Reliability on existing HVDC links feedback

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ABSTRACT

European TSOs have raised concerns about the actual experienced levels of reliability and availability of existing HVDC systems. A Task Force within ENTSO-E has the target of improving HVDC system reliability and availability. Possibilities to decrease the average number of HVDC link trips, leading to forced outages, and to shorten the average duration of the forced outages are evaluated. Especially cable faults are challenging events, as they may be difficult to locate and require lots of resources to repair. Submarine cable faults need special vessels and repair time can be significantly longer than in land cable faults. This paper shows experiences and examples of such cable faults and concerns.

KEYWORDS

HVDC; Cables; Experiences; Reliability; Availability; Faults; Statistics; Repair.

BACKGROUND

HVDC has become very important for the bulk transfer of electrical power for the Pan-European transmission grid and its importance is expected to continue to increase in the future. More than 50 % of new transmission lines by 2030 are anticipated to be HVDC infrastructure, including even separate HVDC grids.

Both worldwide and regional HVDC performance surveys have been analysed for getting a realistic view of the performance levels of HVDC systems in recent years:

- CIGRE worldwide HVDC performance statistics 2005-2014 concerning 27...41 HVDC-links [1-5] .
- ENTSO-E DISTAC group's statistics of HVDC outages and limitations 2012-2014 concerning 14...15 Nordic HVDC-links.

Based on the analysis of both above surveys, the main concerns regarding reliability and availability of HVDC technology are:

- Forced outages of overall HVDC systems are quite frequent: the average number of forced outages per link and year is 7.1 acc. to CIGRE and 4.4 acc. to the Nordic statistics. Only 49% of all reported links have experienced less than 5 forced outages/year. These levels may well justify ENTSO-E's concern.
- Unavailability of overall HVDC systems due to forced outages is relatively high: Even though the durations of the outages to recover from faults are very short in the vast majority of fault cases (some hours), they can sometimes be very long: each year some HVDC links have forced outages that last up to 10 days. In worst cases, they can last up to several months. Unavailability levels due to forced outages vary greatly between different HVDC links and the majority of them operate on a good availability level, as 73% of the links have FEU ≤ 0.5%. However, there are still several links with higher unavailability levels.

ENTSO-E, the European Network of Transmission System Operator for Electricity, represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe. ENTSO-E members share the objective of setting up the internal energy market and ensuring its optimal functioning, and of supporting the ambitious European energy and climate agenda. Important issues on today's agenda are integration of a high degree of Renewables into the grids, development of consecutive flexibility, and more focus on customer centric approach, while still maintaining a high level of security of supply.

ENTSO-E Roadmap aims at improving the reliability and availability of existing and new HVDC systems. So far, there is no commonly agreed classification into good, acceptable or unacceptable levels for HVDC availability. The specified availability level vary between different HVDC links. The links built earlier have aimed at fulfilling the requirements of former specifications. For these cases it is possible that any higher HVDC availability and reliability requirement levels set up today cannot even be expected to be met. Considering the role of HVDC to facilitate the power transmission needs of electricity markets and integration of renewables, the target should be towards higher availability and reliability levels.

HVDC industry is currently preparing for a further development step into HVDC grids. In order to gain fully from foreseen advantages of HVDC grids, it is essential that the reliability and availability figures of new HVDC systems would be better than the average figures of the links of today (as mentioned before in the bullets).

ENTSO-E TASK FORCE HVDC RELIABILITY

After European TSOs had raised concerns about HVDC system reliability and availability, ENTSO-E arranged an internal HVDC Reliability Workshop in 2015 in order to review the members' experiences regarding HVDC reliability and availability levels.

With the existing knowledge and experience, which was brought together and highlighted in the ENTSO-E workshop on HVDC reliability in Oct 2015, some of the most critical and common HVDC failure modes were listed, of which the ones concerning cables are mentioned later in this report. Based on the outcomes of the workshop, a number of ideas and suggested possible actions for the TSOs, HVDC system owners, manufacturers and other stakeholders to improve HVDC reliability were collected. One of the collected actions and ideas was to form a common Task Force (TF) to work further on this important matter.

The main targets of the TF are to:

- define the role of ENTSO-E in the HVDC field,
- identify HVDC system reliability and availability improvements for the TSOs by sharing best practices and knowledge and
- provide guidelines and a HVDC reliability position

paper in order to influence the industry.

The TF wants to enhance experience and knowledge sharing broadly between TSOs, between TSOs and manufacturers and also between TSOs and other stakeholders like standardization bodies and regulators.

CABLE FAULT STATISTICS

General

Cable related faults may lead to long forced outages of the HVDC link and may be very costly to repair. This is especially the case for submarine cables. Therefore, special focus should be set onto cable fault location, monitoring and repair preparedness.

Available HVDC cable fault statistics are not very comprehensive, because the only worldwide and long-term collection of HVDC performance data is done by CIGRE SC B4 "HVDC and FACTS" Advisory Group AG04 and classified quite roughly. There is a class "TL = Transmission Line", which includes overhead lines (OHL), cables, joints and cable end terminations with auxiliaries. More detailed worldwide cable fault statistics is collected by CIGRE SC B1 Working Groups, but not regularly. There is an on-going WG B1.57 working currently on "Update of service experience of HV underground and submarine cable systems", so it is expected that updated cable fault data will be published in the near future. Only a few other, but limited, CIGRE reports and studies of cable reliability have been made during the past recent years.

HVDC failure statistics

The CIGRE SC B4 HVDC Performance Survey statistics 2005-2014 [1-5] show the following main findings:

- They cover 28-41 HVDC links, totally 339 link operation years.
- Converter station faults are frequent, the average being 6 trips/year
- Transmission line faults average 0.7 trips / year (0.46-0.98). This covers not only cable faults, but also DC OHL and cable end termination faults.
  - Worldwide ≈ 9 faults with more than 1000 hrs outage (0.9/year). Most submarine cable faults are expected to be in this category.
  - Worldwide ≈ 16 faults with 100-1000 hrs outage (1.6/year). This category is expected to include e.g. land cable faults.
  - Worldwide 10...15 faults with 50-100 hrs outage (1-1.5/year). This category may include also cable faults.
  - 60...70% of the faults are very short outages (< 8 hrs). These may be flashovers, OHL-faults, etc.

DC cable failure statistics

The CIGRE SC B1 Cable Survey reports "Update report on service experience of HV underground and submarine cable systems between 1990-2005 [6] and Third-Party Damage to Underground and Submarine Cables [7] show the main findings listed below. Naturally, the surveys cover only part of the actual installed cable assets in 2005, although there were replies from 25 countries:

- 32,000 circuit km underground (land) AC cables,
- 3,600 circuit km AC submarine cable,
- 3,366 circuit km submarine DC-cables
  - 13% SCOF, 80% MIND and 7% XLPE
- 800 circuit km DC land cable
  - 41% SCOF (>110kV), 59% XLPE (<220kV).

The findings of the survey reports are following:

- Underground DC cable faults were too few and thus, not representative. All 18 faults belonged to same SCOF cable project, the cable age being 6-8 years.
- Faults with external origin are more frequent than internal cable failures.
- Based on AC cable experience, problems are reported most frequently to be found in auxiliary oil equipment, joints and terminations.
- Based on mainly AC cable experience, average repair times are for 220-500 kV (or 60-219 kV) applications:
  - extruded: 25 (15) days
  - SCOF: 38 (20) days
  - direct burial: 15 (14) days
  - ducts/troughs/tunnel: 45 (15) days
  - joints: 15-20 days
  - other equipment: 1-3 day
- There were only 22 submarine DC cable faults, of which
  - 82% (18) of faults were on cables, 14% (3) on joints and 5% (1) on termination.
  - 11 external reasons (7 trawling, 3 anchoring, 1 excavation).
  - 4 internal failures, two of them on same SCOF installation. No correlation to cable age found.
  - In majority of cable fault cases, the cables were laid in shallow water, depth < 50 m (76%), and they were mechanically unprotected (62%).
  - Repair time was in
    - 36% of cases < 1 month
    - + 14% in 2 months
    - + 5 % in 3 months
    - + 14% in 4-5 months.
    - 32% of cases were not reported.
  - Average repair time was 60 days.
  - Average annual fault rate was 0.12 faults/year.
- Conclusions:
  - Failure caused by an external impact is the most frequent type of failure. About 70% of the failures are caused by external mechanical damages.
  - About 40% of third-party damage has to do with insufficient information exchange between cable operators and construction companies.
- Conclusion for submarine cable faults:
  - MI submarine cables are generally used in sea areas with extensive fishing activity and shipping.

Type of fault	*MI-cable*	*SCFF/SCOF-cable*	*Annual failure rate per 100 km*
Internal fault	0	1	0.035
External – Anchor	3	0	0.017
External – Trawling	7	0	0.039
External – Excavation	1	0	0.006
Other + Unknown	6	0	0.033
Total	**17**	**1**	**0.10**

Table 1: External submarine cable fault types & rates

CABLE ISSUES AND FAULTS

ENTSO-E members' experiences

The concerns regarding HVDC cable issues that ENTSO-

E members have brought up in its HVDC Reliability work could be divided into groups, one being focused into HVDC cables. Even though a cable failure is very unlikely to occur, the repair of especially a faulty submarine cable is a major project. Therefore the TSOs need to be prepared for such. Following main sub-groups belonging to HVDC cable issues were identified:

Cable breakdown - internal

Reasons for internal cable breakdowns may be in design, manufacturing, material, or installation quality. These errors may lead e.g. to water ingress partial discharges, or overheating, which may all further lead to internal cable breakdown.

Comprehensive QA (Quality Assurance) and type testing is essential in verifying the cable design and manufacturing quality. One example of an internal quality error is from the Fenno-Skan 1 cable, which suffered from two similar trips in 2005-2006 due to a hole in the lead sheath at earthing connection points, which were found to be not fully according to the design instructions. Damage in the lead sheath may have caused fatigue cracking in it during expansion and contraction cycles over the years of operation, through which water may have finally been able to penetrate to the insulation. Additionally the very thin earthing wire could have been damaged during the cable manufacturing. In the end, the root cause remained uncertain. The cable repair times in these two breakdowns were 87 days and 71 days, respectively.

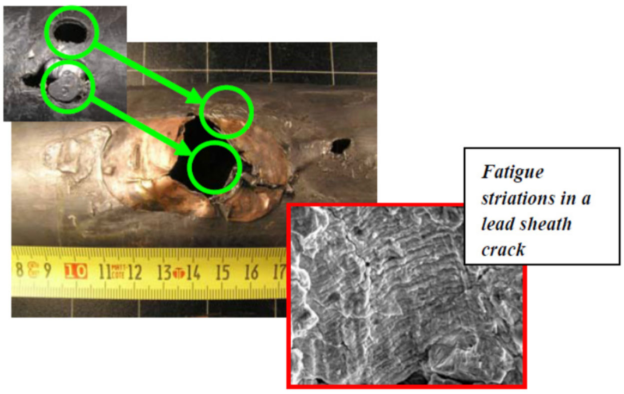


Fig. 1: Internal failure of Fenno-Skan 1 MI-cable

Cable crossings may be another challenge. They must be designed with care. EstLink 2 output power had to be limited 25-100 MW from nominal 650 MW during 5 months 2015 due to high cable temperature alarm located at a cable crossing. The main crossing design is with PPL-duct (separation and protection). There are 18 crossings with 21 different cables and pipes, with a total length 0.5 km. For securing the nominal power transfer capability of the cable, the upper half of the PPL duct was removed in all cable crossings in water depth lower than 30 m.

Fig. 2: Crossing PPL-duct principle

Fig. 3: Crossing PPL-duct of EstLink2

The lessons learned were:

- The fibre optic temperature measurement system may need calibration over a longer distance. There was an error: the actual temperature was lower than the temperature measured with the optical fibre.
- There is a need for proper crossing design selection taking into account the thermal properties of soil and protection method, including also the effect of the crossing sinking in the seabed.

Cable mechanical breakdown - external

As statistics show, cable mechanical breakdowns due to external reasons are dominant. Therefore, some means to protect the cable mechanically should be considered. However, many protection methods are considered quite expensive and, therefore, often compromised or even left out.

As an example, it is difficult to completely avoid submarine cable faults due to trawling and anchors, even if the submarine cable is buried into the sea bottom. In land cables, faults due to excavation can be effectively avoided only using rigid mechanical protection. Both of the mentioned protection methods are relatively expensive and, thus, left out from certain installations based on cost and risk assessment.

This report does not cover the cable fault risk due to external reasons in detail.

Joint failures

The joints can be the weakest points of a cable. Some joints need to be earthed, whereas the earthing wire and its penetration point need to be sealed properly against humidity/water entering the joint. Also the robustness of the joints and their thermal conductivity are essential for their long-term reliability. Thus, the joints must be properly designed, manufactured, tested and installed.

European TSOs have during recent years experienced several cases of joint failures, some of which are presented here:

GRITA (GRE-ITA) HVDC-interconnector with both 43 km land and 163 km submarine cable sections was commissioned in 2001. Failures started to occur on the joints of the 400 kV SCFF land cable after 8 years of operation. When the fault rate increased in the age of 12, it was decided to replace all joints.

Fig. 4: Damage in joint failure of GRITA

Cracking of the lead sheath occurred a few inches from the joint due to misalignment of the cable-joint axis. Root cause for this was excessive overheating and melting of bituminous compound inside the outer protection of the joint. As a consequence, there was leakage of oil.

The repair solution adopted for the 50 joints was a completely new design, laid in rigid configuration and with improved thermal capacity and thermal monitoring. Repair work duration was 19 workdays per joint. It consisted of:

- removal of outer PE protection of joint and bituminous compound,
- lapping of inner part of joint with self-amalgamating tape and application of heat shrinkable tube against water penetration and for mechanical protection,
- cable-joint axis alignment (if not in correct position),
- adding thermal gauges for thermal monitoring,
- filling joint bay with high thermal conductivity backfill.

EstLink 2 (EST-FIN) suffered in 2014, after less than one year of operation, from two trips due to joint failures on the MR (Metallic Return) XLPE type UG (underground) cable on Estonian side. Outage duration was 12 days and 8 days, respectively. Finally, all 11 joints on the length of 12 km were replaced with new ones.

Fig. 5: Investigation of joint failure of EstLink 2

The root cause of the faults was the way the earthing wire was installed in the joint. The earthing wire installation enabled water to penetrate into the joint, compromising the lifetime of all the joints with the same design. In addition the earthing wire installation procedure did not include detailed information of the required water ingress protection measures.

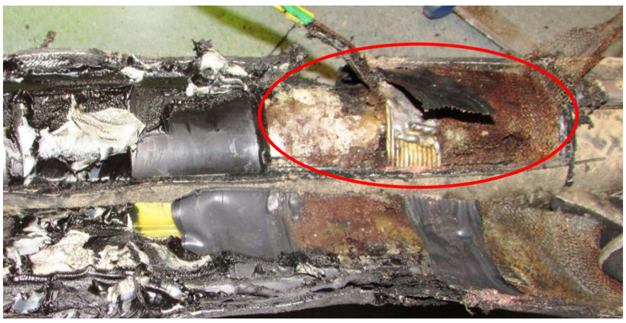


Fig. 6: Moisture damage in EstLink 2 joint failure

Following conclusions could be made from the failures:

- Based on new calculations, not all of the joints needed to be earthed. The original calculations were on the conservative side.
- It could be advantageous to repeat type testing for any possible design modifications, even if they are small.
- The faults might have been noticed by more effective site supervision: neither the installers nor the supervisors noticed that the installation was not going to be fully waterproof.

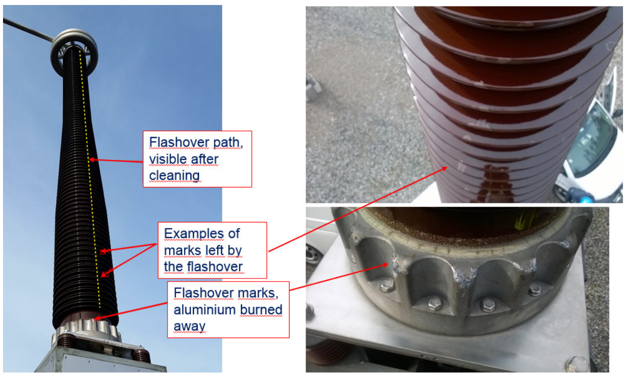
NordBalt (SWE-LIT) VSC (Voltage Source Converter) type HVDC link, which was commissioned in Feb 2016, tripped already during its 1st year of operation 8 times due to joint failures of the pre-moulded EPDM underground splices of the ± 300 kV XLPE UG cable 2x(40+12) km. Repair time after each incident was 4-11 days. The root cause of these failures are still under investigation, but the conclusion is to replace all installed UG joints. Luckily, no failures have been found in the submarine cable joints.

Cable end termination flashover

The difficulties in dimensioning the insulation of the DC cable end termination has caused several fault cases for the TSOs. Some examples are described below:

Fenno-Skan 2 (SWE-FIN) 800 MW LCC link suffered from several (8 pcs) 500 kV DC circuit earth faults occasionally during years 2012-16, usually at humid weather and near to 0 °C temperatures. The DC circuit consists of both OHL and submarine cable sections. Mostly, automatic re-start of converter was successful. Open line tests did not reveal the fault location. Establishing the root cause was difficult:

- Firstly, flashover in overhead line section was suspected. Nothing was found during patrols.
- Secondly, flashover in DC equipment was suspected. Nothing was found in inspections conducted from ground level. Based on TFR curve readings, it wasn't even possible to determine with certainty whether the fault was on the Swedish OHL, submarine cable or Finnish OHL side.
- Thirdly, thorough warranty inspection of cable end termination was done 2015, and marks of a flashover was found on the porcelain insulation surface. It was to be seen clearly only from near distance and in an outage.



Root cause of the faults was that creepage distance of cable end termination porcelain insulator was designed too near to its limits, for the environmental conditions it was put into. Actual conditions like humidity, icing, frost and icy fog & rain were not handled by the specification nor the design of the termination and this caused flashovers at the termination in the named severe conditions. Instead of replacing the cable end termination, the electrical withstand level of the termination in these severe conditions was improved by coating the termination. The coating may increase the maintenance efforts and costs to the respective TSOs. As a lesson, the creepage distance and electrical withstand should be specified higher due to the environmental stress in future contracts. Conditions requiring this may also be due to pollution or salt from sea.

Faster and improved fault tracing should be considered by:

- Best solution would be to add on-line monitoring of the DC circuit sections to immediately distinguish whether the fault is on the OHL or cable parts ➔ Needs special equipment, like new measuring points and detection devices based on e.g. travelling wave technology.
- With LCC, efficient use of Open Line Test (OLT) and Open Converter Test (OCT) to distinguish whether fault is on DC-yard, -OHL or -cable ➔ Requires good/detailed instructions & thorough operator training. Still this method is somewhat rough.
- Efficient methods, equipment and availability of skilled manpower are needed for pin-pointing fault location more accurately.
- Thorough inspection of all equipment and circuits at an earlier stage. It was not expected that the fault would be at the cable end termination.

Similar types of DC circuit flashovers on cable end terminations in extreme conditions have been reported also from other LCC-type HVDC links, e.g. NorNed (NOR-NED) and Skagerrak (NOR-DEN).

Cable termination oil leakage

Mass Impregnated cables, similarly to the oil filled cables, have the disadvantage of oil filled and pressurized terminations. The terminations and their pressurizing systems may have leakages and therefore it is important to have continuous monitoring of the oil level and pressure so that corrective actions can be taken before the leakage lead to damages of the cable.

Cable fault risk due to termination oil or pressure leakages is not further covered by this document.

Cable problems in J-tube for Offshore HVDC

Offshore HVDC installations have additional challenges compared to the HVDC-links with converter stations onshore.

First experiences with offshore HVDC have shown that especially the installations in the J-tube (the construction or mechanical protection, usually J-formed, used for bringing up the cable from the sea bottom to the platform) have suffered from swinging phenomenon and hot spots. Special attention needs to be taken in order to come up with sufficiently rigid fastening of the cables in the J-tubes and to minimize the risk of excessive hot spots on the cables.

However, offshore cable fault risks will not be elaborated further here.

CABLE FAULT LOCATION AND REPAIR

As cable faults occur quite seldom, the TSOs may have had insufficient focus on efficient fault location and minimizing repair times. However, these issues need attention, because the importance of the HVDC interconnectors may vary in time, sometimes being essential for the electricity market or even for the operation security. Therefore, actions to decrease fault location and repair times should be highly promoted.

As seen from the described fault cases above and based on TSO experience, following conclusions can be made of what is needed for faster DC circuit fault location:

- On-line monitoring
- Efficient use of OLT and OCT
- Availability of efficient methods and equipment for pin-pointing fault location accurately
- Availability of skilled manpower
  - grid operators,
  - 24/7 engineer-in-duty or stand-by maintenance personnel,
  - maintenance staff with ability to do pin-pointing,
  - divers, etc.
- Ensuring constructors and other parties getting the exact and correct location data of the cable route.

Especially for reducing HVDC cable repair times, following may be needed:

- Availability of spare cable, spare joints and other parts and tools, which are kept in good condition.
- Repair preparedness contracts,
  - Availability of cable repair vessels (submarine cables),
  - Availability of jointers.
- Luck (suitable weather conditions, submarine cables).

CONCLUSIONS

The importance of HVDC has risen and will rise in future ever more. ENTSO-E member TSOs have been more and more concerned about the reliability and availability of their HVDC systems. Therefore, even though cable faults are uncommon, they may be difficult to locate and lead to long outages due to the repair time needed, especially for submarine cables. All HVDC link trips should be systematically cleared, their root cause clarified and corrected before they lead to frequent re-occurring trips, as this causes extra costs to the TSOs for each case separately, including possible costs also for counter-trading.

Knowledge sharing is important, e.g. to learn from mistakes and mal-operation of existing systems. It is also important that all the stakeholders of the HVDC field strive together for better solutions and quality assurance and for actions to improve reliability and availability of both existing and new HVDC systems.

Acknowledgments

Special thanks to Mr. Jussi Rantanen, Fingrid, for his valuable expert review of this report.

REFERENCES

[1] M.G. Bennett et al., 2008, B4-119 "A Survey of the Reliability of HVDC Systems throughout the world during 2005 – 2006", CIGRE 2008 Session

[2] M.G. Bennett et al., 2010, B4_209_2010 "A Survey of the Reliability of HVDC Systems throughout the world

during 2007 – 2008", CIGRE 2010 Session

[3] M.G. Bennett et al., 2012, B4_113_2012 "A Survey of the Reliability of HVDC Systems throughout the world during 2009 – 2010", CIGRE 2012 Session

[4] M.G. Bennett et al., 2014, B4-117 "A Survey of the Reliability of HVDC Systems throughout the world during 2011 – 2012", CIGRE 2014 Session

[5] M.G. Bennett et al., 2016, B4-131 "A Survey of the Reliability of HVDC Systems throughout the world during 2013 – 2014", CIGRE 2016 Session.

[6] CIGRE Technical Brochure 379, 2009, "Update on Service Experience of HV Underground and Submarine Cable Systems", WG B1.10,

[7] CIGRE Technical Brochure 398, 2009, "Third-Party Damage to Underground and Submarine Cables", WG B1.21.

GLOSSARY

TSO: Transmission System Operator
HVDC: High Voltage Direct Current
ENTSO-E: European Network of Transmission System Operator for Electricity
CIGRE: Council on Large Electric Systems
DISTAC: Disturbance, Statistics and Classification
TF: Task Force
SC: Study Committee
FACTS: Flexible Alternating Current Transmission System
OHL: Overhead Line
WG: Working Group
SCOF: Self Contained Oil Filled
MIND: Mass Impregnated Non-Draining
XLPE: Cross Link Poly Ethylene (Extruded)
QA: Quality Assurance
LCC: Line Commutated Converter
PPL: Polypropylene
SCFF: Self Contained Fluid Filled
PE: Polyethylene
MR: Metallic Return
UG: Underground
VSC: Voltage Source Converter
EPDM: Ethylene Propylene Diene Monomer
TFR: Transient Fault Recorder
IEC: International Electrotechnical Commission
OLT: Open Line Test
OCT: Open Converter Test