored in the CMMS system. Modern day CMMS also have asset management systems integrated into them to assist with life assessment decisions.

The following is some information about the collection of data from HVDC schemes throughout the world from those HVDC schemes that have submitted the information. This information can be useful for benchmarking or for discussions with staff from HVDC schemes that are similar.

5.2 Survey of availability and reliability of HVDC systems in the world

5.2.1 General

CIGRE SC B4 collects operational performance and reliability data of HVDC systems in commercial service in the form of annual reports. Such reports are prepared in accordance with a standardized protocol published in accordance with CIGRE Technical brochure 590 "Protocol for reporting the operational performance of HVDC transmission systems". Also refer to IEC TR 62672.

Performance data includes reliability, availability and maintenance statistics.

Reliability data is confined to failures or events which result in loss or reduction of transfer capability. Statistics are categorized in order to indicate which type of equipment caused the reduction in transmission capacity.

Advisory Group B4.04 of CIGRE Study Committee B4 (DC systems and Power Electronics) summarizes the performance statistics for all reporting schemes every two years in a CIGRE paper entitled "A Survey of the Reliability of HVDC Systems Throughout the World".

High levels of equipment reliability for individual HVDC links are also visible from the CIGRE performance reports. The CIGRE performance report also contains sections with the yearly number of forced outages and duration of forced outages (in equivalent outage hours) for each equipment category.

Converter station equipment is classified into six major categories: AC and Auxiliary Equipment (AC-E), Valves (V), Control and Protection (C&P), DC Equipment (DC-E), Other (O) and Transmission Line or Cable (TL).

5.2.2 AC and auxiliary equipment

This major category covers all AC main circuit equipment at the station (from the incoming AC connection to the external connecting clamp on the valve winding bushing of the converter transformer). This category also covers low voltage auxiliary power, auxiliary valve cooling equipment and AC control and protection. It is subdivided into following subcategories:

- AC filter and shunt bank AC-E.F

Types of components included in this subcategory would be capacitors, reactors, and resistors which are included in the AC filtering or shunt compensation of the converter station.

- AC control and protection AC-E.CP

Assigned to this subcategory are AC protection, AC controls, and AC current and voltage transformers. AC protection or controls could be for the main circuit equipment, for the auxiliary power equipment or for the valve cooling equipment.

- Converter transformer AC-E.TX

The converter transformers and any equipment integral to the converter transformer such as tap changers, bushings or transformer cooling equipment is assigned to this subcategory.

- Synchronous condenser (compensator) AC-E.SC

The synchronous condenser (compensator) and anything integral or directly related to the synchronous machine such as its cooling system or exciter is included in this subcategory.

- Auxiliary equipment & auxiliary power AC-E.AX

This subcategory includes auxiliary transformers, pumps, battery chargers, heat exchangers, cooling system process instrumentation, low voltage switchgear, motor control centres, fire protection and civil works.

- Other AC switchyard equipment AC-E. SW

This subcategory includes AC circuit breakers, disconnect switches, isolating switches or grounding switches and AC measurement equipment.

The classification of other groups can be found in IEC TR 62672.

5.3 Operating history

Records of equipment operating history are an integral part of equipment maintenance, and are required to verify the suitability of maintenance practices, in order to achieve the design life of the HVDC equipment.

Equipment operating history generally contains basic equipment technical data, maintenance intervals, detailed records of maintenance activities completed during the scheduled outages, components replaced to keep the equipment operational, forced outages caused by the equipment, results of scheduled inspections and diagnostic tests and results of tests done after replacement of components. The data also includes the root cause analysis reports for each forced outage and the corrective actions taken.

The data collected is used to assemble equipment condition assessment reports which assist in identifying any requirements to increase and change maintenance, repair or replace equipment.

5.4 Major equipment/system/sub-system failure/refurbishment summary

Modern thyristor based HVDC links are designed to last at least 30 to 40 years.

Not all equipment used in the converter stations will have a lifetime of the full 30 to 40 years. Therefore, if running the equipment to failure is not an option due to expensive consequential equipment damage and long unplanned outages, midlife replacement and refurbishment of HVDC equipment is a valid option.

The major HVDC equipment requiring life assessment activities are: converter transformers, valves, valve electronics, controls and protection, valve cooling, AC filters, DC filters, smoothing reactors and circuit breakers.

For HVDC links constructed in the 1970s (early thyristor links) the following life assessment activities were undertaken:

- Valve controls and valve electronics upgrade: between 16 and 44 years in service after commissioning. Some systems are still in service.
- Control and protection system upgrade: between 26 and 42 years. Some systems are still in service.
- The replacement of thyristors in some projects was completed after 21 to 30 years of thyristors in service.
- Cooling systems have been upgraded or replaced after some 25 years of service.
- Replacement of oil filled smoothing reactors (with air core or oil) and oil filled direct current transformer (DCCTs) after some 35 or more years of service.
- Refurbishment of converter transformers after about 30 years of service.

For the HVDC links constructed in the 1980s, the following life extension activities were undertaken:

- Control and protection system upgrade: between 23 and 35 years. Some systems are still in service.
- Valve cooling system upgrade: after 24 years in service.
- Valve upgrade (together with valve cooling) after 25 to 31 years in service. Some valve systems are still in operation.

5.5 Life assessment and various options for a refurbishment project

As mentioned in 4.6 various components of the HVDC system have different design life. In order, to maintain the performance of the HVDC link at an acceptable level, the components can be replaced as they approach the end of their design life.

Therefore, the refurbishment options fall into two categories:

- Selective repair and refurbishment or replacement of HVDC equipment;
- Complete replacement of HVDC converter stations.

a) Selective repair and refurbishment or replacement of HVDC equipment

As some components (e.g. controls) have a much shorter design life than the major components like converter transformers, selective refurbishment will be required during the expected lifetime of the project (30 to 40 years).

It is very important that equipment can be repaired as spare parts remain available, and the knowledge base (engineering and technical staff) is retained.

Equipment replacement is required if spare parts are not available (OEMs are no longer in business). The parts are phased out, discontinued, cannot be remade or they are reverse engineered locally, or the knowledge base is lost (maintenance personnel familiar with the equipment have retired).

Selective equipment replacement is an excellent method to achieve the design life of the HVDC link if other components that are not refurbished or replaced can last until the end of HVDC converter station extended life.

b) Complete replacement of HVDC converter stations

Complete converter station replacement is required when the majority of the equipment is at the end of its design life; the HVDC link is still required for power transfer, or AC system performance improvement. This can ultimately be a combined economic and/or technical decision to determine the scope of replacement.

The advantage of complete replacement would be a much larger design life and a system which has been uniformly engineered and supplied by a single supplier whereas the disadvantage would be the higher cost. Complete system replacement would mean longer shutdown of the HVDC system. Depending on the staging of the replacement and the placement of the new station, outage times can be minimized as a new station can be built next to the existing (running) one. However, for that, additional space is necessary.

Complete replacement of HVDC converter stations is also an opportunity to increase the steady state power transfer capability, dynamic power transfer capacity of the link or where a lengthy outage to the existing converter stations is not acceptable. In some cases, this is an opportunity to switch from LCC technology to VSC technology.

In any case, actions for extending converter station life can be addressed before HVDC link reliability and availability are impacted.

Irrespective of the choice of replacement technology (LCC or VSC), the following options can be considered for determining the economic impact.

- 1) Build a greenfield new station near the existing station, then transfer over.
- 2) Build a new station near the existing station but use some of the components of the original converter.
- 3) Build the new station at the same location.

The economic impact of replacing the LCC converter with a VSC converter will depend on what option is chosen for replacement. Issues related to replacement of LCC converters with VSC converters are discussed in Annex B.

- **OPTION 1 – Build a greenfield new station near the existing station, then transfer over.**

In this option a new station using all new equipment is built near the existing station. This option will result in the shortest outage time. The existing system will continue to transmit power while the new station is being built. Once the new station is ready, an outage of 3 to 6 months will be required to commission and integrate the new station into the system. This option will result in a minimum amount of revenue loss.

- **OPTION 2 – Build a new station near the existing station but use some of the components of the original converter.**

In this option, an additional several weeks will be required to move the equipment from the old converter to the new converter. This time will be in addition to the commissioning period as required in option 1. The additional outage time required will depend on what components are being reused.

For example, if the auxiliary equipment (battery banks, etc.) are to be reused, the existing system would be shut down much earlier than if only the smoothing reactor, etc. is to be reused.

The cost of buying new equipment vs loss of revenue resulting from additional outage are generally taken into account in deciding if some components of the old system are used or not.

- **OPTION 3 – Build the new station at the same location.**

In this option, the old system would be shut down completely from the time the removal of the existing equipment starts until the new system is in operation. If the existing valve halls cannot be reused, the old buildings would be demolished and a new building built at the same location. This will result in outage time being the longest of the three options. This duration is estimated to be at least 5 to 6 months to remove the existing facilities and building a new building and equipment takes an additional time in the range of 28 to 32 months.

The final choice is determined by the following factors:

- Availability of land nearby

The availability of land depends on the location of the existing station. If the station is located in an open area outside the populated area, it is likely possible to purchase land adjacent to the existing station. However, if the station is located inside a populated area, it is likely not possible to obtain land for building a new station.

- Cost of outages

The cost of outages is determined by the function of the HVDC system in the overall power system. In cases where the HVDC system is transmitting power from a dedicated generating station to the load centre with no parallel transmission system, the cost of outages will be higher than the cases where a parallel transmission system is available.

In other cases where an HVDC system was built to transmit power from a dedicated thermal generator, the cost of outage is much lower if the generators are refurbished/replaced at the same time.

- Feasibility of using the old equipment

Major equipment like converter transformers, smoothing reactors and bus work have a much longer design life than the rest of the equipment. These components are allowed to be reused for the refurbished system provided the system rating has not been increased.

If old equipment is reused, on-site spares (e.g. spare converter transformers) can be available to reduce the outage time in the event of failure.

- Feasibility of using the existing valve halls

Most HVDC systems that require complete refurbishment/replacement are more than 40 years old. Even though the number of thyristors required have been reduced to less than 50 % it does not automatically mean that the new thyristor valves can be installed in the old valve halls.

The feasibility of fitting new valves in the existing valve halls needs to be evaluated with the vendors before going to valve refurbishment.

If the standard design of valves will not fit in the existing valve halls it becomes necessary to custom design the valves if the existing valve hall can be used. This will result in additional cost.

5.6 Methods for assessing reliability, availability and maintainability of existing components

CIGRE's survey of the reliability of HVDC systems throughout the world enables HVDC link asset owners and operators to compare the performance of their own HVDC link against the performance of similar HVDC links in the world. It is recommended for owners seeking to assess the reliability, availability, and maintainability of components, to actively participate in the CIGRE HVDC survey.

The goal is that the accumulated data from several systems would establish a basis against which performance of individual HVDC links could be judged.

Performance of any HVDC system can be evaluated using data on energy availability (EA), energy utilization (EU), forced energy unavailability (FEU), scheduled energy unavailability (SEU) and thyristor failure rates, as well as examining equipment categories causing forced outages or reduction of HVDC system capacity.

In the CIGRE survey and statistics carried out by Advisory Group B4.04, the following definitions are used:

- 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.
- 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 programs.
- Forced outage – The state in which equipment is unavailable for normal operation but is not in the scheduled outage state is referred to as a forced outage.
- Forced outages can be caused by trips – sudden interruption in HVDC transmission by automatic protective action, manual emergency shutdown, or unexpected HVDC equipment problems that force immediate reduction in capacity of HVDC stations or system but do not cause or require a trip.
- 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.
- Energy unavailability (EU) – A measure of the energy which could not have been transmitted due to outages is referred to as energy unavailability.
- Energy utilization (U) – A factor giving a measure of the energy actually transmitted over the system.

For example, comparing the performance of one HVDC link against similar pairs.

Scheduled equipment unavailability (SEU) has less significance than forced equipment unavailability (FEU) in comparing different systems since scheduled outages are allowed to 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. As each system follows different maintenance practices, the scheduled energy unavailability (SEU) can vary considerably between systems. For example, some systems shut down the entire system for two weeks every year for scheduled maintenance whereas other systems perform maintenance only once every four years for a week.

5.7 Basis for replacement/refurbishment of equipment

HVDC converter station equipment (and subsystems) is complex and has varying design lifetimes. Each piece of equipment, system or subsystem is generally assigned a "normal" lifetime which, as it approaches, could trigger a life assessment.

The criteria for equipment replacement and refurbishment are related to the risks the asset owner is ready to take and potential lost revenue which is correlated to equipment performance.

For example, capacitors can be replaced after design life is exceeded. However, they can also be replaced after the number of failures exceeds a percentage of installed capacitors per year (e.g., 2 %). The latter option implies a number of filter bank trips or loss of redundancy (maintenance outage), which are the consequence of failed capacitor cans.

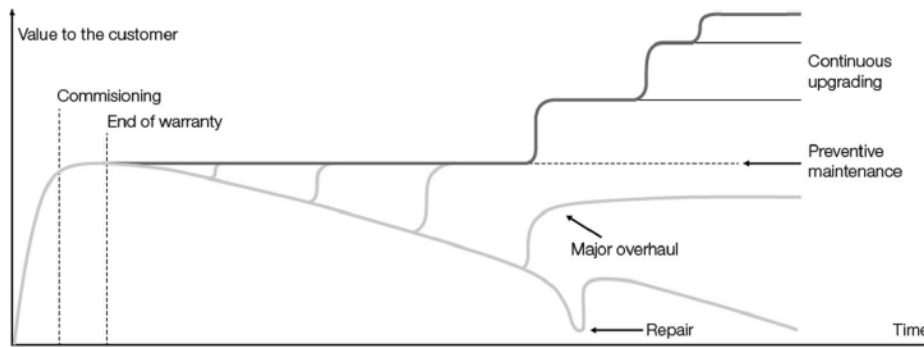


Figure 2 – Typical equipment performance curve

Figure 2 shows equipment performance with the passage of operational time based on equipment failure rate and ageing. The curve also shows the requirement of major overhaul and additional investment/effort in order to achieve the same value to the customer as well as indicating the importance of the HVDC link by carrying out suitable upgrades.

A conservative approach would be not to run the equipment beyond the manufacturer's recommended design life. An assumption is that the spare parts and skilled maintenance personnel are still available.

The following conditions could require equipment replacement or refurbishment even before the design life is exceeded:

- Poor performance of equipment. An unacceptable number of HVDC trips caused by this equipment reducing HVDC availability, or long scheduled outages required to keep the equipment in a serviceable condition.
- The type of equipment is not manufactured any more (for example circuit breaker) and there are no spare parts available. It is possible to postpone the replacement of the whole equipment fleet, say of circuit breakers, by replacing one or more circuit breakers, and using the parts from the units removed from service as a source of spares. In some cases, the parts can be reverse engineered by the utility if it has the knowledge or by other firms such as tap changer parts which specialize in this field.
- Engineering and maintenance staff retiring and the knowledge base of how to maintain some equipment is being lost and the supplier also cannot support maintenance of the equipment.
- The results of equipment condition assessments showing poor or deteriorating equipment conditions (for example very low degree of polymerization paper inside converter transformers), could justify earlier replacement, even before equipment design life is exceeded.
- Failures of the same type of equipment at other HVDC links, could justify unscheduled equipment condition assessment, and if required, early replacement.
- Manufacturer instructions to remove equipment from service due to a production defect (e.g. use of unsuitable material for components during production) could result in early equipment refurbishment.
- Under direction from an outside regulatory body (safety or environmental issues for example).

- Technical obsolescence – older software versions are no longer supported by the OEM and the new software requires new hardware.
- High cost of operations maintenance and administration. OP-EX stands for operating expense. COMA – stands for cost of operations, maintenance and administration.

5.8 Performance after replacement and refurbishment

Reliability performance data collected for CIGRE reporting purposes (data on energy availability, energy utilization, forced and scheduled outages and other data in accordance with the reporting protocol per IEC TR 62672) can be used to evaluate success of equipment replacement.

Performance improvement is generally visible by comparing HVDC reliability data and loss of redundancy data (number of forced outage events and the equivalent forced outage hours relevant to replaced equipment category) two years before replacement and two years after replacement.

However, if the equipment was performing well and had enough spare parts (for example the control and protection system) but was replaced with the new model due to obsolescence, then good performance in the future will be the sign of successful equipment replacement. If equipment is replaced as a result of condition assessments identifying poor or deteriorating equipment, prior to the equipment affecting performance indicators, there could be an expectation of a reduction in maintenance and that is generally reflected in maintenance records and maintenance hours required.

6 Life assessment and life extension measures of equipment

6.1 General

This Clause 6 discusses the life assessment and life extension measures of the HVDC equipment from a technical point of view based on the premise that all types of the equipment have been properly maintained by following the maintenance instructions recommended by their original equipment manufacturers (OEM). The AC switchyard equipment is not covered in this Clause 6, except for the converter transformers.

The first and most important part of the life assessment procedure is to inspect the site works. During the inspection any visual defects or damage to equipment are noted. Discussions are conducted with the operating teams and maintenance teams on site to note their observations and suggestions. Station maintenance, availability and reliability and equipment failure logs are reviewed. Changes in the system as compared to the system during design of HVDC system can be noted and its effects on the HVDC system determined. Availability of spares in store as well as whether spares are still available for purchase from the manufacturer are noted down. Recurring problems due to design defects are also noted down. In the case of control and protection systems' components, cards and relays can be checked to check if they have become obsolete. Operating systems are checked for the supplier support availability. Modifications from original design are also noted.

Site testing involving testing of different equipment to determine the health of the equipment is an important part of life assessment. This includes measuring parameters like resistance; capacitance, inductance, tan delta as well as dielectric withstand tests. The scope of testing is limited by the site conditions, available test equipment on site as well as requiring the shutdown of the plant for testing. In some cases, special test facilities (mobile testing system) are also brought to the site for more detailed testing. The test results show not only the health of the equipment, but also present parameters of existing equipment which are needed in case of refurbishment of other equipment.

In general, the health of the existing equipment can be ensured to define the exact scope of the planned refurbishment.

This can be done via visual inspection, check of sequence of events recorder (SER) and transient fault recorder (TFR) messages, and the knowledge of abnormalities observed during maintenance outages.

Most converter stations employ some kind of computerized maintenance management system (CMMS). It can be part of a larger system, a standalone system or a home-grown system. There is continuing pressure to reduce maintenance costs and outage times and some utilities have moved to reliability centred maintenance (RCM) systems and away from time-based systems. RCM generally relies on doing maintenance based on levels of inspections, importance of equipment, is condition based and relies on appropriate and timely maintenance intervention. This has the effect of improving reliability and availability and reducing maintenance costs. This can be a hard sell to existing converter station staff who are used to a time-based system.

During the warranty period of the OEM, maintenance requirements can be followed and well documented to prove that the maintenance has been completed. After this period condition-based maintenance or RCM can be adopted.

It is very important to have good maintenance records to analyse the equipment performance with the root cause analysis of any failures. Complete systems have been replaced by utilities because the root cause of the problem was not identified and thus the problem was still there after replacement. Trend analysis is also very important as a bad reading or information, or statistical analysis can skew an analysis with very little data. Good records are also very important to assist in justifying any refurbishment or replacement as it can be readily shown how much improvement is possible and what the benefit could be in increased revenue.

6.2 Spares

The number of spares that are available especially for items such as the DC controls can impact the usable life of the equipment. Spares can be broken down in many ways, one way is as follows:

- RAM and performance guarantees spares – Spares required to meet the RAM, and performance guarantees requirement of the contract, usually 2 years.
- Initial spares – Spares for the first 10 to 15 years to get a record of the failure rates and then to order more. The supplier will usually guarantee availability of spares for that period.
- Insurance spares – Spares to cater for infrequent failure (e.g. DC wall bushing).
- Consumable spares – Items to be consumed due to normal failure rates (e.g. fan, motors).
- One-supplier items – Some items are only available from the OEM, control cards are an example whereas AC filter capacitors are available from many vendors on relatively shorter notice, and thus stocking levels will likely be different. In most instances exact replacements are generally available; however, in certain instances a re-design of the bank is required.

Some utilities are starting to specify that enough spare parts be supplied to last the 35 to 40 year life of the project. This could help ensure the viable life of 40 years of these types of devices.

6.3 Converter transformers

6.3.1 General

An HVDC converter transformer is, in many ways, similar to an AC transformer. This Subclause 6.3 will only focus on the differences between them from a life assessment and extension point of view.

6.3.2 Life assessment

The life of HVDC converter transformers is expected to be around 40 years, but it can differ greatly depending on many factors.

Life assessment of a converter transformer is similar to that of an AC transformer. In addition, special consideration for the converter transformer includes the following:

- **DC bushings.** The oil end of a DC bushing (including the condenser core) is an integrated part of the transformer insulation structure. The condenser foils are aligned with the DC barriers such that only a bushing with the exact make, type and model can be used for replacement. Thus, lack of spare DC bushings can be a major factor limiting the service life of the converter transformer. The life of a DC bushing is expected to be 30 to 35 years, but its remaining life is hard to predict. It is advisable to periodically perform the capacitance and power factor tests and other tests recommended by the OEM in order to identify signs of potential failure. It is possible to take oil samples, but it is not generally recommended by the bushing manufacturers considering that it would risk contaminating the oil and is likely to require the replacement of a nitrogen gas cap. This is generally done only when absolutely required and following the OEM's instructions. In some instances, a valve is provided at the bushing flange, which makes this a lower risk operation.
- **Tap changers.** The tap changer of a converter transformer operates much more frequently than that of an AC transformer. For example, a typical HVDC scheme can have more than 5 000 tap changer operations per year at the inverter and many more operations at the rectifier. Because of such a high number of operations, regular inspection and necessary overhaul are required in order to keep the tap changer operating reliably. The condition of the tap changer can be determined by reviewing its maintenance records. Its operating characteristics can be easily monitored in real time thanks to advances in technology. The number of operations and the measurement of the amount of wear on the arcing contacts are indicators of end-of-life (EOL) or a need for refurbishment. The diverter conservator filling or removing of oil while in service is an indication of an oil seal or O-ring failure between the main tank and the diverter vessel.
- **Core and windings.** A converter transformer is more prone to internal failure due to its additional complexity (e.g. DC cocoon insulation, DC bushing as part of the insulation structure, etc.) and special service conditions (e.g. AC and DC voltages/currents, harmonic currents, etc.). Oil gassing is an indication of potential internal failure. Online hydrogen monitoring can give a quick indication of any gassing concerns which would then be followed up with oil sampling and dissolved-gas analysis (DGA). It is noted that DGA is not a substitute for condition assessment and the information from DGA merely provides a high-level indication of a potential problem and when to conduct a more detailed assessment. Testing of a converter transformer for a condition assessment generally follows the manufacturer's instructions. This could include frequency response analysis, core vibration tests, partial discharge tests as well as the periodic dielectric tests. When a failed converter transformer is repaired in the factory, this could provide an opportunity to assess the condition of the unit and extrapolate this information into the other transformers, as they are usually similar in design.

6.3.3 Refurbishment/Replacement

The replacement or refurbishment of a converter transformer is similar to that of an AC power transformer. In addition, special consideration for the converter transformer includes the following:

- **DC bushings.** If a DC bushing fails, it can be replaced with a spare having the exact make, type and model as previously described. Because DC bushings are very expensive as compared to AC bushings, it is more economical to refurbish a DC bushing by replacing its core and/or seals if required, but it would be done by the OEM. The current revision of the IEC/IEEE 65700-19-03:2014 converter transformer standard requires the manufacturer to provide sufficient information so that replacement bushings can be obtained if the OEM is not available or no longer in business. In some cases, the utility or contractor is capable of replacing seals, processing, and testing.

- Tap changers. Spare/replacement parts for older tap changers are difficult to find and/or costly to procure. Some utilities have refurbished the tap changers using reverse engineered parts. In other instances, the entire tap changer has been replaced with the assistance of the transformer manufacturer. Retrofitting of vacuum type diverter switches and tap changers is offered by many suppliers and can be considered if full replacement is warranted. This can help reduce maintenance costs and frequencies.
- Core and windings. It is sometimes economical to replace either the windings or the core, but not both. A business case analysis is generally conducted taking into consideration any design improvements and the associated benefits. The remaining life of all other components such as the bushings, tap changers, etc. can also be included in the analysis. It is possible to repair a tap changer lead or other connections in the field depending on internal access. These are generally done by the OEMs or under their supervision. Loose core laminations can be fixed to some degree and loose blocking can be repined, again depending on access. In the event of having loose core laminations, online degassing allows the converter transformer to stay in-service until a scheduled shutdown. This was successfully done by one utility for several years. An online multi-gas analyser can be added during the degassing or to the transformer of concern in order to provide instant notification of any changes to the gassing pattern.

6.4 HVDC control and protection

6.4.1 General

HVDC control and protection (C&P) systems usually covers bipole control functions, pole C&P functions and group C&P functions of the HVDC system. The control and protection functions are closely integrated, and therefore always designed, installed and replaced/upgraded together. Valve base electronics (VBE) provides monitoring and protection for each valve and serves as an interface between the VG control and thyristor valves. The pole/group controls and VBE are covered separately. Older HVDC systems used analog controls, however with only a couple of exceptions the analog controls have already been replaced with digital controls.

6.4.2 HVDC converter controls

6.4.2.1 General

Digital C&P systems have been commonly used in modern HVDC systems. Their control and protection functions are realized with programmable controllers each consisting of highly integrated modules such as CPU modules, I/O modules, communication modules, interface modules, etc.

6.4.2.2 Life assessment

Rapid advances in technology, design, hardware, and software as well as changes in system requirements tend to make the service life of digital systems relatively short. The service life of digital systems is typically 15 years. It is noted that C&P hardware is bought by supplier around 2 to 3 years before planned commissioning to perform factory system test (FST) before the delivery.

The digital system usually comes with full redundancy and comprehensive self-monitoring functions. A single mode failure does not normally result in a system outage. This combined with a shorter service life makes the digital system virtually immune from the various performance related issues resulting from component ageing and failures.

After 10 years of operation or as needed, a digital system is assessed for its remaining life with a focus on the following potential limiting factors:

- Spares. Most of the parts in a digital system are single source items, i.e. they are available only from the OEM. The various functional modules are an example. Lack of spare parts in stock and inability to procure them will result in the EOL of the digital system.