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Lifecycle Management for HVDC Systems

ERIK JANSSON, URBAN ELGQVIST – ABB Sweden
HVDC USERS - Europe and Americas

urban.elgqvist@se.abb.com

SUMMARY

This paper presents a lifecycle management approach to service, based on operating experience, digital services, refurbishment, and upgrades of existing HVDC Systems. Each HVDC system is unique and will have differences in the life time expected for every piece of equipment or sub-systems due to its diverse usage, geographical location, environmental conditions and intervals for preventive and corrective maintenance, among other factors. Lifecycle availability and reliability are of utmost importance for the future electricity market. We collaborate with our HVDC Users to get their operation experience of converter stations including real service operation input. Showing the station lifecycle overall configuration, what services are applied, and investigating what topics are important for users at different life-cycle ages. Paragraph ‘Real Operation Examples’ is based on input from HVDC Users in Off-shore wind, Back-to-Back, and Interconnector-segment.

KEYWORDS

HVDC, reliability, availability, lifecycle, offshore, onshore, asset, upgrade, maintenance, remote, outage.

LIFECYCLE AVAILABILITY AND RELIABILITY

Lifecycle availability and reliability are main requirements for all HVDC systems, the importance of which cannot be underestimated. CIGRE [1] collects data on the reliability performance of HVDC systems in operation throughout the world. Data such as energy availability, energy utilization, forced and scheduled outages, statistics on the frequency and duration of forced outages per year with data from previous years to present a cumulative average from 1988. Including back-to-back stations and two terminal and multi-terminal stations with one and two or more converters per pole. CIGRE keeps a continuous record of reliability performance for the majority of HVDC systems in the world since they first went into operation. Industrial high-voltage services comprise traditional-, digital-, new services, and these services together with HVDC systems (valves, cooling, and control) constitute integrated solutions. Integrated solutions where systems are designed for services and services for systems, will influence overall equipment effectiveness.
HVDC applications (Interconnectors, Offshore Wind Connections, Back-to-back, and others) are unique, with different requirements, and hence will need tailored services.

Our practices affect the reliability and availability during the plan, build and operation phases. Contractors and Users’ need to collaborate to sustain the availability.

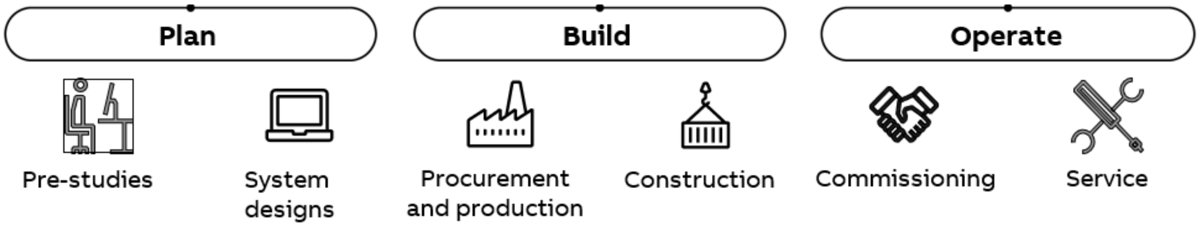

Figure 1: Our practices affect reliability and availability from the plan, via build and through the operate phase (our focus)

The scope of this paper focuses on Lifecycle Management during the operate phase:

a) The level of reliability and availability of the HVDC link, and the factors affecting.
b) Lifecycle management practices and their effect on reliability and availability.
c) Possible improvements to the reliability and availability of HVDC systems.
d) Understand component, system, and grid-level reliability & availability.
e) The cost of unavailability and unreliability of the HVDC fleet now and in future.

LIFETIMES

Lifecycle Management is about how to efficiently maintain and optimize HVDC systems through the life-cycle, from the cradle to retirement, the period for this lifecycle typically spans from 30 to 40+ years. Lifecycle management is needed from the yard, via the control room, and to the remote service-center. Main equipment's are usually designed for many years of usage through adverse weather conditions. Most main equipment is static, but if movable, it is designed for a high number of operations, and as long as it is properly operated and maintained across its life time, it tends to last for long periods of time. Equipment and subsystems highly dependent on the electronic equipment and software industries (such as the SCADA/HMI layer, and to lesser extents, the control computers and the I/O) will however suffer a faster aging in terms of components obsolescence and compatibility due to the rapid rate of change.
Lifecycle management should be interpreted considering the characteristics specific to each HVDC installation. Below is the guideline of lifetimes made by IEC 2017 [2].

Main Equipment	Lifetime (years)
Converter transformer	40
Cooling equipment	25
Thyristor valves	35
Control System	12-35
HMI	7
Civil work	50

Figure 2: The life time of a HVDC System components varies from 7 years up until 40+ years. [2] IEC Guidelines on asset management.

An HVDC station is a complex, well-integrated system comprising many components and advanced subsystems. Many components are well understood in the power industry, such as breakers, disconnectors, arresters, measuring equipment, transformers, reactors, filter capacitors, etc. These component lifetimes are typically well known to utilities – the life expectancy of most is well beyond 40 years. However, in some cases lifetime depends on usage. For example, it may be economically justifiable to replace circuit breakers with heavy switching requirements earlier, as the alternative would be frequent maintenance and major overhauls. [3]

LIFECYCLE MANAGEMENT

Throughout a lifecycle various services, upgrades, processes, and tools are applied. Some are planned, and some are forced.

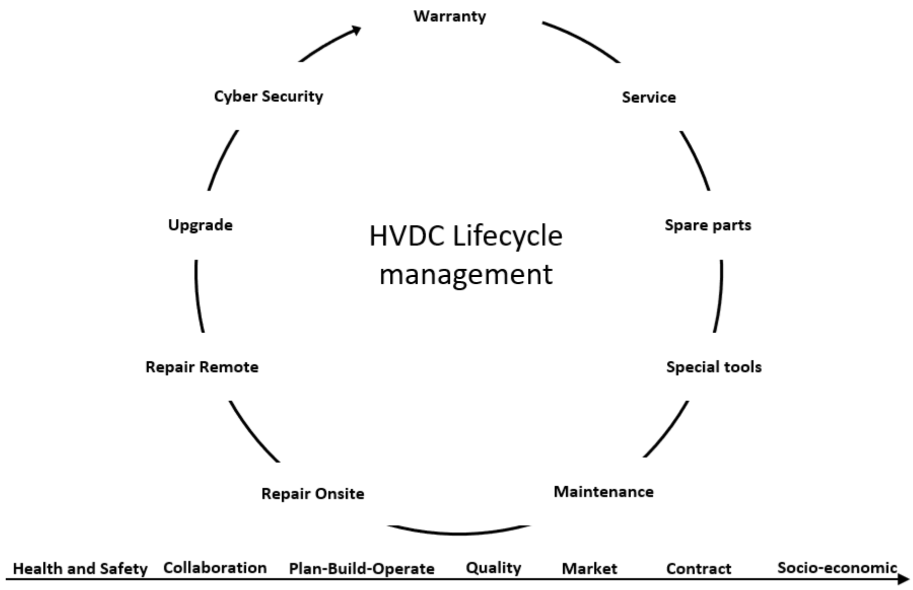

Figure 3: Lifecycle management as a wheel rolling forward through the system lifecycle.

Upgrades [3] to newer and better technologies appear during a system lifecycle, making it possible to improve performance, security, or introduce new functionality. An upgrade can at this point add many years to the system life time, as well as further increase performance, availability and reliability. An HVDC station is a complex, well-integrated system comprising many components and advanced subsystems. Many components are well understood in the power industry, such as breakers, disconnectors, arresters, measuring equipment, transformers, reactors, filter capacitors, etc. These component lifetimes are typically well known to utilities – the life expectancy of most is well beyond 40 years. However, in some cases lifetime depends on usage. For example, it may be economically justifiable to replace circuit breakers with heavy switching requirements earlier, as the alternative would be frequent maintenance and major overhauls. Systems unique to HVDC stations are HVDC valves, and control and protection systems.

Maintenance [2] is a fundamental part of the lifecycle availability and reliability. The HVDC converter equipment should be maintained in line with the recommendations of the Contractor. 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 bi-pole 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:

a) The interval between scheduled maintenance outages.

b) The Contractor maintenance instructions.

c) A qualified trained working crew of adequate size for the work.

Maintenance agreements are provided by Contractors to complete the Users own in-house resources. The balance between Users inhouse and outsourced resources varies from case to case, each System/User is unique.

Repair can be done from remote and on-site, and depends also on spare part availability, special tools, and other service processes.
The objective is to achieve high levels of availability and reliability with minimum schedule outage. The User 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.
In general, wherever possible, provision of alarm, fault indication, monitoring and test facilities. Where possible components are self-checking designs and redundant components.
Provision of a maintenance or repair procedure and check list, drawings and manuals to facilitate repair, servicing, and maintenance.
System is designed to be maintained and repaired from remote and on-site using the relevant people, processes, test equipment, special tools, or operating sequences.

Case reports (forced outage reports) from the site engineers, in close collaboration 24/7 with $1^{st}/2^{nd}$ line engineers and the subject matter experts, must be efficient to minimize outage time – every minute counts. And needs to enable root-cause-analysis so that the case is closed, not repeated, and the lesson is learned - once and for all.

Cyber security [5] must be addressed throughout the entire lifecycle. The industry recognizes the importance of cyber security in control-based systems and solutions for infrastructure and industry and collaborates to address the new challenges. Measures taken to protect the reliability, integrity, and availability of power and automation technologies against unauthorized access or attack. System nodes and software shall be updated using the latest validated patches, updates and/or service packs for software. It is recommended that updating is done regularly and not only before major upgrades.
Control and protection including the valve electronics are unique since they are complex and responsible for the control of large quantities of power transmission and stability. The systems are integrated with the power electronic main circuit equipment and are reliant on IT components. A system could consist of vendor specific devices with proprietary firmware and software, combined with common IT hardware and software as servers, workstations, and routers. All with different expected lifecycles, both from a cyber security and operational lifecycle perspective. Cybersecurity is a continuous process, changing during planning, building and operation stages, and includes Cyber security activities such as:

- Vulnerability and impacts of changing regulatory requirements
- Cyber asset reduced life expectancy and replacement timelines
- Technical resource availability, training requirements and continuous security and maintenance programs
- Specification of responsibilities for a cyber security asset, divided among product vendor, system integrator and User

Spare parts availability [2] is part of the planning process for a system. It is imperative to keep a specific number of critical spares to cover failures of equipment critical to the operation of the system. The number of spares is derived based on recommendations, historical failure rates, replacement times and impact of outages. The unavailability of critical spares can have a severe negative impact on the availability of the HVDC system, and best

possible spare part management should be applied to remedy potential long delivery times of these, sometimes specially designed, spare parts. Most Users consider critical 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.
d) Control and protection digital signalling cards and components.

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, available from the Contractor. These tools are available on-site, or instruments brought at service intervals, and spans from classic service tools to modern digital tools such as augmented reality glasses, drones for site inspection, and data analytics. Efficient services (maintenance, repair and spare part provisioning) are delivered through people and processes empowered with relevant special tools on-site (and remote). Special tools on-site are also fundamental for safe working conditions for all site-personnel and should always be readily available and calibrated.

Lifecycle reliability & availability is being enhanced with new technologies such as Industry 4.0, augmented reality, remote services, cyber-security, data analytics and predictive maintenance have entered the industrial service space alongside existing services. Communication standard IEC 61850 enables communications between different vendor products in substations, and 5G wireless systems enables remote communications, satisfying demands for performance, low-latency and real-time fault management are coming. Communications that needs to operate in varying territories, remote rural areas, urban areas, onshore and offshore. Secure Communications handling the risks and challenges related to Industrial Control Systems. Empowering local/regional/central response centres to provide front-end services to systems/owners together with the players in the ecosystem.

REAL OPERATION EXAMPLES

Based on collaboration and dialogue with HVDC Users, we here aspire to increase knowledge in areas affecting reliability & availability. The Users in this investigation have HVDC assets at different stages in the lifecycle, and with different HVDC Applications used:

- Offshore Wind Connection (OWC) - 9 years in operation since 2010.
- Back-to-Back (B2B) - 19 years in operation since 2000.
- Interconnector (IC) - 25 years in operation since 1994.

We addressed the following areas together [6], as a collaboration for Cigre Canada, decoupled from Contractor/User normal work responsibilities and obligations:

- Lifecycle management (LCM) practices
- Sustain reliability and availability.
- Cost of unavailability.
- Varying Contract models - effect on reliability and availability.
- Split between inhouse and outsourced resources.

Figure 4: The areas addressed aspire to increase knowledge affecting reliability & availability through collaboration - for the greater good.

A concern for users is the potential need for major refurbishments, the risk if a major primary equipment fails, and aging/obsolescence of the station control & monitoring, main control and protection equipment. Also, Obsolescence Windows versions support, and portability of applications. Cybersecurity compliance with ISO27001 in Europe for IT security, and other standards such as NERC-CIP.
To mitigate this risk and sustain the asset, **practices**, maintenance programs are applied, based on Contractor maintenance instructions as well as experience and knowledge from transmission & distribution area. Preventive and predictive maintenance according to the Contractors manual (for equipment) and repair of obsolete boards for control-system.
Spare parts availability can delay repair, cause loss of redundancy, and higher trip risk. A user database for maintenance planning is valuable including documentation, as well as equipment failures and trips. Users internal maintenance program are based on the Contractors maintenance instructions as well as other experience and knowledge from transmission & distribution maintenance.
Also off-shore transformers corrosion and blocked motor operated valves in the cooling system has been a problem since sea water sometimes has been used to cool the transformers.

The present level of reliability and availability of the HVDC Converter station is according to Users sufficient, with few trips based on robust technology. And after a trip the links normally could be reinstated quite fast.

The reliability is **sustained** by performing frequent maintenance according to manufacturer recommendation, in some cases do even more preventive maintenance for specific components (replacement of hard drives, automatic backups etc.). It is important to follow-up trends from maintenance records and step in when we see a negative trend. Root-cause analysis should be applied as far as possible, to close faults at first occurrence. This needs a tight collaboration between the front-line and the back-end subject matter experts.
Cybersecurity Services are needed, starting with an assessment of the current situation, recommendation of patches to install and possible setting changes to improve cybersecurity and regular reports on available new and verified patches.

Here it is important with contractor-user dialogue and the user-user dialogue. An important resource is experienced, educated and rapid reaction from personnel in readiness as well from back-office engineers. Rapid 24/7 stand-by services with adequate knowledge and competence experts with short response time supported by a technical “back-office” (with even higher level of knowledge/competence). Remote support for internal uses is also considered.
Some possible improvements where pro-active maintenance measures and refurbishments at the right time to avoid unplanned outages. Also, knowledge and competence from 2nd line experts with short response time supported by a technical “back-office” with even higher level of knowledge/competence.

Other suggested improvements from off-shore OWC where:

- General use of panic locks for HVDC rooms.
- Optimized fire detection system, to avoid un-necessary trips in the landstation.
- Use of non-gel type batteries for UMD system, which are very sensitive.
- Careful design of climate system for control building, high temperatures in the control room, leading to failing server hard disks.
- Always use redundant dehumidifiers for the HVDC rooms.
- The offshore station POW controller in the grid side switchyard always require staff onboard after a trip to reset.
- Valve-cooling improvements:
    - placement of temperature sensors to avoid too high differences between A- and B-system.
    - Make valve cooling control for the bypass control more efficient.
    - Avoid possible risk for damage when the valve cooling medium stays below 20°C and the air is heated up above 32°C

The **cost** (or order of magnitude) related to unavailability can be calculated in various ways. For OWC the cost of unavailability is a calculation of possible compensation of the wind farm dependent on the actual available wind power generation at the start of the unavailability. And additional cost will be for unplanned minimum manning of the offshore station for a minor repair/restart of systems. For B2B the unavailability value can be up to 150 times more than the availability value. For Interconnector we can calculate the price difference between the two ends (markets) of the Interconnector, and multiply with the capacity and time.
It is also important to understand the socioeconomic value [4] for HVDC (critical infrastructure). The order of magnitude of the costs related to the unavailability and unreliability can be estimated based on the cost of long outages average values. For the short-forced outages, an estimate was derived averaging the recent countertrading costs due to forced outages. With the present availability and reliability and considering the coming increase in the capacity of the Nordic HVDC fleet, the estimated range of the cost could be more than doubled in 2025. Such order of magnitude highlights very well the need and value to address the measures to enhance the reliability and availability of the HVDC systems in a more systematic manner.

Contract models/agreements between User and Contractor can affect the reliability & availability, depending on what kind of service is behind the contract. Assuming a correlation between quality, response time versus cost level. The challenge is to find the optimized level between these two sides. Industrial services greatly vary in terms of underlying

characteristics, key success factors, and need for resources and competencies needed. One part is input based contracts – a promise to perform a deed, as compared to output based contracts – a promise to achieve performance. Another input was to include a “carrot-and-whip” clause.
Some Users mean that the contractor shall guarantee that the asset will be operating until the end of the lifecycle. For the Contractors it is here important to agree a relevant service delivery-limit for the asset.

Another concern is the balance and needed **resources** and split between inhouse and outsourced resources related to technical knowledge and competence depending complexity of an HVDC Interconnector. Very complex equipment and failures which also happen very seldom should be handled by the Contractor and more frequently and not so complex in nature failures etc should be handled inhouse or at least solved by local contractors.

SUMMARY

We must continue to develop lifecycle management, existing digital and new services, which together with HVDC systems constitute integrated solutions. This is necessary to fulfil the needs of the evolving grid, high-voltage industry, Users, Partners, Contractors, End-Users, and other stakeholders. Integrated solutions of systems and services are important parts in lifecycle management.
This paper is written as a collaboration between Contractor and Users for Cigre Canada, decoupled from our normal work responsibilities and obligations. It is supposed to contribute to our common general understanding, increase the knowledge of the topic, and hence contribute to the greater good.

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