

HVDC O&M Strategy

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SUMMARY

Over the last 20 years, how Operation and Maintenance (“O&M”) is carried out at HVDC and FACTS installations has changed from the classical approach of a fully staffed station with routine scheduled maintenance to remotely monitored or partially staffed stations. As more and more HVDC/FACTS systems are being coupled with isolated generation, not only does the O&M have to follow the schedule of the generation, but it may be very limited in when it can be performed as to not “trap” generation and potential income. A new HVDC/FACTS owner/operator must address these issues while also considering strategies to address the training requirements for new O&M staff. Coupled with this is that while modern HVDC equipment typically has a life span of 25-35 years, aspects of the control, protection, and monitoring systems have a much shorter lifespan and need to be accounted for in the original O&M design and planning of a modern HVDC station.

This paper looks to compare various installations of HVDC systems in several stages of their lifecycle, with an added focus on North American cybersecurity practices. The authors will attempt to quantify the various O&M practices and staffing plans for the various types of owners of HVDC systems (merchant, utility owned, etc.); outline strategies for how a new owner/operator can efficiently integrate long-term HVDC O&M into their existing company through effective personnel training; and lastly, look at how the different lifecycles of HVDC equipment vs. control systems impact the overall O&M of an HVDC system.

KEYWORDS

HVDC, Planning, Operations, Maintenance, NERC-CIP, Cybersecurity, Lifecycle, Staffing, Training, Generation

1. INTRODUCTION

This paper looks to compare the various O&M practices of HVDC systems from the author's experience across the world. Prior to project completion, O&M planning must consider site staffing requirements. In the early years of site operations, the HVDC Owner must consider O&M staff training & retention, the impact of trapped generation on HVDC O&M practices, and the impact of NERC CIP standards (North American Reliability Corporation Critical Infrastructure Protection standards) on O&M. Lastly, this paper comments on the shortened lifecycle of modern HVDC monitoring, control, and protection equipment, particularly as impacted by NERC-CIP maintenance considerations.

2. SITE STAFFING CONSIDERATIONS

At a high level, O&M practices are first shaped by staffing requirements for the most critical system infrastructure, for example, an HVDC link's converter stations. An HVDC Owner's choice of staffing model depends on weighing the importance of various factors of cost with link reliability, availability, and utilization. These weightings may shift depending on the needs and restrictions of the local bulk electric system. In addition, geography plays an important factor; a two-terminal DC link may have multiple remote critical infrastructure sites in addition to the converter stations, such as transition compounds where overhead line transitions to underground or undersea cables, or remote telecom sites for interstation telecommunications. For North American utilities, NERC considerations (especially NERC-CIP), also play a significant role in shaping staffing requirements (see Section 5.2).

Operations, engineering, and support services staff are vital in preparing, maintaining and completing successful O&M programs. In general, it is difficult to recruit personnel who have had prior HVDC experience. Utilities or owners with new HVDC assets may contract more experienced owners, utilities, or vendors to provide support during the first number of years for O&M development and implementation. In addition, dedicated staff must be considered to address NERC-CIP requirements for HVDC cyber assets.

2.1 STAFFING MODELS

There are a number of staffing models an Owner/Operator of an HVDC link may employ. Any combination of these models for the various sites may be used to best suit the Owner's/Operator's needs. The models include, but are not limited to:

1. **Fully Staffed** - For a critical HVDC link, Owners may employ a fully staffed O&M model. Each end of the link has stations with full-time staff that perform operations tasks as well as maintenance.
2. **Partially Staffed** - A partially staffed model includes part-time (e.g. 40 hours weekly or less) operations and/or maintenance staff. It is essential that all pertinent information for remote monitoring and control is available to the sites to be able to respond to emergencies in a timely manner and identify any issue that arises.
3. **Unstaffed (Remotely Operated)** - A remotely operated HVDC link has no permanent staff at either end. Monitoring and control are completed from a remote control centre located at another facility. O&M tasks will be completed by staff stationed out of the main operations office, or contracted from the Vendor and/or other external companies.

The number of O&M staff may vary depending on the age of the HVDC link. For example, the staffing approach for a newly completed HVDC link may include having a higher volume of operators during the first few years of operation to address any "bugs" or issues that arise. Once a comfort level is reached with system reliability, a reduction strategy may be implemented to meet the daily operation requirements. Similarly, additional engineers and

asset specialists may be required in the first years of operations. For example, temporary asset specialist staff may be utilized to help with the initial volume of information to be reviewed and incorporated into PM programs and schedules. Once the bulk of the programs are established, only the core specialists may remain to manage the day-to-day work. A gradual shift from a fully staffed model to a partially staffed model may also occur.

2.2 OPERATIONS STAFF

Operations staff may include but is not limited to, electricians, millwrights, operators, technologists, and powerline technicians. The number and location of operations staff are based on the staffing model employed by the HVDC Owner. For example, a merchant link may be operated with little as one technologist and one engineer, with contracted support. However, with a fully staffed model, operations staff will be located at each end of the HVDC link. Powerline technicians may also be located at offices with strategic access to the DC transmission lines, especially if the lines are long. Cable maintenance & installation technicians are considered separately, as a subsea or buried DC cable failure requires extremely specialized and expensive equipment to be mobilized and the tools and staff may not offer appreciable benefit being stationed near the cable.

The Owner/Operator of the link may leverage local utilities to assist with regular inspections, routine maintenance activities, emergency calls, or other work associated with lines and remote sites to help reduce outages and potential impact to customers.

Recruitment of staff to remote areas is a challenge for most utilities, owners, and vendors. Shift rotations versus stationed positions may be considered to help attract personnel as well as utilizing a partially staffed model. This may be impacted by local unions and other working group agreements.

2.3 ENGINEERING STAFF

Engineering staff may include planning engineers, operations engineers, and asset specialists. Engineering staff can be located in a centralized location (main operations office) or located at each end of the HVDC link, depending on the O&M practices of the Owner and the preferred staffing model.

Typically, engineering provides support to field personnel and will travel to remote sites as required to provide support in outage response, troubleshooting efforts, equipment installations, material management, training exercises, development of maintenance programs/scheduled, compliance with standard and regulations, etc.

2.4 SUPPORT STAFF

For a local utility owner, support services staff often includes planners, schedulers, stockkeepers, and administration. Support services staff can be located in a centralized location (main operations office) or located at each end of the HVDC link. They will ensure adequate resources are in place for staff at remote sites (proper infrastructure), transportation needs, spare parts will be maintained and accessible to field personnel, and work orders and PMs will be entered in a database or tracking tool in a timely manner and scheduled to ensure completion.

For a merchant-owner, many of these support services are more economically supplied by the Vendor and other contractors.

3. OPERATIONS, MAINTENANCE, & ENGINEERING PERSONNEL TRAINING

Even though most converter station equipment has unique designs and specifications, much of that equipment will follow similar maintenance practices to the related equipment found in an AC station, including:

- AC switchyard equipment (AC breakers, disconnects, shunt capacitor/filter banks).
- AC protection and control.
- AC/DC auxiliary systems.
- Station service transformers.

Some of the unique equipment that may require substantially different maintenance includes:

- Converter transformers (due to their large ratings, size and utilization rate).
- Converter valves and valve cooling.
- HVDC control and protection and measuring equipment.
- DC breakers and switches.
- Special tools and software (this includes system models, replica controls, and RTDS systems and other items that are beneficial to ensuring reliable operation).

Many merchant-owned links will contract the Vendor for all O&M. For all other staffing models, a training program needs to be developed and maintained to ensure staff are able to operate and maintain an HVDC station reliably. Operations and Engineering staff must have comprehensive knowledge of the HVDC equipment and systems to ensure proper O&M, response to emergencies, troubleshooting techniques, and so on.

The critical tasks of the staff at an HVDC station will be:

- Responding to faults and restoring service.
- Replacement of equipment as required (both minor and major).
- Routine maintenance and inspections.
- Schedule and optimize outage maintenance.

In order to this, staff will need to:

- Understand the key apparatus differences between AC substations and HVDC converter stations. This includes understanding HVDC theory.
- Understand the control architecture. This includes the interactions between the AC system and the HVDC system; and understanding the vendor-provided tools, HMIs, sequence of events recorder, and alarms.
- Perform station isolation and operations sequences.

Typically, as part of the Vendor's deliverables, a training program will be provided that will allow for official training of the O&M and engineering staff. This training program typically includes:

- Operator training to safely operate the HVDC system without the Vendor present.
- Planning engineer training to modify and run the LCC computer models.
- Maintenance training, including preventative maintenance, corrective maintenance, as well as troubleshooting tools and techniques.

In the author's experience, most of the failures for an HVDC link that affect power transfer are expected up-front during the performance guarantee period, or towards the end of life, as modelled by the modified "bathtub" curve in Figure 1.

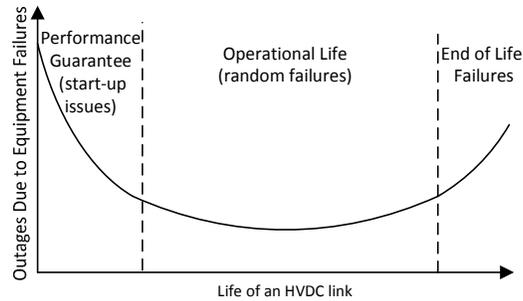


Figure 1 - Outages over the life of an HVDC link

Some of the most valuable experiential training will occur during the project implementation stage, so it is paramount to have the operations staff (operators, technologists, as well as planning engineers and operations engineers) involved in the commissioning and site works to develop a familiarity with the project and the equipment. During the project implementation, the staff will have the chance to:

- Review the detailed design documents to gain a better insight into how the station is designed.
- Participate in the acceptance testing of the equipment. This is particularly important for the control and protection systems as it will give the staff a deep understanding of the key systems such as the high-speed control and protection, the HMI and sequence of events recorder, the sequences and interlocking and the troubleshooting associated with the controls and protections.
- Provide assistance during the system commissioning to facilitate hands-on training.

During this phase, the Vendor will be providing detailed commissioning plans for each of the main systems associated with the HVDC link (C&P, Auxiliary systems, etc.) and given the hopefully long-time between failures of any given system, retaining staff knowledge is a must.

One way to retain this knowledge is for the Owner's engineers to set-up detailed procedures for each system and/or main piece of equipment during the commissioning (or shortly after). This way, while the information is fresh in the staff's mind, the required procedures (including, isolation requirements, spares, troubleshooting and testing methods, etc.) is developed. These procedures can then be used as training tools for new staff and can be integrated into the O&M procedures.

Once the system is up and running, it will be hard to take the system down for training, and all operations are now under a tightly controlled environment. In order to keep the operators training up-to-date and to train new staff, a training simulator could be employed. These simulators are able to replicate the operation of the HVDC station and allow operators to perform most tasks as they would be from the HMI of the actual station. This includes:

- Blocking/deblocking the scheme.
- Ramping.
- Enabling special protection systems.

During each of the above tasks, a trainer could cause a fault on the system for the operator to diagnose and work around. This could be something such as a stuck disconnect during a deblock sequence. This allows for real-world training without running on the actual system. This also allows one to develop new screens and test new points in the HMI/SCADA system.

In the past, one operations person would be specialized in AC protections while another would be specialized in telecommunication systems and another in generator controls. While

it is still a good idea to have staff with an in-depth knowledge of each system, due to the potential remote locations of the sites, it may be hard to maintain a high level of expertise without developing HVDC “generalist” roles. This approach can be aided by modern control systems, as all aspects of the remote station can be monitored from the other station, and a lot of detailed diagnostics can be performed even prior to dispatching staff to the sites.

4. MAINTENANCE CONSIDERING TRAPPED GENERATION

As large generating plants continue to be developed over the world in remote locations, the economics are increasingly favourable for HVDC links versus AC systems to transmit bulk power to the load centre. The traditional asset management maintenance models, whether they be condition-based, risk-based, age-based, or even run-to-fail, must consider that the generating plant has variable short windows of time each year when the plant can be shut down. For example, HVDC Owners connecting to a hydroelectric dam must be prepared to have limited “shoulder seasons” each year (between periods of maximum demand and minimum head, i.e. reservoir water levels) to schedule monopole outages for valve hall corrective maintenance or converter transformer planned maintenance.

For a merchant link connected to a generating plant, maximizing return during peak market price will be the driving scheduling motivator, and the maintenance windows will be squeezed between periods of maximum market prices. In this case, the asset management model for the equipment that requires a monopole maintenance shutdown will necessarily be risk-based, and will necessarily be incorporated into the economic model for the operation of the link.

Similarly, for a utility-owned link connecting a generating plant with critical customers, reliability during peak loading will be the driving scheduling motivator, and the maintenance windows will similarly be squeezed between periods of maximum customer loading and availability of backup generation. The asset management model for equipment requiring a monopole maintenance shutdown will also be risk-based and will need to be coordinated continually with the transmission system operator (SO).

Maintenance on redundant critical systems (such as valve cooling) will be able to be performed during normal operations, however, will be scheduled to reduce the impact of a monopole outage.

5. CYBER ASSET IMPLICATIONS TO OPERATIONS & MAINTENANCE

The trend for the control, protection, and monitoring systems within modern HVDC converter stations is towards increasing digitization. This has led to industry-wide innovations such as IEC 61850 compliant cyber assets and cyber systems (i.e. electrically programmable equipment) which have much simpler Ethernet cabling than their older electrically wired predecessors and greatly enhanced monitoring and control. However, there are two significant areas of concern from this trend to digitize HVDC converter stations.

1. The lifecycles of critical digital control, protection, and measurement cyber systems are substantially shorter and more complicated than the physical apparatus they are connected to, as the product lifecycles are now dependent on many third parties.
2. The burden of effort required by North American utilities to abide by NERC-CIP standards, typically increases as the HVDC converter stations gain more digital control and monitoring. Most systems that can negatively impact the bulk electric grid must abide by strict cyber-security best practices for documentation and vulnerability patching.

These two areas are explored in the following sections.

5.1. CYBER ASSET LIFECYCLE

A modern control, protection, or measurement system manufacturer relies more than ever before on third-party software, firmware, and hardware subsystems they can combine and modify to create their end-product. Practically, this allows the manufacturer to outsource components of their system to specialized third parties who can provide a superior product with more features for a lower cost.

As beneficial as this evolution seems to be, the additional product complexity and reliance on third-party manufacturers shortens the cyber-asset's usable life. For example, this paper will look at one of the HVDC systems with the most substantial reliance on third-party suppliers: The Human-Machine Interfaces (HMI) for the main HVDC controllers. Prior to the introduction of industrial PCs in the 1990s, these HMIs were primarily composed of parts that could be stocked by the manufacturer for decades and managed much like the spare parts of other equipment around the station, such as a relay or a transformer. Maintenance was mostly corrective for HMIs: only when failures occurred. See Figure 2 for a simplified historical HMI architecture.

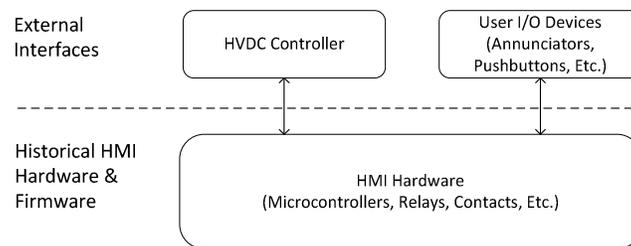


Figure 2 – Historical simplified HMI architecture

In comparison, a modern HMI is built on general-purpose hardware with many supporting components built by independent third parties. Each hardware and software component in Figure 3 can represent one or more separate subsystems that can be provided by a unique third-party, many of which are general purpose consumer products. Consumer products have shortened manufacturer product lifecycles (<10 years) compared to traditional utility equipment (>30 years), and when this shortened lifecycle is associated with a major third-party component such as the software Operating System, this shortens the number of years that a manufacturer can maintain a particular HMI system product line.

HVDC link owners will find that they will be replacing their HVDC HMIs roughly every 7 years [1] at the cost of typically several million dollars (CAD) which must be accounted for in capital expenditure planning. Similarly, modern digital HVDC controllers only have an installed lifespan of 12-15 years [1] versus an average of 35 years of life for the older analogue HVDC control systems. Replacement/refurbishment of an HVDC controller can cost up to tens of millions of dollars (CAD).

If cybersecurity is not a significant concern, it will be possible for the HVDC link Owner to operate and maintain their cyber systems several years beyond the product end-of-support date provided by the manufacturer by simply maintaining an extensive spare parts inventory of their cyber assets. However, the next section explores the implications of NERC-CIP for North American utilities, which invalidates that approach.

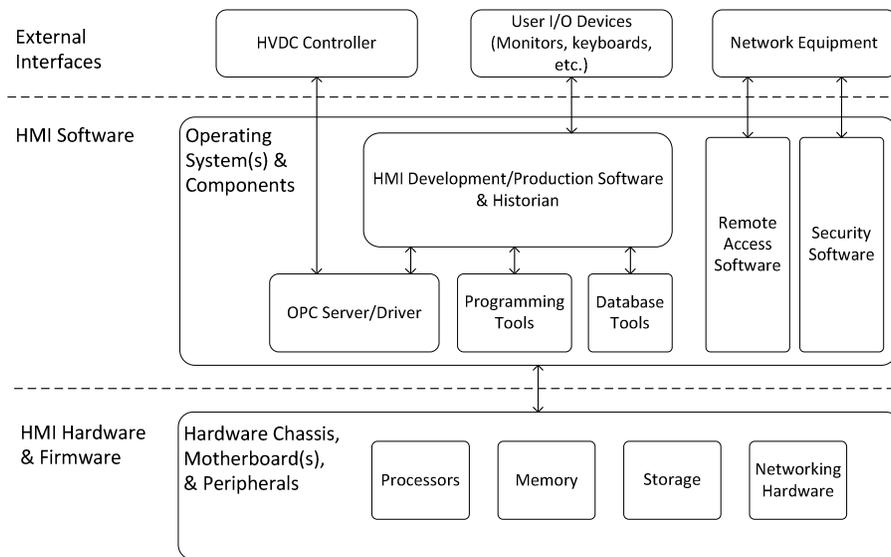


Figure 3 – Modern simplified HMI architecture

5.2 CYBERSECURITY CONSIDERATIONS

The trends to digitize the converter station and for manufacturers to rely on third-party subsystems does not merely affect system lifecycles, but also have impacts on operations and maintenance. In North America, the NERC-CIP standards for cybersecurity are imposed on all cyber systems and cyber-assets that can negatively impact the bulk electric grid. Due to the high power transfer capability of HVDC converter stations, they are almost always in the scope of the CIP standards. Most of the electrically programmable systems in the stations will also fall under the CIP standards (and even some building automation systems). Most of these systems can be directly manipulated to impact the grid, or they can be used to indirectly manipulate critical systems via their Ethernet or Industrial Ethernet connections.

The CIP standards mandate several practices that affect cyber system and cyber asset operations and maintenance activities, but this paper will focus on the following:

1. Create a baseline configuration detailing all information needed to identify what security vulnerabilities may be present on any in-scope cyber asset or cyber system.
2. Perform continuous monitoring for new vulnerabilities discovered in industry, and mitigate those vulnerabilities on applicable cyber assets and cyber systems.

A new HVDC link Owner in North America will have specified that their new facilities will have been built to meet CIP requirements, which initially will require all cyber assets and cyber systems to be fully documented and with up-to-date firmware and software. However, in the author's experience, even if the HVDC link vendor has built a system that is 100% CIP compliant, significant effort will still be required to incorporate new facilities into the Owner's existing networks and security patch management systems, as well as into any existing CIP documentation management programs. And, if the HVDC link Owner does not have a pre-existing compliance program, it must be noted that a perfectly CIP-compliant HVDC link is missing critical technical elements for a successful CIP compliance program. These include, but are not limited to:

- Reliability Standard Audit Worksheet (RSAW) evidence management program. This effectively organizes the CIP program evidence submitted for the audits.
- Vulnerability and patch management system. All pieces of software and electronic hardware must be regularly evaluated for patches (e.g. all components of the HMI shown in Figure 3), and some will have patches published monthly.

- Baseline configuration and technical evidence management system. There must be a system to prove what firmware exists on the in-scope assets on site. This includes devices not connected to an external network.
- There are many additional requirements for physical site security, electronic access, and even human resources, etc.

An Owner may also consider building a patch-testing environment or test-bench. This may include a sample of every type of protective relay, PLC, and bay-control unit (BCU) that will be patched; the HMIs (which can only be partially tested before being connected to the HVDC controllers); time-synchronizing equipment; networking switches, routers, and firewalls; and SCADA equipment such as protocol translators and aggregators (i.e. RTUs).

On an ongoing basis, the maintenance effort to keep up with security patching will also create high costs. A typical converter station will contain several hundred devices that each require periodic security patching. Some cyber assets (such as protective relays) will require partial recommissioning after a firmware update, adding to maintenance costs. It is recommended that when setting up a CIP compliance program, an HVDC link Owner hire consultants who have performed and/or experienced the full audit process from an Owner's perspective, so they may share the key lessons they learned.

Finally, CIP compliance can force the HVDC link Owner to upgrade systems that have reached the end-of-support from the manufacturer. If a manufacturer has released a new system that has patching support, the HVDC link Owner will have to annually justify to the CIP governing body the reasons why they are not patching/upgrading the existing system, the risk of doing so, and the mitigating measures put in place.

6. CONCLUSION

From the author's experience, it is beneficial to begin planning for O&M well before the HVDC project has begun, balancing cost versus reliability over time. To achieve an optimal balance, additional staff may be necessary for the first few years of operation.

When commissioning has begun, the HVDC Owner/Operator will benefit from having a core O&M team already in place so they can witness and learn from the commissioning activities. This will take place in coordination with Vendor training, allowing O&M practices to be cemented under the guidance of the Vendor and during dynamic testing of the most probable failure scenarios. The Owner/Operator may additionally hire an Owner's Engineer to assist with knowledge transfer to the O&M staff and accelerate training.

Depending on the link Ownership model, if the HVDC link is connected to a large remote generation plant, then the Owner must coordinate their asset management model with their economic model and/or the system operator.

In North America, Owners of HVDC links connected to the bulk electric system must consider the operational and maintenance impacts of achieving cybersecurity best practices. If the Owner/Operator does not have a NERC CIP program already in place, they will benefit from hiring NERC-CIP expertise who can recommend efficient programs, policies, and procedures to optimize data collection and management. Additionally, following NERC CIP standards will lead to reduced lifecycles of some of the modern control, protection, and monitoring systems on site, which must be considered for capital expenditure planning.

7. BIBLIOGRAPHY

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