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TECHNICAL REPORT

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HVDC installations – Guidelines on asset management

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HVDC installations – Guidelines on asset management

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HVDC INSTALLATIONS – GUIDELINES ON ASSET MANAGEMENT

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 62978, which is a technical report, has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
115/148/DTR	115/159/RVDTR

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

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

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- withdrawn,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

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

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INTRODUCTION

Asset management is defined as the act of structured and coordinated efforts by an organization to optimally manage its assets and their associated performance, risks and expenditures over their life cycle.

The management of physical assets (their selection, maintenance, inspection and renewal) plays a key role in determining the operational performance and profitability of industries that operate their assets as part of their core business.

In general, High Voltage Direct Current (HVDC) systems have specific requirements that need to be addressed separately as compared to conventional High Voltage Alternating Current (HVAC) power transmission due to underlying differences in technology.

HVDC systems are a well proven technology employed for bulk power transmission all over the world, mainly because of its superior controllability of transmitted power. It can be utilized for various applications such as stabilization of the connected Alternating Current (AC) network, dynamic control of frequency and modulation of active and reactive powers. In addition, HVDC is more economical for long distance transmission of bulk power and applicable for interconnecting asynchronous AC networks.

An international standard defining key elements of asset management framework for HVDC installations is therefore crucial to provide ample foundation for best practices to be implemented to achieve high efficiency, availability and reliable long-term operation.

At present the activities with respect to asset management are standardized as International Standard in the ISO 55000 series. The general principles are given in ISO 55000 with further details in ISO 55001:2014, Asset management – Management systems – Requirements and ISO 55002:2014, Asset management – Management systems – Guidelines for the application of ISO 55001. These standards are developed from the British Standard Institute (PAS-55:2008), which recommends a general asset management framework for physical assets. The PAS 55-1:2008 document was referred to in the initial development of this technical report.

In the absence of a credible standard reference on asset management of HVDC, utilities all over the world presently practice HVDC asset management based on their own interpretation and experience gathered through the years, which may not be in line with the best and prudent practices. This IEC Technical Report on the guidelines of asset management for HVDC installations is the first step, moving forward, in providing a standard framework and reference point for operators and owners of an HVDC installation based on best industry practices.

HVDC INSTALLATIONS – GUIDELINES ON ASSET MANAGEMENT

1 Scope

This document gives guidelines on the current asset management perspectives for HVDC installations based on best practices of asset owners, operators, users, original equipment manufacturers and regulators within the power industry.

Asset management is a set of systematic and coordinated activities and practices through which an organization optimally and sustainably manages its asset and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan.

An asset management system is the embodiment of the asset life cycle starting from asset planning, creation, utilization, operation, maintenance, and to the extent of, the retirement and disposal of the asset. It consists of the organization's asset management policy, asset management strategy, asset management objectives, asset management plans and the activities, processes and organizational structures necessary for their development, implementation and continual improvement.

The scope is limited to the DC plant/equipment side of the HVDC system including related AC components of the HVDC converter station. This document covers all equipment of HVDC converter station and electrode station but does not include DC lines and cables.

This document covers HVDC systems with Line-Commutated Converters (LCC) and can be generally applied to Voltage Sourced Converters (VSC), not including specific equipment or sub-equipment required under VSC.

This document on asset management covers:

a) policy and strategy;
b) training;
c) information management;
d) change management;
e) life-cycle costing;
f) tools;
g) performance monitoring and measurement;
h) documentation, operation and maintenance; and
i) risk management.

This document provides base guidelines on fundamental aspects and prudent practices to be considered by stake holders in managing HVDC assets. Compliance to additional requirements and recommendations stipulated in this document by the supplier or OEM are non-obligatory, unless explicitly specified by the customer.

The guideline was prepared based on the following references to establish best practices:

– published documents from other related organizations e.g. CIGRE;
– an international survey on current practices of HVDC installations conducted by IEC TC 115 (see Annex B);
– regional and international forum on management of HVDC assets;

– HVDC user working group; and
– asset management practitioners.

The international survey document and results on the asset management practices are available with the Secretariat of IEC TC 115.

The main objective of this document is to highlight an asset management standard framework for HVDC installations based on best known industry practices. This guideline can be beneficial as reference document in the management of HVDC assets.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60633:1998, *Terminology for high-voltage direct current (HVDC) transmission*
IEC 60633:1998/AMD1:2009
IEC 60633:1998/AMD2:2015

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply; other terminology is as per IEC 60633.

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
asset inventory
list of assets in service or kept as spares

3.2
asset manager
person who manages the plant/asset and is responsible for the overall planning, operation, maintenance and performance of the asset in accordance with set criteria as assigned by the asset owner

3.3
asset owner
person who owns the plant/asset or is given the role as the operator, caretaker or manager who is responsible for and manages the plant/asset on behalf of the owner, sometimes functions as the asset manager

3.4
asset worker
staff/worker/employee who carries out the work as set out by the asset manager

3.5
asset useful life
time interval of the asset, from its first use to the end of life, where user requirements are no longer met due to economics of operation and maintenance, or obsolescence

3.6
asset tagging
identification method to recognize an asset and its associated information

3.7
barcode tagging
identification method using barcode labelling to embed asset details

3.8
computerised maintenance management system
CMMS
coordination of maintenance activities through specialised computer applications

3.9
condition based maintenance
CBM
preventive maintenance based on the assessment of physical conditions

3.10
condition monitoring system
CMS
system used in obtaining information about physical state or operational parameters

3.11
corrective maintenance
CM
maintenance carried out after fault detection to effect restoration

3.12
delivery point performance
DPP
performance measured at the point whereby the asset ownership and its functions are transferred to another entity

3.13
emergency response plan
ERP
set of pre-defined processes used to protect critical assets of an organisation from hazard risks, e.g. from unplanned outages, system disturbances and disasters, and to ensure the continuance of plant/equipment operation within their planned lifetime

3.14
energy availability
EA
measure of the energy which could have been transmitted except for limitations of capacity due to outages

3.15
energy unavailability
EU
measure of the energy which could not have been transmitted due to outages

3.16
exposure hours
EH
maximum number of hours that it is considered the HVDC system could have been in service if there had been no failures of equipment within the scope of supply. It is the number of hours in the reporting period adjusted for reductions in operating time due to unavailability of

external equipment (for example, AC transmission lines and outages caused by other equipment not in the contractor's scope of supply).

3.17
forced outage rate
FOR

number of forced outages that would occur during a one-year exposure period. It is calculated from the number of forced outage events caused by the equipment in the OEM's supply during the exposure hours in the reporting period

Note 1 to entry The Forced Outage Rate should be calculated in accordance with the following formula:

FOR = number of Forced Outage Events during the reporting period (Exposure Hours (EH)/8760).

3.18
life cycle activities
activities carried out throughout operational life cycle of equipment, particularly to prolong performance and/or useable life span

3.19
life cycle cost analysis
analysis to estimate prospective cost throughout the operational life of equipment/plant

3.20
life extension/refurbishment strategy
strategy to prolong useable lifespan of equipment/plant

3.21
minimum stock level
least possible quantity of a product/plant/equipment to be kept as spares

3.22
nameplate tagging
identification method using traditional nameplate to engrave relevant asset details

3.23
operational based maintenance
OBM
generic maintenance technique in which in-service equipment maintenance is performed based on operating conditions, period and other related parameters

3.24
original equipment manufacturer
OEM
company (manufacturer) that makes/produces the individual equipment/plant/system/subsystem which is purchased/used/utilised by another company (herein referred to as the asset owner)

3.25
preventive maintenance
PM
maintenance carried out to mitigate degradation and reduce the probability of failure

3.26

rehabilitation and refurbishment
activity conducted as part of asset renewal, commonly done at the end of asset life

3.27
reliability
ability to perform as required without failure for a given time interval under given conditions

Note 1 to entry: The reliability will be assessed by determining the Forced Outage Rate (FOR) of the HVDC system.

3.28
reliability centred maintenance
RCM
systematic method for determining the respective maintenance actions and associated frequencies, based on the probability and consequences of failure

3.29
schedule maintenance
maintenance carried out in accordance with a specified time schedule

Note 1 to entry: Also referred to as Time Based Maintenance (TBM).

3.30
service provider
entity that provides services in the management of the asset, mainly in the areas of maintenance, training and provision of parts and technical support

3.31
strategic spares
critical spare parts of equipment/plant/system that are purposely kept to ensure rapid or immediate maintenance operation when required

3.32
supplier
party that supplies goods or services to organizations, differently than contractor, with added specialized input such as overall engineering and system design

Note 1 to entry: Can be a manufacturer or Engineering, Procurement and Construction (EPC) contractor.

4 HVDC asset

4.1 Asset background

Electrical power is generated as an Alternating Current (AC) and transmitted as well as distributed as AC, and apart from certain traction and industrial drives and processes, it is consumed as AC.

In many circumstances, however, it is economically and technically advantageous to introduce Direct Current (DC) links into the electrical supply network and in some particular situations, it may be the only feasible method of power transmission. When two AC systems cannot be synchronized or when the distance to transmit the large power by overhead line or cable is too long for stable and economic operation, a DC transmission is often the most viable solution.

High Voltage Direct Current (HVDC) is a well proven technology employed for power transmission all over the world, given the need for large bulk power transmission which has grown along with the consumption, and the increased exchange of energy between different power pools. This power exchange results from it being more economical to utilize the installed generating capacity in different regions than to build new power stations in each region.

The development of the HVDC technology has also contributed to make HVDC more competitive in comparison to HVAC, thus making HVDC feasible in more projects than before.

A well-known technical advantage of HVDC is in its inherent ability for control of transmitted power. The controllability can be utilized for different objectives such as stabilization of the connected AC network, control of the frequency of a receiving island network and in assisting frequency control of generator radially connected to the rectifier of an HVDC transmission. Combined active and reactive power modulation feature can be applied when found advantageous.

By the early 1970s thyristor valves began replacing mercury arc valves, and until late 1990s all systems have employed the same semiconductor technology. This is now complemented with the development of Insulated Gate Bipolar Transistors (IGBT) with high voltage ratings, which in turn accelerates the development of Voltage Sourced Converters (VSC) for HVDC applications, mainly in the weak power network and lower power range. VSC uses self-commutated semiconductor devices.

4.2 Asset facilities

Most of the facilities required for the HVDC converter stations, AC switchyards associated with the converter system, cable terminal stations, electrode stations, fibre optic communication systems and other works are as specified below, including but not limited to the following:

a) all civil works, foundations, firewalls and structures and perimeter fencing for the AC / DC switchyards associated with the converter station including the transformers and AC filter areas;
b) AC switchyard equipment including power transformer and buses;
c) valve hall;
d) DC switchyard and DC filter;
e) AC switchyard control and relay equipment;
f) AC / DC converter equipment;
g) cable terminal stations including all facilities, buildings, fencing and surveillance and security systems;
h) DC ground electrodes including terminal facilities;
i) firefighting system including water storage and pump house, and
j) transformer oil and glycol containment and oil-water separation systems.

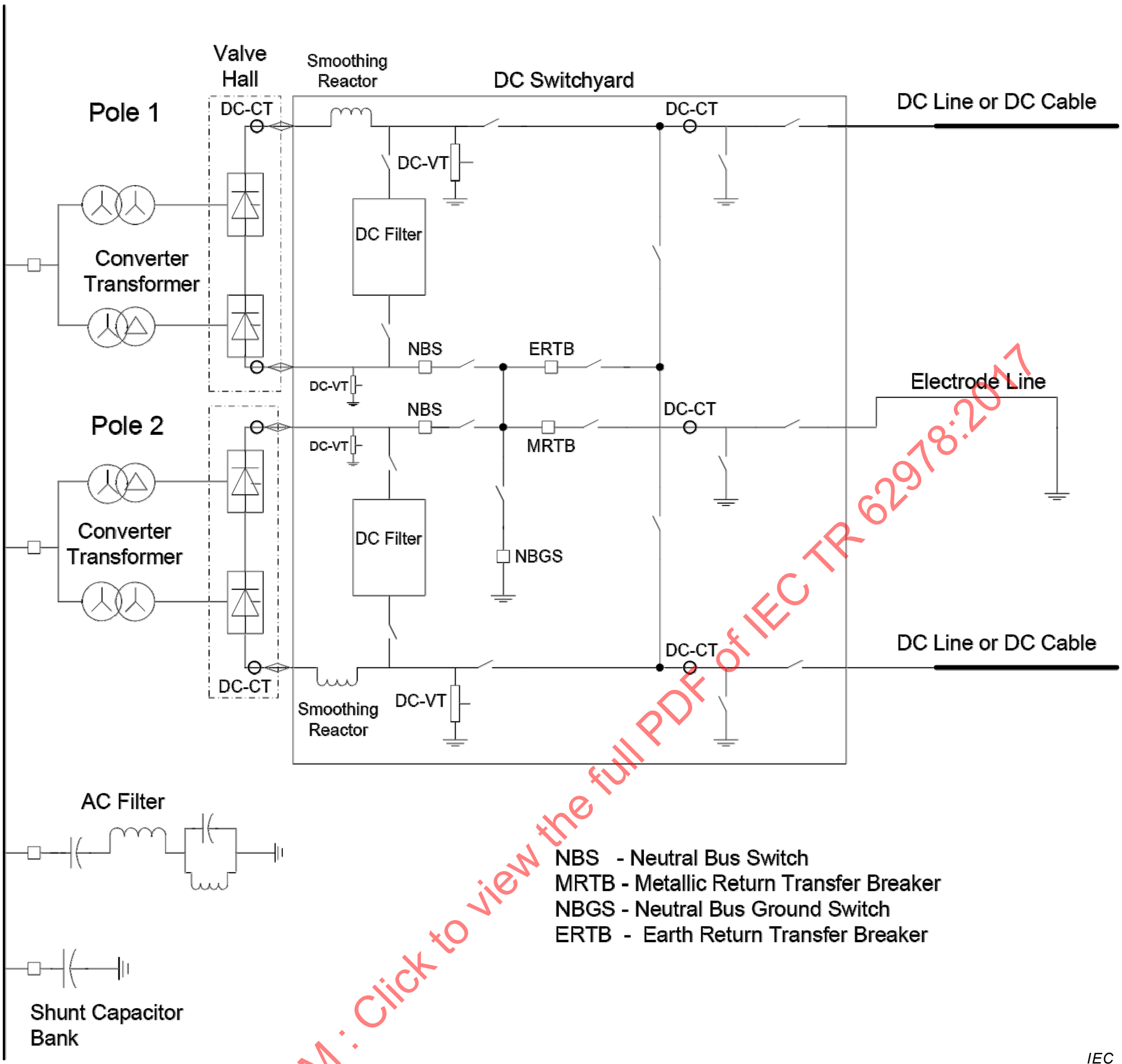
4.3 Asset components and layout arrangement

The main assets for HVDC installation at the facilities as mentioned above are given in Table 1 and a typical simplified layout arrangement in Figure 1.

Table 1 – Main asset components of an HVDC system

	Asset	Component/Equipment
1	Converter	Thyristor valves and valve base electronics. Valve cooling equipment and cooling control
2	Converter transformer	Converter transformer and associated equipment.
3	AC filters and high frequency (HF) Filters	AC harmonic filters and shunt capacitor. AC-side high frequency filters for the converter transformer connections to the AC.
4	Smoothing reactor	Dry or oil filled smoothing reactor connected in series with converter (bridge).
5	AC shunt reactor	AC shunt reactor and assosiated component.
6	DC filters and high frequency (HF) filters	DC harmonic filters and associated component. DC-side high frequency filters for connections to the DC switchyards. DC neutral bus surge capacitors. Blocking filter arrangement, e.g. tuned to fundamental frequency, to mitigate coupling from parallel AC circuits.
7	DC switchyard equipment	DC measuring devices for current and voltage. DC wall bushings for high voltage and neutral buses. DC switchgear including surge arresters, high speed circuit breakers and any associated equipment needed to ensure current zeros can be achieved, DC high speed switches, high voltage and low voltage disconnectors, earthing switches, bushings, insulators, tubular bus, conductor, connectors and other associated hardware as applicable. DC neutral bus equipment. DC switchyard structures and connections. Fault location coupling devices.
8	AC switchyard equipment	AC circuit breaker. Disconnector. Current and voltage transformers. AC switchgear equipment related to converter station and associated equipment including surge arresters, earthing switches, bushings, insulators, tubular bus, conductor, connectors and other associated hardware as applicable.
9	AC and DC control and protection equipment	Control and protection for the HVDC system, DC converters, DC switchyards, DC transmission line and DC cables, converter transformer, smoothing reactor and DC filter equipment. Control and protection for AC switchyard equipment, AC filter and reactive power compensation equipment. Control and protection for valve cooling system. Station auxiliary system control and protection. Electrode line protection and monitoring systems. Fault location and fault recorder equipment for HVDC transmission lines and HVDC cables. Control equipment required for electrode and electrode line protection and monitoring, and associated communication interfaces for exchanging signals with the associated converter station.

10	Fire detection and protection systems	Fire detection and alarm systems for the converter stations including but not limited to: All fire protection systems in the valve hall, including the DC switchyard and DC filter buildings and AC switchyard control buildings. Water deluge fire protection systems for oil immersed transformers and reactors and oil filled bushings. Stand-by diesel pump for fire protection. Fire protection water supply and storage.
11	Electrode stations	Land or sea electrodes. Connecting cables between electrode segments and incoming electrode lines. Disconnects to isolate electrode or segments of the electrode. Current measuring devices for electrode segments. Electrode line protection and monitoring.
12	Auxiliary AC supply	LVAC supply to cooling and valve for the converter asset. AC distribution board. UPS for AC supply to critical equipment.



NOTE 1 Actual station configuration subject to individual HVDC scheme project specification.

NOTE 2 The scope excludes DC lines and DC cables.

Figure 1 – Typical bipolar thyristor based HVDC system

5 Asset management policy and strategy

5.1 General

In asset management, an integral part of the management system is to establish policy and strategy for the organization in terms of its asset management principles, approach and directions. The policy and strategy are to be applied throughout the life-cycle management of the organization's physical asset. The policy and strategy should also comply with any legislative or other legally-binding regulations in regards to the organization's business and operations.

In the asset management policy, the document is expected to provide the asset management framework to support and in alignment with the organizational strategic plan as well as the mission and vision of the organization. The framework should be in accordance with the organization portfolio of physical assets and nature of its business operations. Additionally, the policy should be consistent with respect to other established organizational policies.

For the asset management strategy, the document is expected to derive further detail of the asset management framework stated in the policy. In doing so, the strategy should state the desired outcome from the assets for the long run in support of the organizational strategic plan. The strategy document should also clearly state the enablers and controls in the asset management system, along with the applied methods, as a platform in the implementation of the asset management activities and in ensuring sustainable development of the asset management system.

Additionally, criteria on prioritization and optimization of the assets should be established for comprehensive implementation of asset management activities within the organization's resources and capacity towards significant and impactful result and performance.

Both documents should be documented and maintained appropriately. The documents should be reviewed for any changes to the organizational strategic plan and/or changes in the principles, approach and directions of the organization's asset and its asset management system. Furthermore, both documents should be communicated accordingly to all relevant stakeholders including OEMs and contracted service providers, if applicable.

It is considered adequate to have a common set of asset management policy and asset management strategy which applies for all the organization's physical assets, i.e. electrical utilities for its HVDC and HVAC assets. However, separate asset management policy and asset management strategy can be established if the organizational strategic plans of HVDC and HVAC assets are different.

5.2 Common policy and practices

Most utilities have established a common set of asset management policy and strategy, which applies to both HVAC and HVDC power system assets. A separate asset management policy and strategy can be beneficial, particularly if dissimilar operating performance and cost structure are expected throughout the life-cycle of the HVDC assets. This may include aspects such as engineering design philosophy, maintenance strategy, spares availability, life extension strategy, replacement, refurbishment and disposal of equipment.

Information sharing on asset management processes and methodologies between OEM and the utilities will enable an increase in the profitability and efficiency on the use of HVDC assets while at the same time safeguarding required performance levels and minimizing life cycle costs. An integrated optimization process enables the utility to determine how to minimize the total life-cycle cost of owning and operating infrastructure asset while continuously delivering service levels demanded by customers.

The following aspects are considered important and should be included in the management of HVDC asset:

– planning aspects;
– engineering and system design;
– development;
– operation and maintenance; and
– retirement.

The other aspects to consider include:

– review and evaluation of operational performance data compared to targeted value;
– review and evaluation of scheduled and forced outage trend and impact;
– determination of applicable and useful maintenance method;
– development of maintenance planning;
– review of effect on system performance;
– review and study on financial impact/status; and
– life extension/upgrading and replacement study.

5.3 Asset management framework

The following asset management framework is recommended:

a) plant availability, focusing on:
   – reliable facilities;
   – adequate maintenance;
   – secured spare parts and maintenance crew/engineers/technicians;
b) performance review of HVDC system, focusing on:
   – international benchmarking on performance or similar nature on project data or state of owned project performance;
   – key performance indicator or index for criteria evaluation of HVDC performance;
c) optimized and least cost solutions that emphasized on:
   – the necessary investment for project requirements, maintenance cost depending on aging and least life cycle cost;
d) energy and commercial losses due to:
   – energy losses in operation;
   – losses due to scheduled outage;
   – losses due to forced outage;
   – penalty such as un-served energy governed by the contract; and
e) acceptable and manageable risks:
   – focus on the fact that 100 % guarantees are not required, but the risk level has to be clearly under control in relation to the risk appetite of the stakeholders.

The embodiment of asset management policy, strategy, plan and objectives in a coordinated framework is illustrated in an asset management perspective as in Figure 2.

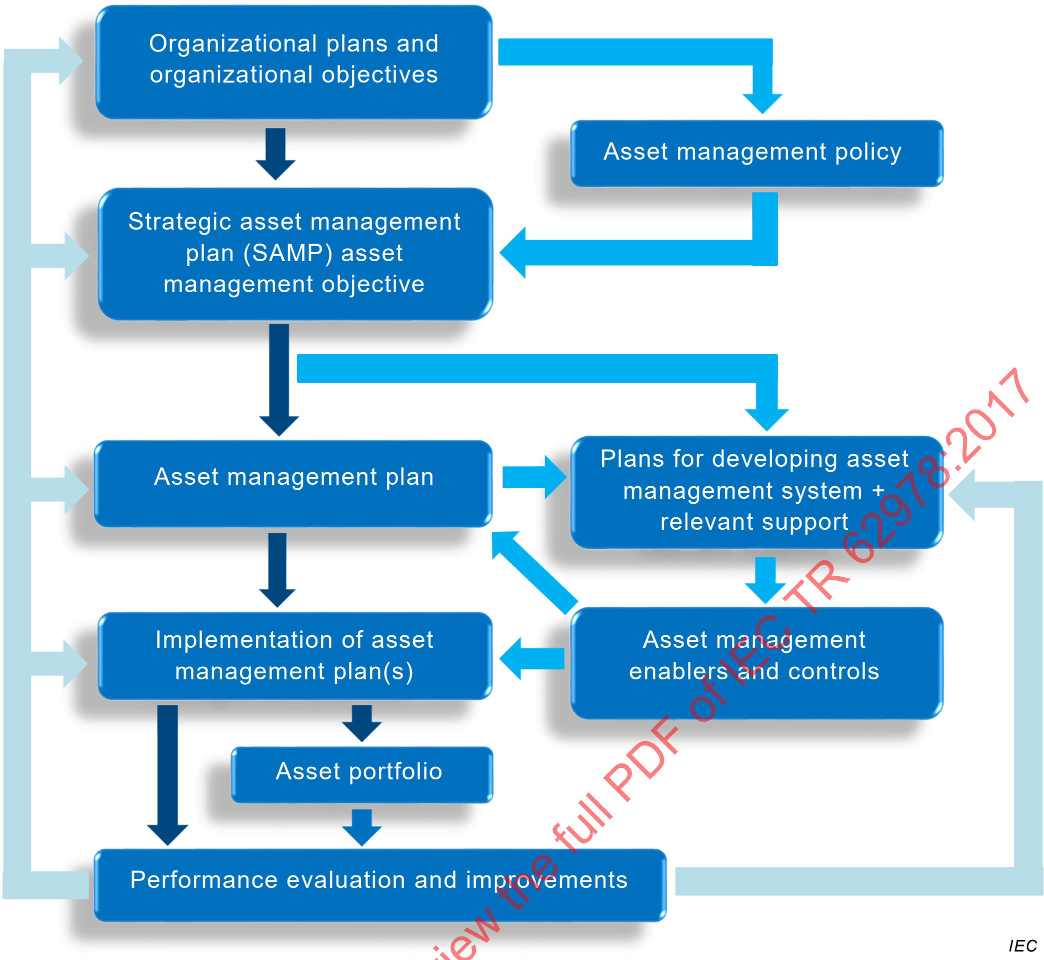


Figure 2 – Asset management perspective

6 Risk management

6.1 General

In order to safeguard against operational and financial uncertainties, risk management should be integrated into the asset management system throughout the whole intended life cycle of HVDC installations. The main purpose is to comprehend the cause, effect and likelihood of adverse events affecting HVDC installations and to provide adequate auditable proactive actions to control such risks to acceptable levels according to the relevant legal and statutory requirements. This can be achieved by the following:

a) Identifying potential risks affecting normal asset operation.
b) Identifying all affected equipment and their main functions.
c) Defining criticality and likelihood of identified risks.
d) Determining whether these risks are acceptable.
e) Devising and implementing appropriate risk control measures to eliminate or minimise impact.
f) Performing regular risk analysis, review and audit.

6.2 Risk management requirements

Legal requirements involving safety of employees, third party personnel, environmental impact and the general public, shall be managed to comply with the appropriate standards, in addition to compliance with the relevant legislation on corporate and financial risk management. The organization managing HVDC installations is recommended to establish, implement and maintain structured documented processes for the risk management of equipment and associated systems throughout the life cycle of the asset. Regular review and audit at pre-defined intervals should be exercised to continuously improve existing processes, particularly in conjunction with other quality management systems deployed by the organization.

The following approach may be adopted for risk management processes:

a) Classification of assets into a list of major equipment, part or system, including all relevant information.
b) Definition of scope and limit of individual risk assessment.
c) Identification of probable risks using a table or matrix of likely events and their root causes.
d) Determination of risk control measures available or proposed through risk reduction hierarchy, namely:
   - elimination,
   - substitution,
   - physical controls,
   - signage or warning signals,
   - administrative or procedural control.
e) Determination of level of risks in terms of likelihood of occurrence and potential impact (with and without control measures being successfully implemented).
f) Determination of tolerability of risk by evaluating adequacy of any control measures to meet relevant legal, statutory and other requirements.

Risk management of physical assets should therefore include consideration of risks across the whole asset life cycle. For example, the design process should include the identification and management of risks throughout the life of the asset, taking into account the operating conditions and criticality of the asset utilization. The overall methodology employed by organization for risk management of HVDC installations should include but not limited to the following:

g) Proportional to the overall level of risk (severity) and likelihood of event.
h) Proactive approach is to be incorporated to manage risk throughout the whole life cycle of the asset.
i) Compliance to relevant statutory requirements, legislations, license conditions, etc., shall be satisfactorily met.
j) Assessment of variability of certain risks due to factors such as aging, atypical usage, exposure to environmental elements and other anomalous operating conditions.
k) Identification of risks that are tolerated, avoided, eliminated or controlled according to the type of equipment involved.
l) Control measures employed are consistent with prevalent organization’s resources.
m) Provision of necessary governance and monitoring of planned and executed actions to ensure completion and effectiveness of control measures implementation.

Since risk is defined as the product of probability and consequence, risk identification and assessment need to recognize and include consideration of both these factors, whereas the complexity of modelling and risk controls should be commensurate with the nature and magnitude of the risks being managed. It is important that risk assessment is applied consistently throughout the organization based on a common approach and methodology whenever possible.

Techniques for identifying, quantifying and managing asset-related risks are well established and may be applied according to specific requirements, as in Table 2.

Table 2 – Typical risk assessment parameters

Risk identification	a) SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)
	b) HAZOP (Hazard and Operability Studies)
	c) Risk assessment workshops
	d) Industry benchmarking
	e) Incident investigation
	f) Auditing and inspection
Risk analysis	a) Threat analysis
	b) Failure Mode and Effect Analysis (FMEA)
	c) Failure Mode and Effect Criticality Analysis (FMECA)
	d) Root Cause Analysis (RCA)
	e) Event Tree Analysis (ETA)
	f) Fault Tree Analysis (FTA)
Risk controls	a) Reliability Centred Maintenance (RCM)
	b) Condition Based Maintenance (CBM)
	c) Risk Based Inspection (RBI)
	d) Instrument Protective Function (IPF)

The organization should ensure that the results of risk assessments and the effects of risk control measures are considered and, as appropriate, provide input into:

n) Asset management strategy.

o) Asset management objectives.

p) Asset management plan.

q) Identification of adequate resources including staffing levels.

r) Identification of training and competency needs.

s) Determination of controls and their implementation for assets' life cycle activities.

t) Overall risk management framework.

6.3 Common policy and practices

The level of risks and associated measures are inherently different between practicing utilities and in the overall context of structured risk management, it varies significantly. However, the resulting risk management initiatives should help to optimise asset returns, particularly in terms of driving high system availability and performance level.

The organization should keep the results of risk identifications, assessments and determination of controls up-to-date throughout the life cycle of the assets. In addition, the consideration of risks should be addressed as integral part of the organization's corporate risk management framework. As an example, the design process should include the identification of risks during the operation and maintenance phase of the asset, including its eventual de-commissioning and disposal and taking into account the operating conditions and criticality of the asset.

7 Asset management life cycle activities

7.1 General

Asset management activities such as risk assessment, policy, strategy, objectives and plans are relevant for the entire asset life cycle with the focus on life cycle activities that include acquire/create, utilize, maintain and renew/dispose.

Asset management plan should forecast implications that life cycle and aging infrastructure have on the service quality delivered by the system and the associated changes to the historic levels of capital and Operation and Maintenance (O&M) costs. As the HVDC installation ages, it enters a region of higher risk which may require considerable allocation of fund and investment to ascertain high level of operational availability. In order to effectively convince shareholders and regulators that increased investments are required to mitigate and control such risks, there is a need to improve the understanding of the following aspects:

a) The potential impacts to the company's operating cost and business objectives in order to maintain the required levels of service quality, workforce safety, public safety and environmental performance.
b) How the frequency and duration of forced and planned outages change as equipment approaches its end-of-life, and the resulting financial and operational implications.
c) How the Delivery Point Performance (DPP) of the system would be affected when a significant proportion of the equipment is aging, as the customers may experience a reduction in service quality.
d) The relationship between specific equipment performance and DPP, so that appropriate actions can be directed towards the highest priority assets.
e) Opportunities to take equipment out of service for preventive maintenance may be limited, e.g. for heavily loaded network, which may increase the long-term risk on DPP to an unacceptable level.
f) Technical merits and cost impact associated with refurbishing aging equipment versus replacement options.
g) Key equipment parameters which shall be monitored to determine the condition of these assets, and related methodology to analyze failure risk.

This information shall be effectively communicated to the financial group within the organization and to the regulator to ensure that such costs are accounted for and recovered in accordance with the related cost allocation and agreed design principles. Establishing the risk (probability and consequence) of asset failures on the business values of the company and determining the least cost means of correcting the situation, when warranted, is one of the most important results which shall be delivered by an asset manager.

7.2 Asset management decision process

The asset management decision process can be divided into several parts.

a) Complying with specific requirements of different stakeholders through coordinated strategy for fleet of system equipment.
b) Determination of the total required expenses for performing the actual or replacement value of equipment and to sustain necessary maintenance requirements.
c) Allocation of sufficient fund for capital investment and operating costs on the basis of a prescribed financial limits.

The next step in the asset management process is in the determination of the total asset budget and the decision making process to identify which components in the fleet of equipment that should be maintained, refurbished or replaced.

Figure 3 illustrates certain considerations which contribute to effective life cycle activities in asset management decisions.

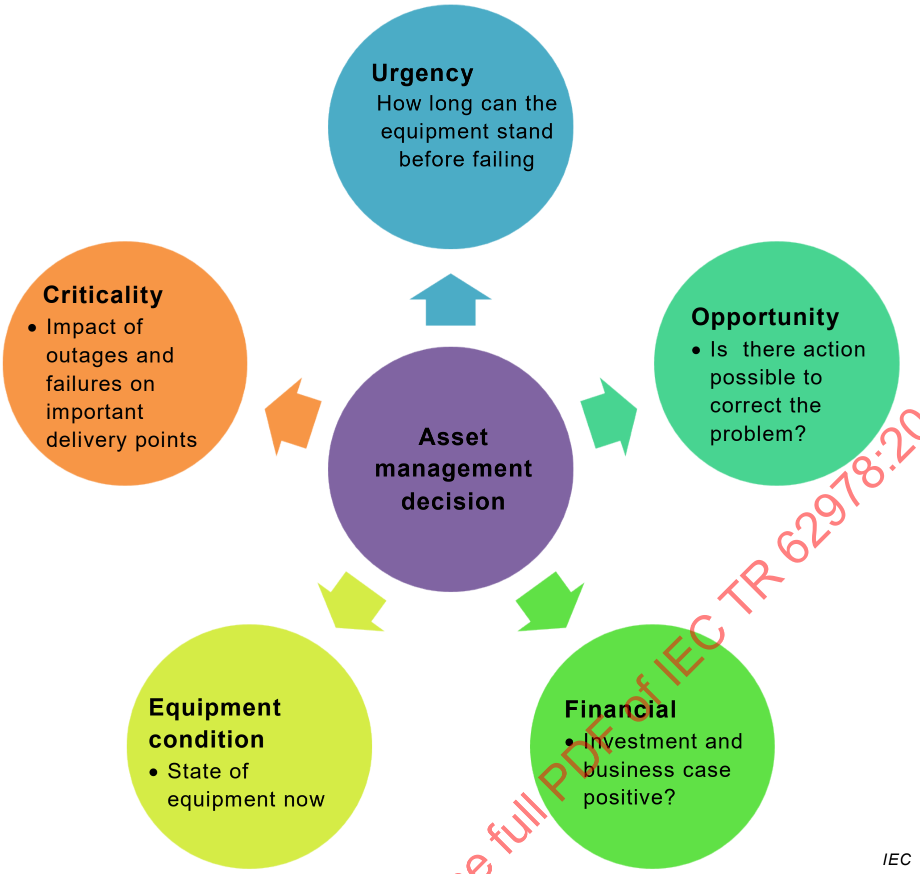


Figure 3 – Issues influencing asset management life cycle decisions

Accurate and updated knowledge of asset condition is vital for effective decision making process, which is typically obtained through systematic acquisition of diagnostic data and supported by expert analysis. In addition, knowledge of prevalent conditions of assets allows them to be ranked for prioritization of actions to be taken. In order to deploy apt and timely remedial actions, it is important that asset managers understand the asset condition in relation to aging effect or deterioration with time and usage. For example, early asset diagnostics typically reveals negligible asset deterioration but diagnostics later in the asset life may detect appreciable deterioration which will eventually lead to failure.

Prioritising of asset maintenance plans can be based on the importance of an asset to the system and to the DPP. Even though availability and avoidance of customer outages are always top priorities for all utilities, system design allows for scheduled outages for maintenance purposes to be taken, if necessary. So, relevant assessment of asset criticality needs to take these perspectives into consideration.

Asset management decisions are also influenced by the prospect and practicability of potential corrective and mitigated actions to be performed. For assets which have known problems, actions to resolve them should be considered for short and long terms purposes, by including factors like functionality, capacity, environmental impact and also excessive stresses on the asset. Timely execution of asset refurbishment and replacement is vital to the success of asset management practices, particularly in combination with network planning strategy. The management decisions should eventually meet prudent company financial practices and inherent constraints to justify expenditure proposed.

The common maintenance strategies employed are as follows:

d) Corrective and remedial maintenance.

e) Schedule maintenance.

f) Condition-based maintenance.

g) Reliability centered maintenance.

7.3 Life cycle costing

7.3.1 General

The approach in life cycle costing of asset management activities are useful in a typical annual business planning effort, particularly for mitigating identified risks with respect to business objectives using the least cost methods. When a significant proportion of the equipment is entering the wear out region, utilities tend to employ alternative methods to forecast the long term implications of system aging. These methods of investigating longer-term implications which require additional information related to project failure rates, repair / refurbish / replace costs and the demographics of the various asset populations are found to be useful for the following reasons.

a) Provide a long term macro view of the problem, which can be used to identify major changes in the historic levels of costs and system performance.

b) Assist in ensuring that asset harvesting is avoided, particularly over a long term period.

c) Validate the sustainability of existing capital and O&M costs, developed through the traditional business planning process.

d) The two main approaches, which are currently widely employed, are described below.

7.3.2 Forecasting O&M costs due to asset failures

7.3.2.1 General

This approach involves investigating historical failure rates of main delivery assets and the associated historical repair / refurbishment costs (O&M costs) not only from the actual project but also from experiences in similar projects, different applications with comparable equipment, CIGRE statistics and supplier information. Asset demographic information is then used to correlate and predict future number of asset failures. Assuming that the new population of assets goes through the same failure and repair / refurbishment cycles, then expected average failure rates and related repair / refurbishment costs can be developed to forecast future O&M costs. The following five-step process has been effectively used by utilities to forecast expected changes in O&M costs, particularly due to system aging / wear out.

7.3.2.2 Investigate the types of failures historically experienced based on selected asset type

One of the examples to be considered is the converter transformer used in a typical HVDC system arrangement (which is subjected to average loading levels and system faults) that was expected to require major refurbishment of the transformer tap changer and cooling system prior to end-of-life.

7.3.2.3 Identifying the age during which these failures are expected to occur

In the above example, it was found that the major refurbishment of the tap changer and cooling system is expected to occur between the transformer ages of 35 to 45 years and, this failure / repair cycle is expected for about 70 % of the related transformer population.

7.3.2.4 Reviewing the costs historically incurred to affect the necessary repairs

For the above transformer example, the actual O&M repair costs were obtained from the historical records within the work management system. These records are typically used to generate an average repair / refurbish cost for the said failure modes.

7.3.2.5 Determining changes in the number of expected failures based on demographic information of the asset type

In the above case, the demographic transformer information indicated that, say over the next 5 years; the number of transformers within this age region would double and remain at this level for about 5 years.

7.3.2.6 Establishing a forecast of work and related costs based on historical experience and demographic information

Based on the above example in the analysis for converter transformers, the utility would be able to predict the expected increase in O&M costs resulting from the aging system. The utility is also able to pro-actively develop a mid-life management strategy for such transformers, which may include coordinated refurbishment of the tap-changers and the cooling systems. This process tends to reduce both the overall costs of the work and minimized outage requirements, as compared to the traditional reactive based approach for dealing with these failure modes.

This kind of approach enables the utility to strategize well ahead for the increases in O&M expenditures, particularly those driven by changes in the demographic profiles. In addition, it also provides the utility with the appropriate rationale for their business case to justify to the stakeholder/regulator. Another benefit is in the ability to forecast potential resource requirements for technical work force, training and equipment needed to perform the work.

7.3.3 Forecasting capital replacement costs due to asset failures

An approach which is used by utilities for the purpose of forecasting capital costs associated with replacement of aging infrastructure is with the use of probabilistic failure curves for the various asset groups in conjunction with projected asset demographic information. The approach is based on utilising probabilistic representations of asset life for major classes of delivery assets and applying these to the related demographic information for each asset group. Such probabilistic representations are obtained from available industry data sources and adjusted according to the experience of the specific utility. A number of regulatory entities around the world require utilities to provide this type of information for the purpose of ensuring that related investment levels are keeping pace with their aging systems, so that unexpected major increases in capital investments are avoided.

The methodology for life cycle analysis is to smooth out the forecasted capital expenditure levels over a long term period for HVDC system. The approach provides information that can also be used to independently validate the capital replacement levels that are identified by the normal business planning process. Typically, the normal business planning process involves collecting information from the field on the conditions of the HVDC installation and making decisions on which items need to be replaced in any given year. The probabilistic analysis uses independent information sources to generate near-term and long-term anticipated levels of capital replacement due to asset failures.

Capital replacement levels can be compared to the results generated by the traditional maintenance planning process and any significant differences can then be rationalised. Comparing and rationalising significant differences between the two approaches result in increasing the degree of confidence in the reinvestment levels and represents prudent planning practice for this important business issue. With the introduction of performance based regulation and the resulting longer periods between rate re-sets, the longer term view using this approach is beneficial in preventing asset harvesting (reducing or altogether eliminating investment in a particular asset for profits) and minimising the risk of unforeseen costs escalation.

7.4 Spares strategies

It is customary to keep a specific number of strategic spares deemed sufficient to cover catastrophic failures of major equipment critical to the operation of the system, such as transformers and switchgears.

The number of equipment spares is usually derived based on OEM recommendations, historical failure rates, related replacement times and impact of outages on customers. With a larger proportion of the asset base entering aging region where wear-out equipment may be a concern, an alternative to proactive replacement would be to keep additional spares which are based on forecasted failure rates.

The methods and models which are presently in use for establishing the number of strategic spares typically assume that the in-service assets are in the useful life region of the hazard rate curve.

Depending on specific equipment demographics, the suitability of these methods and models should be reviewed to ascertain that they remain applicable during the time period. If a large proportion of the asset base is approaching the end of life region, the probabilistic failure projection approach mentioned earlier would provide a more accurate basis for determining strategic spares requirements.

7.5 Life extension strategies

There are a number of techniques used in the power utility industry to extend the life of major assets, which include the following options.

a) Refurbishment of existing equipment, for example control and protection system upgrade, HVDC cooling system overhaul and drying of converter transformer. This approach includes major overhaul activities or remedial maintenance tasks and often involves significant outage times and costs.

b) Derating of equipment to minimize aging. Reduction of the stresses has the same effect of moving the hazard rate function towards the right, or to effectively extend life expectancies in a statistical sense.

c) Increase in maintenance activity or adapting specific maintenance practices to focus on key components for critical equipment.

d) Installing on-line monitoring system for critical equipment to ensure operating stresses are kept to a minimum level, where possible.

Table 3 shows estimation of typical lifetime (that of design or operation or service life) of HVDC equipment (also referred to as Asset Useful Life) in an HVDC installation as published by CIGRE Technical Brochure No. 649.

Table 3 – HVDC equipment lifetime

No.	Equipment	Life time (Year)	Remark
1	Converter transformer	40	
a	AC bushings	25 – 30	25 years for oil impregnated paper bushing; 30 years for resin impregnated paper bushing
b	Tap changer	30	Or 350 000 operations: replace seals and springs
c	Cooling equipment	25	
2	Thyristor valves	35	
a	Thyristors	35	
b	Valve reactors	30	
c	Tubing/piping	25	
d	Fiber optics	35	
e	Damping capacitor	30	
f	Damping resistor	30	
g	Electronic cards	25 – 30	
h	Coolers	25	
3	HVDC control system		
a	HVDC controls (analogue)	35	
b	HVDC controls (digital)	12 – 15	
c	Human/Man Machine Interface (HMI)	7	
4	DC smoothing reactor (oil and air core)	35	Bushing may have a shorter life
5	Optical DC current measuring or DCCT	30	Electronics may have a shorter life
6	DC voltage divider	30	
7	DC surge arrestors and DC insulators	35	
8	DC bushings and wall bushings	30-35	30 years for oil impregnated paper bushing; 35 years for resin impregnated paper bushing. DC bushings have more insulation than AC bushings
9	DC switching equipment	35	Or estimated life as 10 000 close/open according to mechanical endurance class M2
10	DC bus-work and structures	50	
11	Ground electrode	40 – 50	Normal design life
12	Communications systems	15	
13	Civil work	50	

NOTE 1 Excludes design and production run quality issues.

NOTE 2 HVDC station design life of 35 years to 40 years.

7.6 Run to failure strategies

Certain assets making up the HVDC system may be non-critical with respect to the impact of their failure on the short-term performance or the business values of the company. The preferred strategy for such equipment may be to allow them to run to failure before repairing, refurbishing or replacing with new equipment. For example, run to failure strategy can be applied to non-critical asset which is equipped with on-line monitoring. Spares should however be kept for replacement. In the case of HVDC asset, a thyristor can be treated under this strategy where it is fitted with an on-line thyristor level monitoring. However, forecasting the expected number of in-service failures should be implemented, particularly when significant proportions of the asset are approaching the end of their design lifespan.

7.7 Refurbishment of HVDC system

Technical life assessment should be performed to determine the existing conditions of the HVDC system and its associated equipment. Options to extend the reliability and useful lifetime of the asset should be explored, particularly when it is approaching the end of design life cycle. Decisions to refurbish or rehabilitate an existing HVDC system are typically based on the following assessment criteria.

a) Aging or deterioration of equipment under environmental conditions and overload.

b) Obsolescence of equipment technologies – lack of spare parts and support.

c) Reliability and availability of main equipment due to prior failures during operation.

d) Lack of expertise, knowledge and support of the existing sub-systems.

e) Long downtime of the HVDC link due to maintenance constraints.

f) Major changes involving the network configuration or the HVDC link.

g) Frequent major failures of control system.

h) Re-negotiation of bulk power purchase price.

i) Proposed increase in asset utilization.

j) Proposed increase in power transfer.

k) Prolonged operation of the asset for another 10 to 25 years.

l) Systematic failures due to equipment design.

The assessment to substantiate the proposed refurbishment work should indicate that it is the most cost effective and technically viable solution to extend the life of existing HVDC system, without any performance penalty. Refurbishment work typically involves replacing major equipment and critical sub-systems which are approaching their end of useful lifetimes, instead of constructing or installing a completely new DC link of similar rating and type.

In the event of the main equipment being considerably different at both ends, the refurbishment work should be coordinated to commence simultaneously to avoid or minimise additional scheduled outages. It is recommended that periodical meeting and discussion be held to update work progress, resolve pending issues and re-align schedules with respect to the refurbishment work, particularly involving utilities and contractors from different nations.

8 Change management

8.1 General

Where existing arrangements are revised, or new arrangements are introduced that could have an impact on asset management activities, the organization should assess the associated risks before the arrangements are implemented. It should include revised organizational structure, roles and responsibility, revised asset management practices for example, asset management policy, strategy and plan and the introduction of new asset / system / technology / contractor / supplier.

Depending on organization, many transmission businesses are in a deregulated environment which is moving to separate asset ownership, asset management and service provider functions in the belief that the role separation will lead to greater efficiencies. The same applies to HVDC interconnection in transmission systems.

8.2 Common policy and practices

Management of change that impact the asset, taking into account risk assessment prior to implementation, is important and often best accomplished using internal resources, particularly if seamless transition and long-term interests are in mind.

Complete outsourcing of change management by service providers is less preferred particularly because of the lack of thorough understanding of the prevalent organizational issues and systemic constraints.

Prolonged retention of specialized HVDC personnel, in particular with respect to older HVDC design and technology, is essential to sustain operational effectiveness throughout the asset life cycle. Often, this can be addressed through structured remuneration, special incentives and provision of continuous training schemes and exposure.

8.3 Development of resources in HVDC system

8.3.1 General

One of the challenges in HVDC technologies is that most of the HVDC system and installations are proprietary and very specific to OEM design, especially on control and protection system and thyristor valve and associated equipment. The design and characteristic of equipment between OEMs are different and can be compounded based on the technology in a particular time. Both utilities and OEMs often faced a problem in retaining specialized personnel with respect to older HVDC design and technology.

8.3.2 Skill retention and development in HVDC system

The type of specialized skills and knowledge on the high technology content in HVDC system to be retained by asset managers or asset workers is a fundamental decision for each organization. It will depend on their views of the strategic importance of retaining certain skills or knowledge and the economics of retaining some non-core skills within each organization. Organizations using outsourcing of both intellectual and labour resources claim a number of benefits. However issues such as the loss of basic technical knowledge or understanding of the condition of their assets and the impact of outsourcing on the skill retention and development of the internal and outsourced workforce are amongst other factors which have to be considered.

These issues should be considered when setting up outsourcing models to avoid costly outcomes at a later stage. Organizations proceeding on this path firstly need to identify the mainstream functions for which a distinct knowledge or skill base is an essential component and whether it is a core function or not. Once the extent of these functions in the organization is identified, the relevant skills and the level of retention can be assessed. Prior to assessing whether a skill or knowledge base is to be retained or outsourced, it is important to have a process to clearly understand who is currently providing the key knowledge. The capacity of the provider to continue to provide the skill over the longer term should be assessed and be able to be monitored.

8.3.3 Factors in deciding level of HVDC skill retention

The following factors determine the level or degree to which specific HVDC skills or knowledge should be outsourced and when these processes should be implemented:

a) cost difference if skill is outsourced;

b) importance and availability of emergency response;

c) completeness of maintenance standards;

d) ease or difficulty in specifying and assuring quality performance;

e) uniqueness of the skill or knowledge;

f) need for internal asset workers to grow their own business using this skill;

g) organizational need to exploit new technology;

h) need for delegated responsibility in the asset worker;

i) level of condition monitoring information available to the asset manager;

j) commonality of strategic directions between asset manager and worker;

k) age of the asset base;

l) status and capability of industry training organizations and processes;

m) retention of sufficient expertise so that the asset manager can be a knowledgeable buyer of outsourced service provider skills; and

n) availability of skills with suppliers and consultants.

Another input to this process is to consider the relevance of different business drivers of internal and external service providers and their synergy with the organizations for different activities.

8.3.4 Skill retention under different organizational relationships

There are a number of possible organizational relationships that will achieve the required level of skill retention. If high performers are suitably positioned in the relationship they can make less than optimum organizational relationships still function well. The aim however should be to have organizational relationships that facilitates skill retention and development, independent of personalities. To this end it is important to recognize the relevant strengths and weaknesses in the different organizational models.

One way to facilitate this is to have a clearly defined area of responsibilities. It will not matter who has the individual responsibility, provided the associated activity can fit in with the training and skills of the assigned group.

8.3.5 Establishing a productive work culture

The impact on the asset workers' motivation can be even greater if the asset manager is perceived to exert unfair power over the asset worker. In some instances, this has created enormous tensions between asset managers and asset worker / service providers and led to inefficiencies or even rejection of the asset manager/service provider model. The challenge therefore is to create two separate roles without reducing the care and attention by the asset worker on the HVDC equipment or the competence of the asset manager, as this could impact on HVDC system reliability. Achieving overall asset management objectives require close teamwork between the two functions.

The two main challenges are:

– setting the level of skill retention and its ongoing development; and

– establishing a culture where the asset manager and the service provider work productively together and avoid unnecessary conflict.

A preferred path is to create a culture where both the asset manager and the asset worker understands their respective roles, take pride in their jobs and are motivated by their responsibilities. The emphasis is required on increasing teamwork and cooperation between the respective groups by increasing their level of understanding of each other's roles and the importance of each role. If this teamwork can be achieved, priorities should be aligned.

Possible ways to enhance teamwork include the following:

a) Developing HVDC maintenance policies and standards through a process led by the asset manager with representatives from both groups. This process draws on the collective experience from both groups within the organization and ensures collective ownership of the policies.
b) Involvement by the asset worker in expenditure decisions made by the asset manager. This ensures that first-hand knowledge of the HVDC assets and any HVDC system operating problems are taken into consideration in any decision making. The priority of projects and tasks can be jointly agreed. The long-term goals of the asset manager and the immediate security concerns of the asset worker can be addressed through such joint decision making process.
c) Delegating to the asset worker full responsibility for expenditure decisions for routine maintenance work in accordance with the asset manager's criteria:
   – maintenance policies and standards;
   – long-term strategies for the transmission assets;
   – strategies specific to particular plant items; and
   – any other guidelines issued by the asset manager.
d) Application of common performance measures for any group where their input has an impact on an asset. An integrated process of asset operation will allow teams and individuals to identify where their contribution makes an impact. This will ensure that all participants are seen as important contributors and that their input can be identified.

8.3.6 Alliances and partnership

Another strategy in the management of change is by alliances or partnership with an external service provider, who may for example be an equipment manufacturer / OEM or engineering company / supplier. This is useful in the application of new technology and for more effective utilization of existing technology. A new design of HVDC equipment offering a step reduction in operational costs can be introduced by a cooperative effort early in the production process with both parties sharing any inherent risks that may be associated with its early performance. With existing technology a service provider / manufacturer may be in an advantageous position to provide advice in relation to his equipment on:

– What is the minimum maintenance to sustain life expectancy.
– What maintenance practices will allow design life to be achieved comfortably.
– What operation and maintenance strategies prolong service life beyond design life.

Alliances / partnering when correctly applied have broad potential for cost savings in relation to specifications, tendering, marketing and contract management. For a win-win outcome it is essential for the alliance partner to share responsibilities and rewards for performance based outcomes.

8.3.7 Maintaining capabilities over the long term

Industry restructuring can give rise to a number of risks associated with loss of expertise. However, these risks may take a long time to materialize, especially if an HVDC system is particularly well supplied with skills at the commencement of the restructuring process. Once lost, these skills may be difficult to rebuild. It is important that an appropriate long-term perspective on skill retention is maintained. HVDC training on planning and processes should be fostered to ensure the long-term provision of adequate specialist skilled resources to meet HVDC system needs.

9 HVDC maintenance

9.1 General

The HVDC converter equipment should be maintained in line with the recommendations of the OEM. Preventive or schedule maintenance should be coordinated between the two terminal stations to minimize down time. Planned maintenance on the transmission lines which requires line outages should be carried out at the same time as converter terminal outages.

Scheduled maintenance should not be necessary more than once per year. Considering bipolar operation, the converter station should be designed to permit maintenance on one pole with the other pole in service so that shutdown of the entire bipole is not required for pole maintenance.

Scheduled outages for preventative maintenance and repairs by the owner should be included in the evaluation of availability and will be based upon the followings:

a) Maintenance will be performed with the interval between scheduled maintenance outages as stipulated by the OEM and accepted by the owner.
b) Maintenance will be performed in accordance with the OEM maintenance instructions. The OEM should be advised when the work will be carried out and may if he chooses witness all scheduled maintenance work during the availability and reliability monitoring period if specified in tender document.
c) Maintenance and repair will be performed with a qualified working crew of adequate size for the work and trained according to the OEM maintenance training program.

The objective in corrective maintenance policy or practices of the HVDC system is to achieve high levels of availability and reliability with minimum schedule outage. The owner or operator should give careful attention to related factors affecting the HVDC system performance including, but not limited to, sub-system and system testing, spare parts and redundancy of design.

The HVDC system should be operated and maintained to continue in operation and to prevent undesired power outage or reduce power capacity due to equipment failure, malfunction, or operator error.

For bipolar operation special attention should be given in the maintenance procedure of the converter station to avoid bipole outages due to repair work on any equipment failure or any HVDC control system.

The design basis required for the converter station should be such that under normal balanced bipolar operating conditions, no single failure of equipment furnished should cause a forced outage resulting in a DC power transfer capacity reduction greater than the rating of one pole. Where this is not practical it should be demonstrated that the expected number of incidents in which power transfer capacity reductions greater than one pole when occurred is acceptable and comparable to other recent bipolar systems. For a bipolar operation, the converter station should be designed to permit maintenance on one pole with the other pole in service. The converter station should be designed so that shutdown of the entire station for any corrective maintenance is not required.

The design of the converter auxiliary system and associated controls and protection should provide corrective maintenance feature whereby a single equipment failure should not cause any reduction in DC power transfer capacity. For example, in the event of failure of a portion of the cooling system for a piece of power equipment, the increased temperature rise should not be injurious to the power equipment. All cooling systems should have sufficient reserve capacity built into cooling pumps, cooling fans and heat exchangers to allow for the loss of any single piece of equipment in the cooling system without reduction of the HVDC system power transfer capacity. If necessary, cooling pumps, cooling fans, and heat exchangers should be duplicated to meet this requirement.

In general, wherever possible, the following design principles should be followed in implementing corrective maintenance policy of the HVDC system:

d) Provision of alarm, fault indication, monitoring and test facilities. Where applicable the components are with fail-safe and self-checking designs.

e) Redundant components, with equipment and control circuits of board by means of either duplication or triplication with automatic transfer facilities. Where feasible, provide physical separation of redundant control board and circuits for control and protection system.

f) Designs which, in the event of component failures, may provide for transfer to a less complex operating mode.

g) Provision of a clear maintenance or repair procedure and check list, easily-read drawings and manuals with sufficient details and cross-references to facilitate repair, servicing, and maintenance.

h) Use of equipment, designed to be maintained, repaired, and operated at the converter station without the need for special operating and maintenance environment, test equipment, special tools, or complex operating sequences.

i) Provision of modular construction to permit rapid replacement of modules with failed components or sub-assemblies.

Owner or operator of HVDC system should provide a record and statistical maintenance report which can be used by site maintenance personnel to track system reliability.

This document mainly covers recommended practices for maintaining HVDC installations after defect warranty period, in particular during the usable lifespan of the asset. Maintenance of new installations during the warranty period should depend on the stipulated contractual terms and conditions agreed upon for the project. During such warranty period, all critical routine or preventive maintenance activities should be implemented together with the OEM and in association with their recommendations as part of the practical training program for the asset maintenance personnel.

9.2 Common policy and practices

In order to ensure prolonged equipment reliability and availability, maintenance methodologies such as Reliability Centred Maintenance (RCM), Condition Based Maintenance (CBM), Predictive Maintenance (PM), spares management strategy, etc., are deployed by utilities. It includes such practices as life extension strategy by replacing critical parts of main equipment in accordance with defined intervals, set criteria prior to equipment failure, or other criteria.

Typical HVDC maintenance activities, execution intervals and chosen methodologies employed are summarised in Table 4.

Table 4 – Typical HVDC maintenance activities, intervals and methods

No	Activity	Interval	Type of maintenance
1	Routine inspection of main HVDC equipment other than thyristor valve	Weekly	TBM
2	Routine inspection of ancillary equipment at valve hall	Weekly	TBM
3	Maintenance of convertor transformer	Yearly	CBM, RCM
4	Maintenance of thyristor valve	Yearly	
5	Maintenance of AC/DC switchgear equipment	Yearly	
6	Maintenance of cooling system	Yearly	
7	Control and Protection	Yearly	

NOTE 1 TBM: Time based maintenance, is also referred to as Scheduled Maintenance.

NOTE 2 HVDC ancillary equipment refers to general equipment for the valve hall such as local auxiliary power supply, environmental control system, etc.

From OEM perspective, the following maintenance activities should be implemented and to the extent shown in Table 5.

Table 5 – Time frame and scale of maintenance activities

No	Activity	Scale	Time frame
1	Maintenance of convertor transformer	3	4 years
2	Maintenance of thyristor valve	3	4 years
3	Maintenance of AC/DC switchgear equipment	2	4 years
4	Maintenance of cooling system	2	2 years
5	Routine inspection of HVDC equipment	1	weekly
Scale: 1: Minimal (e.g. visual inspection) 2: Standard 3: Full compliance			

A summary of the common maintenance methods employed for HVDC asset maintenance activities is shown in Table 6.

Table 6 – Summary of maintenance methodologies

No	Activity	TBM	OBM	CBM	RCM
1	Routine inspection of main HVDC equipment other than thyristor valve	√			
2	Routine inspection of ancillary equipment at valve hall	√		√	√
3	Routine inspection of electrode station	√	√	√	
4	Maintenance of convertor transformer				√
5	Maintenance of thyristor valve			√	√
6	Maintenance of AC/DC switchgear equipment	√		√	√
7	Maintenance of cooling system		√	√	√
8	Control and protection			√	√
NOTE 1 All OEMs may provide maintenance activities for main component of HVDC to their customers as part of contractual requirement. NOTE 2 HVDC ancillary equipment refers to general equipment in the valve hall such as firefighting equipment, AC local auxiliary supply, air-conditioning and dehumidifier system, etc. NOTE 3 TBM: Time based maintenance, is also referred to as Scheduled Maintenance.					

9.3 Special tools and maintenance equipment

Special tools and maintenance equipment include all tools and maintenance equipment which are specifically used for installed equipment at the converter station and cable terminal station, normally available only from the plant OEM.

A summary of special tools and maintenance equipment commonly used in HVDC asset maintenance activities are as shown in Table 7.

Table 7 – Special tools and maintenance equipment

No	Description
1	Thyristor valve test equipment capable of testing thyristor level components
2	Valve hall servicing equipment including lifting tool
3	Equipment, tools and instruments needed for valve component replacement
4	Equipment for aligning shafts of pumps and motors on the valve cooling systems
5	Special lifting devices (special ladder), including valve module handling equipment (if necessary for maintenance)
6	Special lifting devices for changing capacitor units in filter and shunt banks
7	Special lifting devices for tap-changer units
8	Capacitance measuring equipment with sufficient sensitivity to identify failed internal fuses within capacitor units
9	Computer software development systems for each type of computer subsystem used

9.4 Impact of major spares

The unavailability of major spares can have a severe negative impact on the availability of the HVDC system. Although major spares are a relatively large component of the converter station costs, it is worth purchasing them as the delivery times of specially designed items such as converter transformers can be up to a year or longer. Most users consider major spares mean the following equipment:

a) One converter transformer of each type.

b) One smoothing reactor coil of each type.

c) Sufficient thyristors and other valve components to rebuild at least one valve module.

NOTE 1 Valve module comprises a mechanical assembly of thyristors with their immediate auxiliaries but without valve reactors.

NOTE 2 Some users choose to purchase enough thyristors to replace an entire valve.

These major spares would be in addition to spares for other equipment such as electronic parts, measuring transducers, insulators and instrument transformers. The provision of a building for storage of spares on site and an indoor work area for overhaul of equipment such as circuit breakers on site is recommended.

9.5 Strategic spares

9.5.1 Philosophy and common practices

HVDC convertor stations, as with any other plant, need a stock of spare parts for maintenance and repair. The determination of how many spare parts are required is based on a calculation of the required total system availability and the expected statistical failure rates. It is not necessarily a question of "as reliable as possible", but with a measured consideration on the objective of the HVDC link, its reliability with reference to other elements in the power system and its likely performance.

Spare parts philosophy directly affects the cost of an HVDC system. The most important and costly single spare components are the convertor transformer and the smoothing reactor. In smaller HVDC links, if the transport weight of the convertor transformer does not exceed the imposed limit by the authority, a three-phase three-winding transformer is the most favourable solution. However, if a reserve transformer has to be ordered, e.g. where availability analysis indicates the requirement of a spare, a single-phase configuration may be more economical since the spare is provided as a fourth transformer of single-phase rating, instead of a complete three-phase spare transformer.

As HVDC transmission systems are seldom repeated (where there are other convertor stations within a reasonable distance of each other, their ratings are not necessarily identical), the spare parts philosophy for HVDC components is unique for each HVDC link. The distance between the stations and transport limitations will determine whether or not spare parts are separate or common to both stations.

The following major items, which are either of long delivery or specialized items, are usually specified as mandatory spares as they impact on availability of the converter station:

a) Converter transformers – one complete spare transformer of each type plus component spares as for any standard large AC substation transformer with tap changer.

b) Smoothing reactors – one complete smoothing reactor coil so that any smoothing reactor coils can be replaced.

c) Thyristors and valve components – spare thyristors and components:

   – Sufficient thyristors should be provided to completely replace all thyristors in one valve. When each valve requires thyristors having specific characteristics and some spare thyristors do not match to some valves as spares, all the valves should have spare thyristors applicable to them at least three times of redundant thyristors. If this requirement cannot be achieved by the number of thyristors in one valve, additional spare thyristors should be provided.

   – Thyristor and reactor modules or equivalent – for valves of modular design, two modules of each type used in the valves are required, complete with all components necessary to make a functional unit including heat sinks, thyristor clamped assembly, cooling water piping, grading and damping components, thyristor level electronics, reactors, connectors and other hardware. The thyristors assembled in the valve modules are counted as part of the spare thyristors required.

     NOTE Where the valve design is not based on the modular concept, sufficient spare components should be provided to completely replace the components associated with at least six times the number of redundant thyristor levels in one valve including heat sinks, compression hardware, cooling water piping, grading and damping components, thyristor level electronics, reactors and other hardware needed to complete the thyristor levels.

   – Discrete components – at least 10 % of the total number in a single valve of each type of discrete components used in the valve construction should be provided. Such discrete items may include insulators, structural components, hardware, connectors, reactors, as well as any other component included in the valve.

   – Thyristor level electronics – in addition to the spares stated above, the OEM should provide two complete thyristor control circuit boards/ thyristor control units for each of the 12 valves at the station (24 in total).

   – Light guides – 4 per valve layer of each type.

d) AC filter, shunt capacitors and DC filter capacitors – in practice at least 2 % of the number of total capacitor units of each type installed at each station but not less than 1 unit of each type. The spare capacitors should have the same distribution of capacitance variations as the capacitor bank.

e) AC / DC filter reactors – one of each type including AC and DC filter reactor coils and one of each support insulator.

f) AC / DC filter resistors – one of each insulator and one complete bank of resistor elements (also called resistor module) or as much of a resistor as can be speedily replaced on site by site personnel.

g) DC measuring devices – one of each type.

h) Wall bushings and converter transformer bushings- one of each type bushings (only for those which are not covered in a) above).

i) Surge arresters – one complete arrester of each type or typically 5 % of installed/energized spare columns.

j) Control and protection equipment – the number of spares provided should be related to the total number of units installed. The typical spare parts include printed circuit boards, relays, switches and other electronics parts. Table 8 shows the minimum required number of spares related to the number of units installed.

Table 8 – Control and protection spares

Units installed	Required spares
1-9	2
10-20	3
>20	≥ 2 + n/10
NOTE n is the number of units installed and the fraction is rounded up to the nearest higher integer.	

k) Communication, control and protection miscellaneous equipment spares as in Table 9.

Table 9 – Communication, control and protection miscellaneous spares

Units installed	Required spares
1-9	2
10-20	3
>20	≥ 2 + n/10
NOTE n is the number of units installed and the fraction is rounded up to the nearest higher integer.	

l) Valve cooling equipment fans, pumps, motors– one of each type.

m) Most of the other equipment in the converter station such as circuit breakers, disconnect switches and earth switches – one complete (phase) switch of each type including motor operating mechanisms. An additional set of contact parts should also be provided.

n) Current transformers, voltage transformers, auxiliaries, etc. – similar number of spares to that in AC substations.

o) Insulators, clamps and connectors – two units of each type for 50 or more units. For special clamps/connectors – one complete sets of parts to make one number of each type

p) Communications equipment spares.

q) With regard to 'each type' in the above items, it is important to ensure that spares for each type/rating of specified equipment are made available at the station. When a common spares can be used for two types, it may be enough to have only one with the higher rating.

9.5.2 Sharing of strategic spares between users/utilities

Strategic spares may also be sourced out based on sharing methodology between users or utilities for the following reasons.

a) To reduce or minimize rectification work or outage time during contingency by sharing the HVDC spare parts to rectify or replace defective equipment.

b) To reduce or minimize cost in keeping HVDC spare parts by reducing logistic requirement (storage) and maintenance up keep.

c) To increase HVDC spare parts utilization and optimization.

The concept of sharing spare parts is governed in the following manner:

– Databases for all the HVDC spare parts are to be shared by all involved stations and the parts are agreed by both parties as eligible for exchanged purposes.

– All parties involved identify and agree on the identical/similar and critical HVDC spare parts to be shared. This is applicable only for DC equipment where all involved stations have almost identical components.
– The method of sharing should be agreed and complied with by all involved parties whereby the sharing procedure is adhered to.
– All parties involved agree with the optimum number to be kept. Should the optimum number recommended by OEM be different for each party, the higher number should be adopted as the optimum number. Should the optimum number be an odd number, the optimum number may be next even number.
– All parties involved agree that the minimum number is half of the optimum number and to be equally shared.
– All parties involved maintain and ensure that the agreed minimum number of spares be kept at all times in order to achieve the shared optimum number.

9.5.3 Storage considerations

Spare outdoor equipment is provided assembled, partially assembled or crated, such that it is suitable for permanent outdoor storage. It may be noted that some outdoor spares equipment need to be powered up to run heaters to avoid condensation in boxes. Oil insulated equipment is provided filled with processed oil, containing no Poly-Chlorinated Biphenyl (PCB) compounds, with suitable breathers if required for long term storage. Small components are to be packed in such a manner to allow identification and inspection and to provide protection in a normal warehouse environment. Vapour Corrosion Inhibiting (VCI) techniques are to be employed where practicable.

General recommended practices for storing HVDC spare equipment is given in Table 10. The strategy to be deployed should include specific technical, operational and organisational constraints of the installation.

Table 10 – Storage of HVDC spare equipment

No	Equipment	Normal storage	Controlled environment
1	Converter transformer	√	
2	Thyristor valve		√
3	AC filter	√	
4	DC Filter	√	
5	Control and protection card		√
6	Valve cooling system		√
7	DC measuring		√
8	AC switchgear	√	
9	DC switchgear	√	

9.6 Work safety

Electrical substations contain sources of high voltage and high current which can cause serious injury or death. Some of the safety rules to be followed during maintenance work include:

a) Read and understand OEM's maintenance and safety manuals.
b) Only qualified personnel should work on equipment.
c) Follow utility standard safety methods for working with high voltage equipment.
d) Ground all un-energized high voltage circuits.
e) Maintain proper minimum approach distances to live circuits.

f) Keep all equipment in safe and proper working condition.

g) Keep doors to electrical rooms and passageways clear from obstructions.

The valve hall doors are provided with locks whose keys are interlocked so that access into the valve hall is permitted only when the thyristor valve group is isolated and grounded on both the AC and DC sides. The active part of the DC filter is provided with isolating and grounding switches so that it can be serviced even with the passive part of the DC filter is connected and in operation.

9.7 HVDC thyristor valve maintenance – Periodic maintenance

The thyristor valves are designed for periodic maintenance at 12-month intervals. A mobile maintenance lifting platform for accessing thyristors and thyristor level test equipment for testing thyristors and associated components is provided for use during maintenance.

The thyristor monitoring alarm log is used to define in advance the location of thyristor levels with failed components to be replaced by spares. Routine checks on the valves to be carried out annually include:

a) Visual inspection for leaking water of all water pipe joints.

b) Replacing defective components.

c) Check of torque of bus-bar connection bolts (1 % to 2 % of all connections, statistically distributed within each valve tower, should be checked).

d) Visual check of surface contamination.

e) At larger intervals than 12-months, recommend checking the condition of the potential electrodes in the cooling circuit and for the first time, after five years of operation at the earliest. One to two percent of all electrodes, statistically distributed within each valve tower, should be checked.

f) In addition, a thorough visual inspection, cleaning and electrical testing using the thyristor level test equipment should preferably be carried out on two valves out of twelve per year, that is, a six-year cycle time.

The maintenance effort required for the annual maintenance would be approximately 50 man-hours for one 12-pulse group with personnel having the necessary qualification. Due to the necessity of working with the lifting platform, it is possible to work with 2 to 3 persons. One of them should be a trained engineer.

In some valve designs, the thyristor modules are not designed as exchangeable units. In this case, faulty components can still be easily replaced. When thyristor modules are exchangeable, they can be replaced within a shorter time using mobile lifting platform and/or other equipment.

It should be possible for faulty components to be easily replaced within a short time. The replacement of a thyristor typically takes about 10 min to 15 min (where no water connections have to be opened). The replacement of a capacitor or a resistor typically takes up to a maximum of 20 mins depending on its location. The replacement of a reactor requires less than one hour. A failed thyristor electronic card can be withdrawn from its frame and replaced by a new one.

Components are replaced using the mobile lifting platform. The thyristor level test equipment is used to verify proper functioning after replacement. After re-energization of the valve group while in blocked condition, the thyristor monitoring system is used to monitor the status of the valves.

9.8 Converter transformer maintenance

In maintenance terms, converter transformers are quite similar to large high voltage power transformers with on-load tap-changers. The maintenance schedule to be followed should be based on the detailed OEM's schedule suitably amended to take into consideration the power utility's normal maintenance practice for large ac power transformers.

A typical maintenance schedule applicable to converter transformers should be as follows:

a) Visual inspection – monthly.
b) Infrared scan – every 2 to 4 months.
c) Check control cabinet heater – yearly
d) Oil samples and dissolved gas analysis – initially before energization, after 6 months and thereafter every 12 months (additional samples may be required in the first year of operation and the 12 months interval could be reduced in warm climate or where transformer is being regularly overloaded).
e) Core ground measurement – every 24 months.
f) Check bushings for leaks and oil levels – every 24 months.
g) Operate transformer protection – every 24 months.
h) Operational status checks – every 24 months.
i) Tap changer operational checks – every 24 months or use of operation counter.
j) Clean transformer bushings – every 24 months (smaller interval required in case pollution level is high).
k) Diverter inspection and oil change-out – every 36 months.
l) Internal inspection, winding resistance, ratio – every 5 to 6 years or earlier, if required.
m) Bridge test bushings – every 5 to 6 years.
n) Capacitance bridge bushings, windings and core – every 5 to 6 years.

9.9 Converter transformer replacement

Converter transformer failures are very infrequent; however, replacement of a failed transformer with the spare transformer can take several days unless facilities are provided to speed the operation. The time required for transformer replacement can significantly affect the converter station availability.

Facilities that aid in speedy transformer replacement are as follows:

– Arrangement of bus-work so as not to impede transformer removal.
– Arrangement of transformer coolers so as not to impede transformer removal.
– Provision of plugs on control cables.
– A quick method of removing the seal between transformer bushings and valve hall wall where the transformer bushings protrude into the valve hall.
– Channels or rails embedded in concrete in the transformer vault and at right angles alongside of the converter building to facilitate removal and replacement of the transformer using caged multi-ton rollers.
– Provision of pulling eyes for rigging of winch cables.

9.10 Reactor maintenance

Air cored dry type reactors are provided for the smoothing reactor and AC and DC filter reactors and are considered to be maintenance free. During the course of normal operation, the reactor would experience minute levels of expansion and contraction due to fluctuations in operating and ambient temperature.

The following items should be checked during regular maintenance intervals:

a) Check the torque of all hardware connections.

b) Check the surface finish of the reactor for deterioration due to prolonged exposure to severe environmental conditions, touch up or repaint as necessary.

c) Ensure that the reactor insulators are clean.

d) Check the reactor for any broken or damaged wire connection.

10 Asset management of co-owned HVDC project

10.1 General

Asset management of co-owned HVDC project should be managed by the associated organizations consisting of owners, power companies, technical advisory party and other relative organizations for the period from the beginning to the commissioning. The same arrangement should be maintained even after commissioning in order to achieve efficient HVDC system utilization, operation and maintenance management, through the cooperation of owners and system operators.

10.2 Project planning stage

Project planning is fixed through the preliminary study and evaluation of various requirements and conditions by the consortium / organizations which usually consist of respective owners, power companies, independent technical parties and other stakeholders. Project implementation scheme including overall project schedule and organizing executing body are discussed and determined by the consortium.

10.3 Project implementation and commissioning

From the beginning to the commissioning, the project progress is periodically coordinated and managed with the cooperation among the executing organizations and all related organizations. Commissioning tests, based on various test requirements, test schemes, overall test program and criteria, are discussed and fixed by related organizations within the constraints of power system conditions.

10.4 HVDC system maintenance management after commissioning

Optimal asset management of co-owned HVDC system is utilized with maximum availability and maximum utilization rate, and the system life is extended as long as possible. The operation and maintenance schedule therefore should be planned by the organizations comprising asset owners and system operators. Usually HVDC systems are put into periodical scheduled outages which involve ordinary inspection on annual basis and detailed inspection in several years. In order to increase availability and utilization ratio, firstly these scheduled outage schemes should be coordinated between both converter stations owned by different organizations in overall planned stage. Secondly, usually on an annual basis, scheduled outages programs should be reviewed and coordinated by the asset owners and system operators. Thirdly, scheduled outages management such as power system operation should be executed by system operators.

10.5 HVDC system operation management

As mentioned above for the maintenance management, similar procedure is required to manage HVDC system operation. Compared to a power station, HVDC system should be operated as much as possible to obtain higher availability. Therefore, basically HVDC system should be put into operation at all time except during scheduled outage and forced outage.

Figure 4 is an example of a flow-diagram showing the operation and maintenance management for power network involving co-owned HVDC system.

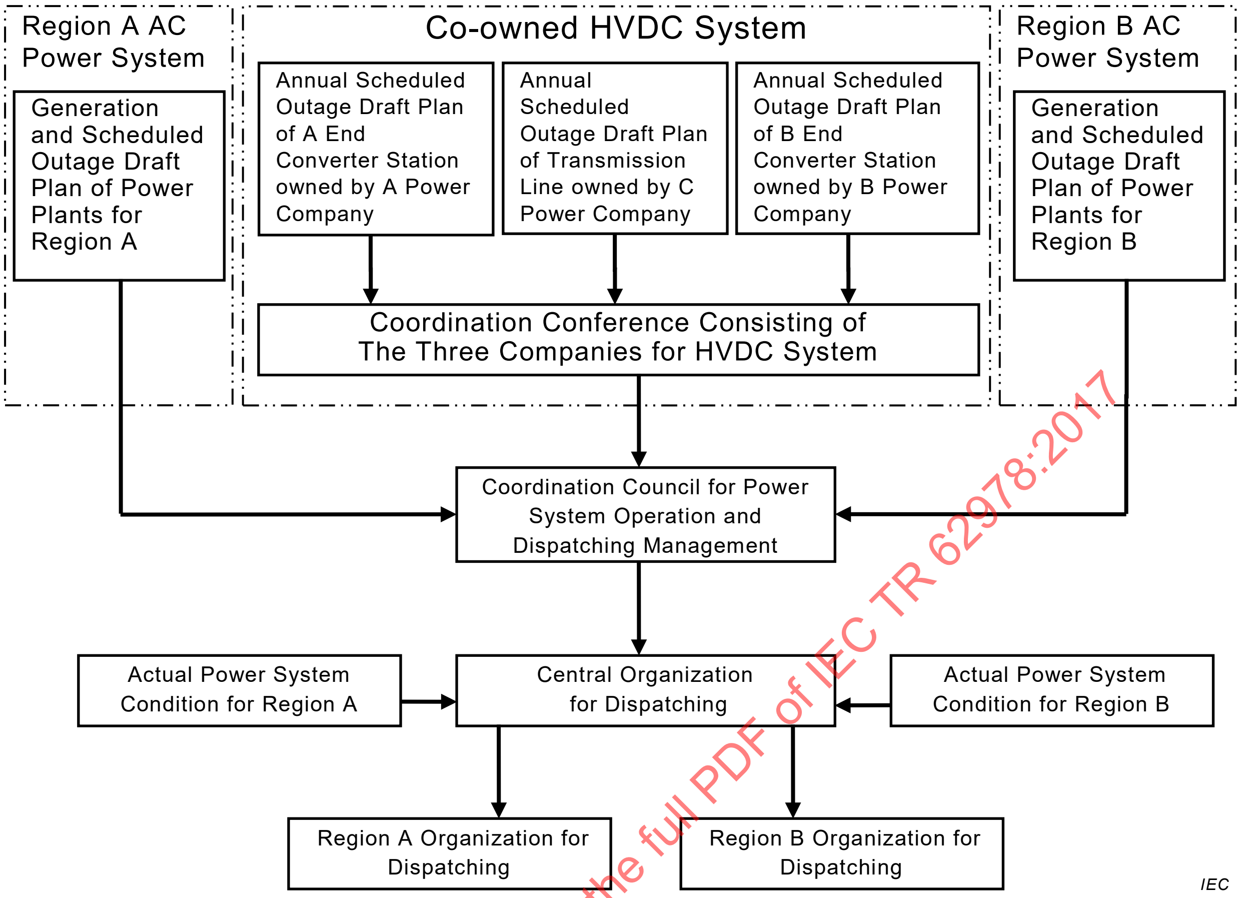


Figure 4 – Operation and maintenance coordination of co-owned HVDC system

11 HVDC reliability and availability

11.1 General

The objective in monitoring the performance is to ensure that the HVDC systems have achieved high levels of availability and reliability as per design. The supplier should give careful attention to related factors affecting the HVDC system performance including, but not limited to, sub-system and system testing, protective relay coordination, proper setting of relays, spare parts, and redundancy of design.

The HVDC system should be designed to prevent undesired power reversals due to equipment failure, malfunction, or operator error.

For bipolar operation special attention should be given in the operation and maintenance of the converter station to avoid bipole forced outages due to equipment failure, malfunction or operator error. The supplier should submit a report explaining the measures taken to minimize the risk of bipole forced outages.

The operation and maintenance of the converter station should be such that under normal bipolar operating conditions, no single failure of equipment furnished by the OEM should cause a forced outage resulting in a DC power transfer capacity reduction greater than the rating of one pole. Where this is not practical it should be demonstrated that the expected number of incidents in which power transfer capacity reductions greater than one pole will occur is acceptable and comparable to other recent bipolar systems. Further, under future bipolar operation, the converter station should be designed to permit maintenance on one pole with the other pole in service. The converter station should be designed so that shutdown of the entire station for maintenance is not required. Scheduled maintenance should not be necessary more than once per year.

The performance of the converter auxiliary system and associated controls and protection should be such that a single equipment failure should not cause a reduction in DC power transfer capacity of more than one pole. For example, in the event of failure of a portion of the cooling system for a piece of power equipment, the increased temperature rise should not be injurious to the power equipment. All cooling systems should have sufficient reserve capacity built into cooling pumps, cooling fans and heat exchangers to allow for the loss of any single piece of equipment in the cooling system without reduction of the HVDC system power transfer capacity. Where necessary, cooling pumps, cooling fans, and heat exchangers should be duplicated to meet this requirement.

11.2 Performance monitoring policy and practices

The performance monitoring is to gauge whether the HVDC system achieves the designed level of availability and reliability and measure its performance through benchmarking against the rest of the utilities.

For key reliability aspects, IEC TS 62672-1 is widely used as a reference document for HVDC systems monitoring. As for benchmarking purposes, the biennial reliability performance reports of worldwide HVDC systems as published by the CIGRE Advisory Group B4.04 are utilised.

CIGRE Advisory Group B4.04 collects data annually on the reliability performance of HVDC systems in operation throughout the world. The report is in the form of a summary of the reliability performance of HVDC systems in operation worldwide for every two years. The report contains data on energy availability, energy utilization, forced and schedule outages and other related data, including statistics on the frequency and duration of forced outages for every calendar year. The categories for the cumulative averages are for back-to-back stations, two-terminal and multi-terminal stations with one or two or more converters per pole.

The data collected, together with published data, provide a continuous record of reliability performance for the majority of HVDC systems in the world from the time they first went into operation. This constitutes over 650 system-years of data on thyristor-valve systems.

In terms of the common failures that caused unplanned outage for HVDC systems, converter transformer, thyristor valve and valve cooling systems are ranked as the main contributor to HVDC unplanned outage statistics. A summary of typical equipment failures on unplanned outage is summarized in Table 11, ranked according to outage duration involved.

Table 11 – Equipment failures that caused unplanned outage time

No	Equipment/Process	Ranking
1	Converter transformer	1
2	Thyristor valve	2
3	Valve cooling system	2
4	Control and protection	3
5	Unrecoverable commutation failure	5
6	AC filter	5
7	AC/DC switchyard equipment	3
8	DC filter	5

NOTE 1 Ranking 1 being failures that caused longest outage; ranking 5 being the least.

NOTE 2 Unrecoverable commutation failure is included even though it is not directly related to equipment failure because it contributes to unplanned outage.

11.3 General requirements on performance monitoring of HVDC system

The owner and OEM should define the following requirements for availability and reliability:

a) The OEM should design and furnish converter station equipment with the design objective that Force Energy Unavailability (FEU), Schedule Energy Unavailability (SEU), FOR and general failures based on the failure of equipment within the OEM's scope of supply, do not exceed the specified design target values.

b) For forced outage rate and unavailability calculations, the effect of certain outage and curtailment events which are beyond the OEM's control will be excluded. Possible examples of such events are as follows:
   – misuse, operator error, or other human cause which contravenes with the OEM's operating and maintenance instructions,
   – environmental conditions, or AC system conditions outside the design criteria given in the owner's requirements, and
   – external causes beyond the control of the OEM.

c) Any failure or incorrect operation of equipment within the OEM's responsibilities under the project contract causing a reduction in the HVDC system power transfer capacity should be considered in the evaluation of the reliability and availability of the design of the HVDC system and the actual HVDC system performance. Such outages should include, but not be limited to, those resulting from the following failures:
   – incorrect operation of control and protection systems due to electrical interference or incorrect settings,
   – failure to start the HVDC system,
   – failure to complete automatic switching sequences,and
   – any reduction of DC power transfer capacity to a level below its rated capacity.

Although outages and curtailment of HVDC system power transfer capacity caused by failures in equipment should be included in the availability and reliability assessment, the HVDC system should be designed with the converter station to function as set forth in the specifications during and following credible faults and failures in the AC system and equipment which interfaces with the equipment within the OEM's responsibility.

The design target values for the forced and scheduled energy unavailability and the forced outage rate attributable to the converter station and cable terminal station equipment should be considered on an annual basis and should be based on the recommendations as set out by the OEM's mandatory list of spare components.

11.4 Availability and reliability measurement

11.4.1 General

The reliability and availability of an HVDC system are characterised by two major indices:

a) Forced Outage Rate (FOR) – the number of outages in a year.

b) Unavailability – this is a measure of the amount of energy that could not be transmitted because the transfer capability of the system has been reduced (or it has been tripped due to forced outage).

The unavailability performance of the HVDC system will be dependent on a number of significant factors as follows:

– the quality and features of the HVDC system equipment; good conservative design with adequate redundancy can reduce the number of forced outages,
– having skilled personnel available to quickly perform maintenance to restore power transfer as quickly as possible after a forced outage event,

– having the right spares and right numbers of spares to facilitate rapid maintenance after a forced outage, which also depends on recouping the store immediately after spare is used, and
– performing preventative maintenance during operation or during annual scheduled outages that will avoid or reduce forced outages in the coming year.

With high reliability design incorporating redundancy in controls and protection, cooling plant, thyristor valves, filters, communications systems and station service power, the number of forced outages can be reduced to about 4 per station pole per year or 6 per pole per year on average based on CIGRE statistics. Most recent facilities would meet these forced outage figures.

Unavailability performance will depend on the response time and skill of maintenance personnel to restore power after a forced outage. Typical outages not requiring major equipment replacement can be restored in 2 h to 3 h plus personnel response time if the required spare parts are available at the site. The HVDC supplier will be required to provide a recommendation for reliability spare parts to meet the unavailability targets in the detailed technical specification. It will be up to the owners' maintenance teams to monitor the consumption of spare parts and re-order or supplement the spares provided by the HVDC supplier as needed based on observed failure patterns.

Thus, unavailability performance is determined both by equipment features and quality and by sustained effort of the owners' maintenance teams and strategy. In most of utilities' experience, and as evidenced by CIGRE statistics, high reliability and unavailability figures can be achieved in practice, with proper attention to both design aspects and maintenance regime.

11.4.2 Scheduled maintenance outages

Scheduled outages for preventative maintenance and repairs by the owner should be included in the evaluation of availability and will be based upon the following:

a) Maintenance will be performed with the interval between scheduled maintenance outages as stipulated by the OEM and accepted by the owner.
b) Maintenance will be performed in accordance with the OEM's maintenance instructions. The OEM should be advised the interval when the maintenance will be carried out and may, if he chooses to, witness all scheduled maintenance work during the availability and reliability monitoring period. The OEM should provide technical advice to the owner's maintenance representatives during such scheduled maintenance outages that falls within the contractual warranty or maintenance contract period.
c) Maintenance and repair will be performed with a qualified working crew of adequate size for the work and trained according to the OEM's maintenance training program. For many activities, time deployed can be reduced by employing larger maintenance team.

11.4.3 Outage and curtailment times

The duration of any outages for the purpose of both evaluation of the design and evaluation of actual HVDC system performance can be based upon the following:

a) The outage will start at the time that a reduction in DC power transfer capacity to below its rated value occurs for any reason. Waiting time, when repair is delayed due to network or other conditions, is excluded from outage duration.
b) The outage will end when the DC power transfer capacity returns to the rated value.
c) The actual time taken on maintenance or repair of the equipment will be included in the outage duration including time required to determine the cause of the outage and switching and clearance time.
d) The outage time for the failure of a converter transformer or oil filled smoothing reactor that needs to be exchanged with a spare unit will be excluded.

11.5 Verification of availability and reliability performance

The owner for HVDC system should evaluate the performance of the DC station to verify that the requirements for forced energy unavailability, scheduled energy unavailability and forced outage rates have been achieved. The availability and reliability evaluation period will commence when the acceptance tests have been completed and the project has been taken over for commercial operation. The evaluation will be for a duration of 1 year of commercial operation and in accordance with the following:

a) The availability and reliability of the DC station will be observed for the full availability and reliability monitoring period to determine fulfilment of the availability and reliability requirements.

b) During the availability and reliability monitoring period, the owner should maintain and make available for the operation records of the number and duration of forced and scheduled outages attributable to the failure of HVDC system or equipment and the amount of outage capacity reduction resulting from each outage. Classification of outages into forced and scheduled outages and calculations of forced energy unavailability, scheduled energy unavailability and the forced outage rate for each year during the availability and reliability monitoring period will be performed by the owner in accordance with the definitions and formulae in IEC TS 62672-1.

11.6 Availability and reliability calculations

All calculations prepared by the owner concerning unavailability and forced outage rates of the DC system and all of the sub-systems therein should utilize definitions of unavailability, forced outage rates and outage state conditions as given in IEC TS 62672-1. Outages time for repair, maintenance, and replacement of components should be based on the premise that all spare parts are on hand and that all of the OEM's schedules of recommended maintenance are adhered to, and that maintenance personnel will be on hand to make repairs immediately on a 24/7 basis and that there is no limitation to perform maintenance due to network / grid side.

The facilities should be assumed to be utilized 100 % of the time for a 12 month exposure period at 100 % rated load.

11.7 Reliability criteria of HVDC control and protection system

One of the major concerns on the HVDC performance is the availability and reliability of control and protection system.

In general, wherever possible, the following principles should be followed in the design of the control and protection system:

a) Use of the least complex design capable of performing a required function.

b) Use of components of proven reliability and maximum use of circuit boards of previously used design. The OEM should provide to the owner material specifications and evidence of component reliability and suitability. All components should be time-proven or have undergone applicable accelerated life stress tests.

c) Use of pre-aged components. A burn-in period, or other equivalent means of assuring reliability, should be applied to all electronic components within the control and protection equipment.

d) Use of circuits capable of operating with a wide range of component tolerances so as to reduce the necessity for matching replacement items to a specific application.

e) Use of design practices, surge protection, filtering, and interface buffers to assure immunity of sensitive components and circuits against damage and interference by induced voltages and currents in external cabling and cubicle wiring.

f) Use of fail-safe and self-checking designs.

g) Use of redundant components, equipment, control cables and circuits by means of either duplication or triplication with automatic transfer facilities wherever necessary to meet the requirements as stated by the owner, but only in addition to the above principles a) through f).

h) Designs which, in the event of component failures, provide for transfer to a less complex operating mode.

i) Use of non-lockout features so that equipment may be re-started remotely if considered prudent.

j) Provision for alarm, fault indication, monitoring and test facilities.

k) Provision of clear, easily-read drawings and manuals with sufficient details and cross-references to facilitate repair, servicing, and maintenance.

l) Use of equipment designed to be maintained, repaired, and operated at the converter station without the need for special operating and maintenance environment, test equipment, special tools, or complex operating sequences wherever possible.

m) Use of modular construction to permit rapid replacement of modules with failed components or sub-assemblies.

n) Physical separation of redundant control cables and circuits where feasible.

o) Use of common software language in controls to the maximum extent possible.

Only components of high quality and adequate ratings margin should be used in the equipment. Electronic components should be operated at voltage, currents and power levels consistent with high reliability operation.

11.8 Alternative methods in achieving high performance

A service provider when employed can often increase the operational efficiency by having a Performance Based Contract (PBC) where the HVDC owner and operator agree to move from a simple owner / contractor (service provider) relation to a new owner / partner scheme where both are involved under a performance based contract.

Under this arrangement, service provider main target is to ensure asset operational condition in accordance with the asset manager's needs. Contract is based on performance indices instead of classical operational specifications. Typical performance parameters to be considered by the HVDC utility asset manager could be tagged to the availability and reliability figures, operational health and safety incidents and budget / revenue fulfilment (operating costs, units sold, etc.). This PBC may create improvements not only in economic parameters, but also in terms of utility image and overall efficiency in managing the asset.

A long term arrangement with OEM for support services is another area often deployed to improve operational efficiency. In the case where utilities' own experienced staffs are available, the need for a contract with OEM regarding long term support services never arise except for very special cases.

The areas of improvement with respect to support services that utilities would like to consider are as tabulated below:

– contractual terms / issues,
– warranty coverage / period,
– technical support,
– commercial arrangement,
– training, and
– prolonged period of spares availability.

12 Documentation and records

12.1 General

Documentation of assets that are within the scope of asset management system which consists of asset inventory, records, application manuals, operating instructions, as-built drawings, detailed schematics, document master list and other relevant manuals should be systematically and securely archived to facilitate easy data access and information retrieval.

In addition to the conventional hardcopy format, it is preferable that the archive includes digital copies which are stored in common and non-proprietary storage formats. Adequate provision of regularly updated backup data storage is recommended to ensure that the archive is not lost in the event of storage device failures.

12.2 Common policy and practices

The documentations to be included in asset management portfolio are governed by respective utilities' policy and practices and should include but not limited to the following:

a) asset inventory;

b) as-built drawings;

c) detailed schematics;

d) document master list; and

e) detailed maintenance and operating procedures.

The supplier, together with the OEM, should supply the drawings, installation, operation and maintenance manuals for all equipment, plant and systems as specified herein. The manuals should cover all aspects of applicable part the HVDC system including but not limited to the following:

– HVDC converter stations,

– cable terminal stations,

– electrode stations,

– DC transmission lines,

– electrode lines,

– AC transmission lines,

– AC switchyards and equipment,

– submarine power cables, and

– submarine telecommunication cables.

12.3 Information management

For successful asset management decision process to be realized, it is essential that the organization identifies specific asset information it requires during all phases of the HVDC asset life cycle. Good asset management practice requires meaningful, quality, timely and systematic management of critical asset information where controlled access to such information should be made available to employees, stakeholders, service providers and other relevant parties depending on their scope of responsibilities and activities.

Asset information management includes all materials deemed necessary for decision making and analysis, which includes asset register, engineering drawings, tendering document, specifications, contract document, licenses, legal, regulatory and statutory documents, policies, standards, guidance notes, technical instructions, user/operating manuals, procedures, operating criteria, asset performance parameters, maintenance records, etc.

The organization should develop, implement and maintain procedures for controlling all information related to HVDC assets to ensure the following:

– the integrity of received information through data checking;
– availability of necessary asset information as and when required;
– the adequacy of information through periodic review and revision control, if necessary;
– the sufficiency of information for particular use, validated and approved by authorized personnel;
– access to information, controlled and appropriately secured including provision of suitable back-up copies;
– obsolete or erroneous information promptly removed from being accessed, or otherwise marked accordingly; and
– allocation of appropriate roles, responsibilities and authorities regarding the origination, generation, capture, maintenance, assurance, transmission, rights of access, retention, archiving and disposal of items of information.

Organizations should consider implementing the following recommendations for managing asset-related information:

– identification and definition of essential information for specific HVDC equipment during the asset life cycle and for a pre-defined period after the disposal of the assets, including defining the acceptable level of accuracy and completeness according to the organization's requirements including legal, regulatory, statutory and other asset management requirements that are applicable to it;
– information assigned at the lowest component level of equipment that requires discrete replacement or maintenance actions, to prevent redundant population of information systems; and
– systems employed make use of a range and combination of media, formats and technologies.

The systems should enable an organization to identify, collect, retain, transform, update and disseminate its asset information securely.

It is not necessary for an organization to establish and maintain a complete asset management information system in-house. Parts of the system may be supplied or operated by others but it is essential that all system components, irrespective of source, are sufficiently compatible with the whole system. The information provided by these component systems shall be consistent and contains suitable cross references to allow cross system analysis.

The systems for managing asset management information should be designed so that data and information is readily accessible using indexed searching method and is made available to all relevant personnel under routine and non-routine conditions, including contingencies and emergencies.

All information required, particularly for the operational activities should be securely controlled and address the following:

– allocation of roles, responsibilities and authorities for the origination, generation, capture, maintenance, retention, transmission, access to, assurance, archiving and disposal of items of information;
– definition of the content, meaning, formats and medium for the representation, retention, transmission and retrieval for each information item;
– requirements for information maintenance, including version control and assurance activities;
– requirements for the generation, capture or importing of the identified items of information;