European Network of Transmission System Operators for Electricity

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Recommendations to improve HVDC cable systems reliability

13 June 2019

Joint ENTSO-E[1] and EUROPACABLE[2] paper

[1] European Network of Transmission System Operator for Electricity represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe.

[2] Europacable is the voice of all leading European wire and cable producers. Europacable members include the largest cable makers in the world providing global technology leadership, as well as highly specialized small- and medium sized businesses from across Europe.

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Contents

Contents....2
1. Executive Summary....4
2. Introduction....5
2.1 HVDC Cables and Systems....5
2.2 Recent Concerns....6
2.3 The Main Objectives of this Paper....7
3. HVDC Reliability risks and incidents occurred....8
3.1 HVDC Cable related incidents occurred and challenges identified....8
3.1.1 Cable faults....8
3.1.2 Joint faults....9
3.1.3 Cable end-termination faults....9
3.1.4 Cable laying....10
3.1.5 J-Tube challenges....10
3.1.6 Cable crossings....10
3.2 Options for improvement and mitigation....11
3.2.1 Cable faults....11
3.2.2 Joint faults....13
3.2.3 Cable end-termination faults....15
3.2.4 Cable laying....15
3.2.5 J-Tube challenges....16
3.2.6 Cable crossings....18
4. Procedures to further improve HVDC cables and systems reliability and availability....19
4.1 Preparations for rapid fault location....19
4.1.1 Methods for immediate location / pin-pointing / accurate location....19
4.1.1.1 Submarine cables....20
4.1.1.2 Land cables....21
4.1.1.3 Combined cable systems with both long land and submarine cable sections (fault on submarine cables) 21
4.1.1.4 Combined OHL + cable systems....22
4.2 Root cause analysis....23
4.2.1 Reaction to faults, namely finding solutions for repair and replacement....23
4.2.2 Co-operation between manufacturer and cable owner....23
4.3 Repair preparedness....23
4.3.1 Preparedness of contracts and availability of different items.....23
4.3.1.1 Availability of jointers, vessels and tools....24
4.3.1.2 Re-testing needs....25

4.3.1.3 Weather restrictions 25
4.3.2 Spares 25
4.3.3 Cable route survey 26
4.4 Preventive measurements 26
5. Conclusions 27
Glossary 28

1. Executive Summary

The vast majority of the high and extra high voltage projects under the ENTSO-E 2018 10-Year Network Development Plan (TYNDP) is planned using High Voltage Direct Current (HVDC) land and submarine cables and systems. Hence it is of critical importance for Europe future security of electricity supplies that HVDC cables and systems fulfil the highest reliability requirements at all times.

MI cables and systems are mature up to voltages of 525 kV and available up to voltages of 600 kV. Extruded HVDC cables and systems have seen a significant development in recent years: Voltage levels of 320 kV up to 640 kV are now available and as suppliers and TSOs are gaining operational experiences, the maturity and "Technology Readiness Levels" are increasing.

Recently an increased roll out of HVDC projects across Europe, many in the adverse offshore environment, has emphasised the significance, and concern for the availability of HVDC cables and systems. Even though the reliability and availability of worldwide HVDC systems have increased during the last decade, there is room for further improvement. HVDC systems are strategic assets within high voltage electricity transmission networks, their availability is therefore considered essential. Impact of HVDC system failures can result in significant consequences in terms of costs and electricity supply. However, the critical features and benefits that HVDC systems provides to the European system, such as support of system stability, sharing of spinning reserve (emergency power), boosting adjacent AC systems' capacity, and inherently with low loss transfer, should also be considered when assessing the optimal solution for the transmission system. These additional features make it even more crucial to prioritize and value a very high level of reliability for the HVDC systems.

TSOs and cable manufacturers aim at preventing efficiently HVDC interruptions (unplanned outages) due to cable failures, minimise any HVDC downtime and – wherever possible – move forward with joint recommendations so as to maximise the availability of HVDC cables and systems. To do so, with this Joint Paper, ENTSO-E and EUROPACABLE:

1. Highlight the importance of HVDC transmission technology as a key component of Europe´s future transmission networks;
2. Strive for ensuring that the already rather mature and fully available HVDC cable and system technology would also meet the users' strict expectations of a fully reliable solution to carry electricity over long distances;
3. Call upon Transmission System Operators (TSOs) and manufactures to follow the recommendations outlined in this document to ensure maximum system availability; and
4. Aim at keeping up a close co-operation and exchange of information to further mitigate any reliability issues like those identified in this document, as further HVDC projects are rolled out across Europe.

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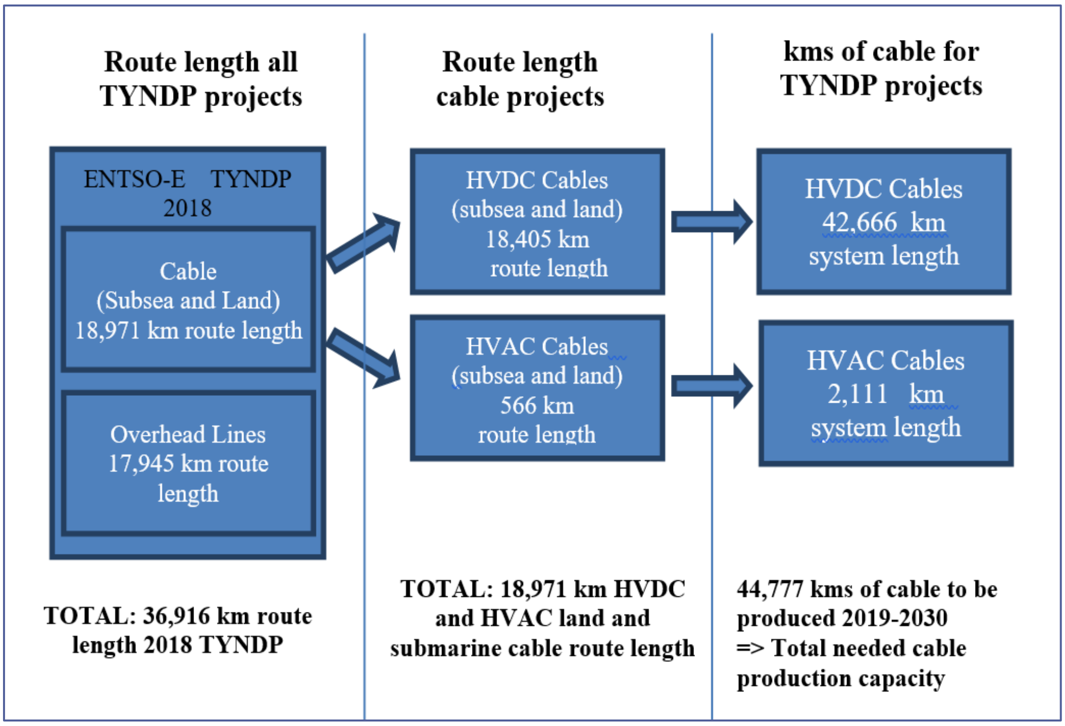
2. Introduction

The European Union's (EU) commitment towards a sustainable low-carbon European economy by 2050 requires a well-functioning trans-European electricity market. Well-interconnected electricity network grids are key in integrating renewable energy sources and promoting the full de-carbonization of the energy sector, and higher levels of electrification will be needed to enable the EU to comply with its energy and climate goals. Investments in electricity infrastructure which is going to become the backbone of Europe's economy and society will be then necessary.

According to the ENTSO-E TYNDP 2018 some 37,000 km of extra high voltage (EHV) power lines on land as well as at sea will need to be built/refurbished by 2030. Power transmission projects with both submarine and land cables would cover 51.4% of the total route length, i.e. 17,945 km, compared to overhead line projects (48.6% and 18,791 km). High Voltage Direct Current (HVDC) underground and submarine cables are to transmit electricity over long distances1. Excluding overhead lines, and focusing on cables only, 97%, of the total route length to be covered through underground and submarine cables, i.e. 18,405 km, are to be installed using HVDC land and submarine cable and system technology.

To cover this network development, ENTSO-E and EUROPACABLE estimate that in total Europe will need some 42,666 km HVDC land and submarine cables in the coming decade. Therefore, it is of critical importance for Europe future security of electricity supplies that HVDC cables and systems fulfil the highest reliability requirements at all times.



2.1 HVDC Cables and Systems

High Voltage Direct Current (HVDC) underground and submarine cables transport high power loads over long distances with minimal losses. They have been in commercial use since the 1950's.

[1] Please see ENTSO-E / Europacable Joint Paper "Forecast Demand and Manufacturing capacity for HVAC and HVDC land and submarine cables", January 2018

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Today, HVDC land and submarine cables can carry medium and high power (100 MW up to approx. 2,000 MW) with voltages up to +/- 600 kV over distances above 50 km. Mass Impregnated (MI) cables and systems are mature up to voltages of 525 kV and available up to voltages of 600 kV. Extruded (XLPE) HVDC cables and systems have seen a significant development in recent years: Voltage levels of 320 kV have already been in service for several years and now XLPE cables are available up to 640 kV. As suppliers and TSOs are gaining operational experiences, maturity and "Technology Readiness Levels" are increasing as can be seen from the table below:

Technologies	**Technology Availability**		
	2020	**2025**	**2030**
Mass Impregnated HV DC Cables, ±600 kV	9	9	9
Extruded HV DC Cables, ±320 kV	7 [1)]	9	9
Extruded HV DC Cables, ±525 kV	5	7	9
Extruded HDVC Cables, ±600 kV	3	5	7

Reference: "Table 4.1 Summary table of the technologies and the respective TRL levels"; ENTSO-E TYNDP 2018 Technologies for Transmission System.
In this table, Technology Readiness Levels (TRL) are defined as follows:

- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
- TRL 8 – system complete and qualified (some smaller improvements need to be done still)
- TRL 7 – system prototype demonstration in operational environment
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 3 – experimental proof of concept

[1)] Note: As extruded cables ±320kV have been in operation since 2013, their technical availability in 2020 is considered to increase to TRL8 (not anymore at TRL7, which is stated in the table above).

HVDC cables and systems are a core technology to build Europe´s backbone power transmission lines, both on land and out at sea.

HVDC transmission has mainly been used in submarine applications, either connecting offshore wind farms to land or transmitting high electrical power over long distance through the sea. From 1996 to 2015 alone, some 8,000 km of high and extra-high voltage DC submarine cables have been installed globally. Looking into the future, notably submarine interconnectors will play a crucial role in creating Europe´s extra high voltage power grids.

Today, HVDC cables are increasingly used for land transmission projects as higher power loads need to be transported over long distances towards centres of power consumption. When compared with AC systems fewer cables need to be used, HVDC underground cables benefit from narrower trenches both during construction and operation. HVDC underground cables are compatible with HVDC overhead technology and can be combined in sensitive areas.

2.2 Recent Concerns

The recently increased roll out of HVDC projects across Europe, notably in the adverse offshore environment, underlines the need for improving the reliability and availability of HVDC cables and systems.

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Most HVDC system disruptions belong to converter station faults (average 7 trips/year according to CIGRE (Council on Large Electric Systems) Study Committee SC B4 "HVDC" Advisory Group's AG04 annual HVDC performance surveys 2005-2016).

Based on the abovementioned CIGRE HVDC performance statistics, HVDC transmission line (overhead lines – OHL – and cable) faults are more infrequent (average 0.7 trip/year) than converter station faults. Unfortunately, there is no comprehensive statistics covering cable faults, as the published summaries cover HVDC transmission lines in general. However, from these statistics it can be derived that HVDC systems:

- using purely **cables** as transfer media have an average fault rate of **0.2 trips/year** or **0.07 faults/100km*years** (the statistics covers 11 cable systems, 10 trips, total length 2.510 km, 53 operating years during a 12 year period, 13.700 km*years),
- having **combined** overhead lines and cables have an average fault rate of **1.1 trips/year** or **0.36 faults/100km*years** (17 HVDC-systems, 126 trips, total length 2.480 km cables + 2.200 km OHL, 117 operating years during 12 years, 17.800 cable km*years + 17.200 OHL km*years), and
- using purely **OHL** as transfer media have an average fault rate of **1.4 trips/year** or **0.83 faults/100km*years** (20 HVDC-systems, 155 trips, total length 18.580 km OHL, 114 operating years during 12 years, 97.650 OHL km*years).

An earlier published statistics, CIGRE SC B1 Cable Survey Technical brochure TB 379 (2009) "Update report on service experience of HV underground and submarine cable systems between 1990-2005" reports an annual submarine cable fault rate of **0.10 trips/100km*years** (based on 3.700 circuit-km of HVDC cables), which is in line with the above figures.

Although the average fault rate with HVDC cables is low, yet when such do occur, they may be difficult to locate and require considerable resources and time to repair. The abovementioned CIGRE SC B1 cable fault statistics shows that submarine cable fault average repair duration was 60 days. Notably faults on HVDC submarine cables and systems result in significant costs, including congestion charge and switching costs, loss of profit, asset maintenance and repair costs which may lead to higher insurance costs.

TSOs and cable manufacturers aim at preventing such interruptions, minimise downtime and – where ever possible – move forward with joint recommendations so as to maximise the reliability of HVDC cables and systems.

2.3 The Main Objectives of this Paper

The main objectives of this paper are to:

- Provide an overview and an analysis of some incidents in HVDC cables and systems outlined in Chapter 3.1;
- Outline available options and joint recommendations to reduce downtime stemming from these incidents outlined in Chapter 3.2; and
- Offer joint recommendations how to further improve the reliability and availability of existing (where applicable) and future HVDC cables and systems installed in Europe outlined in Chapter 4.

3. HVDC Reliability risks and incidents occurred

According to CIGRE HVDC Performance Survey 2005-2016, the root cause of most failures of HVDC systems leading to forced outages is found in converter stations. HVDC cable faults are very rare (average 0.2 trip/year[2]). Faults related to HVDC converter stations may be subject of another study.

For the purpose of this paper, ENTSO-E and EUROPACABLE have analysed aspects mainly related to HVDC cables and cable related accessories and systems. The examples are based on European TSO experiences of HVDC cable (related) faults during the last decade. The issues mentioned here mostly relate to design, manufacturing and installations. It is to be noted that the latest HVDC cable issues have been omitted, as some of them are still under investigation at the time of writing this report.

3.1 HVDC Cable related incidents occurred and challenges identified

As stated above, the failure rate of cables alone is very low. Despite this low failure rate, European cable manufactures and European TSOs have set up a list of HVDC cable incidents occurred and challenges in order to further improve HVDC reliability. The list of occurred cable failures and identified main risks (including some descriptions) are presented in the table below[3]. Solutions on how to prevent and mitigate such issues and to minimize their consequences will be presented in Chapter 3.2.

Type of incident	Type of cable		Reported No. of incidents by the TSOs
	Submarine	Land	
Cable faults	X		Two (2)
Joint faults	X	X	A few cases
Cable end-termination faults	X	X	Several faults on at least three (3) links
Cable laying	X		At least one (1)
J-Tube challenges	X		No trip yet (but risk identified)
Cable crossings	X		At least one (1)

3.1.1 Cable faults

These faults apply to submarine cables.

3.1.1.1 Internal failures

Issue and root cause(s) due to:

- A Failure occurred due to the dimensioning and/or manufacturing of earthing connection points between the armouring and the lead sheath. In this respect, damages in the latter may have caused fatigue cracking in it during the expansion and contraction cycles all over the years of operation, through which water may have finally been able to penetrate the insulation and create a hole. Furthermore, the very thin nature of the earthing wire of the rather old MI cable could have been damaged during the cable manufacturing process. Having said that, unfortunately, a clear definition of the root cause cannot be provided as it remains uncertain;

[2] This figure refers to a sample made of 11 HVDC systems totaling 2.510 km during a 12 year period with an operational life ranging from just commissioned to 50 years.
[3] Cable leakages (related to low pressure oil filled cables) are not included in this report.

- A link operated with higher current than originally specified (i.e. exceeding the rated current) during colder months (2/3rd of a year); fast power reversals combined with a high temperature drop over the insulation as well as a low ambient temperature.

3.1.1.2 External faults

Root causes due to:

- Anchor & trawler damages;
- Pack ice damages;
- The digging process done with a bad map, as well as an unprotected burial activity;
- More examples are given in CIGRE TB 398 und TB 610 publications.

3.1.2 Joint faults

Joint faults refer to both submarine and land cables.

3.1.2.1 Submarine cables

Root causes due to:

- In one case, the burning down of the electrode landing station, i.e. the case of a fire with unknown root causes which did not trigger any alarm.

3.1.2.2 Land cables

Root causes due to:

- The joint design was based on optimistic environmental thermal input data which made it inadequate in terms of heat transfer capability. In presence of high loads during summer, overheating of the joint occurred with melting of the bituminous compound inside the outer protection, ultimately leading to a misalignment of the cables and HVDC disturbance;
- The use of an earthing connection including design changes which were not fully type tested and not fully watertight on many joints (when only some of them would have required earthing);
- One case, where an internal discharge occurred in a SF_6 (sulfur hexafluoride) gas filled transition joint. As a result of this, its high-pressure valve failed, too. The root causes have not been verified;
- The transition joint overheating with root causes unknown;
- Material change in the joint, without appropriate pre-qualification (PQ) testing, as such tests seek to ensure long-term performance of the cable systems (only type testing is not sufficient to do this);
- Improper jointing work.

3.1.3 Cable end-termination faults

These faults apply to both submarine and land cables.

3.1.3.1 DC circuit flashovers

Root causes due to:

- Environmental conditions such as icing fog, rain or frost, exceeded salt deposit density expectations;
- Insulator creepage distance very close to the limits and/or not quite sufficient.

3.1.4 Cable laying

These faults refer to submarine cables.

Reasons found due to:

- One case, where the cable was damaged by mistake for external reasons and where it was found that the actual burial depth at the fault location was less than the designed depth;
- External damage of the cable right after the burial. A loose rock was found stuck between some of the individual cables of a cable bundle.

3.1.5 J-Tube challenges

J-tube challenges apply to submarine cables at offshore applications (both for HVDC and HVAC). They have not yet led to HVDC disturbances, but they have recently been identified as significant risks that need to be considered in the design of the platform systems and with the help of cable manufacturers' experts.

3.1.5.1 Swinging / mechanical wear

Challenges due to:

- Scour effects not sufficiently taken into consideration in the J-Tube design;
- Unexpected movement of the J-tubes.

3.1.5.2 Hotspots

Challenges due to:

- The upper part of the J-tube is filled with air. If there is no suitable protection against direct sunshine, it could lead to excessive increase of the air temperature in the tube e.g. when there is high power and/or high ambient temperature for longer time durations, especially for mono-pipes in which different AC, DC, array and export cables are placed in one J-tube. This can lead to weakening the cooling effect of the cable, increasing the risk that the current in the cable and the HVDC system's power also need to be limited.

3.1.6 Cable crossings

Crossing faults apply to both submarine and land cables. They can be regarded as singular points along the cable route. Abnormal thermal/mechanical issues (e.g. overheating) are mainly due to the lack of the following engineering tasks:

- Survey of both environmental and technical data of the crossing infrastructure;
- Design of the crossing solution and definition of a crossing agreement (where applicable);
- Installation of the cable, including in the crossing area all the protections and mitigations as identified by design.

3.2 Options for improvement and mitigation

With reference to the overview provided in Chapter 3.1, the mentioned root causes can be categorised as follows:

- Improper cable system operation;
- Use of components not fully qualified;
- Design based on unrealistic input data;
- External damages;
- Mechanical and/or thermal stress on the cable system above design limits due to unclear installation conditions.

To improve reliability and minimize downtime caused by the abovementioned faults, ENTSO-E and EUROPACABLE recommend the following practices.

3.2.1 Cable faults

These options for improvement and mitigation apply to submarine cables.

3.2.1.1 Internal failures

	Overall considerations	**Easy solution**	**Complex solution**	**Full scope solution**
Earthing wires and submarine cables in general	Design and compliance with industry standards are the primary drivers for reliability. However, industry standards by definition do not always include the latest experiences and lessons learnt.	- A proper and robust design fully qualified	- A CAPEX focused solution: To raise the awareness and the willingness to have a reasonable focus on and a balance between CAPEX vs quality. - Standards & recommendation: To set up a link to CIGRE and increase the awareness of their role and speed.	Not applicable
Operational parameters	Operating conditions within the specified boundaries are fundamental to prevent premature aging.	- A clear definition of product operational boundaries (without going beyond them). - In case of change, to further discuss with experts and the supplier.	- Online monitoring of main operational parameters can ensure cable is not being stressed above its limits.	Not applicable

ENTSO-E and Europacable recommendations

In order to further increase the internal reliability of submarine cables and notably avoid and/or reduce internal failures, ENTSO-E and Europacable recommend the following practices:

Regarding earthing wires and submarine cables in general

- Cable systems and all their components shall be properly designed and fully qualified, especially regarding long-term operation behaviour/performance of cable systems;
- A too high industrial focus on minimizing CAPEX (capital expenditure) may result in large OPEX (operational expenditure) due to failures and outages. Against this background, quality should come at a (reasonable) price. However, it is important to be aware of the fact that the above-mentioned sentence should be taken as a general statement since in this case the CAPEX influence is extremely minimal.
- Standards and recommendations (CIGRE, IEC - International Electrotechnical Commission, CENELEC - European Committee for Electrotechnical Standardization, etc.) shall be up to date with industry practice, industrial changes, new products and lessons learned. Unfortunately, processes to update or launch such new documents are often (too) slow. In this respect, both Associations wish to underline that the active contribution from both the cable industry and the TSOs to the standardisation bodies is fundamental to ensure that standards reflect the state of the art at any given moment.

As for operational parameters

- Cable systems shall be operated within specified boundaries. Against this background, risk analyses should be performed when there is a deliberate plan to go beyond such boundaries.
- Operational schemes may change over the life time. For instance: few polarity reversals per year to many per week. Or changing environmental parameters, like burial depth or new-built architecture on top of cable systems. Such evolutions of operational parameters should be anticipated as much as possible at time of designing the system
- HVDC converters controls on power reversal might change over cable life time. For instance: how quickly voltage and current are changed. Such evolutions should be carefully assessed.
- Transient overvoltage (TOV) instigated by HVDC converters must be considered carefully, too. These TOVs should be defined and limited to reasonable levels by related existing standards applicable for HVDC converters' and cable system operation (e.g. amplitude, waveform, duration, etc.) to avoid stress on the connected HVDC cable system, for which the cable system is not tested and may otherwise be detrimental for the general reliability.

Other recommendations:

- The requirements for a Cable system shall be specified by the end user both comprehensively and appropriately.
- Cables and accessories shall be manufactured with high focus on quality.

3.2.1.2 External faults

Overall considerations	Easy solution	Complex solution	Full scope solution
A proper installation engineering phase where the following topics are covered reduces both future project and operational risks: - Marine survey, including UXO's (Unexploded Explosive Ordnance) - Burial assessment study - Route engineering - Installation protection engineering	Not applicable.	Not applicable.	A full installation engineering phase will reduce the operational risks as listed in *'The issue and its root causes'* section

ENTSO-E and Europacable recommendations

In order to increase the reliability of submarine cables and notably avoid and/or reduce external failures, ENTSO-E and Europacable recommend the following practice:

- Proper installation engineering, based on all relevant existing practices, should be ensured given the fact that there is no other better option to tackle and prevent external faults from taking place. The installation and cable protection design should be performed on the basis of survey data and risk assessment. More details in Chapter 3.2.4;
- Several factors have an effect on the decisions and installation solutions, including a clear definition of roles and cooperation between all parties involved in the project, the interfaces, the risk assessment, the cost effect of protection solutions, the cable type, the installation method, the soil type and sea bottom topology. All the analyses have to be carried out on a project specific basis. In general, there is a trend towards widespread cable protection which is deemed the only really effective mean to minimize mechanical damages.

3.2.2 Joint faults

These options for improvement and mitigation refer to both submarine and land cables.

3.2.2.1 Submarine cables

Overall considerations	Easy solution	Complex solution	Full scope solution
Possible explanations of the burning down of an electrode landing station: - The voltage monitoring of the electrode cable at the converter station was measured as too insensitive. - The breakdown in the MV (Medium Voltage) electrode cable joint and the consecutive line voltage drop were not detected. - Therefore, the converter current was continued into the failure location resulting in a fire. - The conductor joint was of a MV quality.	Foreseeing more sensitive settings for protecting the electrode cable at the converter stations.	Not applicable	Not applicable

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ENTSO-E and Europacable recommendations

In order to increase the reliability of submarine cables and notably avoid and/or reduce joint faults, ENTSO-E and Europacable recommend the following mandatory station requirement:
- To monitor both voltage and current on return/electrode cables and to set protections accordingly.

3.2.2.2 Land cables

	Overall considerations	Easy solution	Complex solution	Full scope solution
Joint design overheating	- To follow proper design rules. - Need for a more exact knowledge of the environmental/installation parameters that affect the heat profile of the joint.	Managing and monitoring, within the frame of an engineering contract, the cable line route conditions with reference to the major thermal issues which may include: crossing of steam pipes, asphalt routes, etc. during the lifetime of the cable.	Adding an online monitoring system which relies on temperature measurements to be done by fiber optics.	Opting for the first two options as well as a service to interpret findings.
Earthing wire	The problem got worse due to the fact that more joints got affected by the decision to include an earthing wire to all joints. The root cause seems to be the adoption of a non-watertight solution for the earthing wire included in the joint. Proper design and the necessity to (type) test are needed.	- Any design change shall be assessed and verified by tests.		

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ENTSO-E and Europacable recommendations

In order to increase the reliability of land cables and notably avoid and/or reduce joint faults, ENTSO-E and Europacable recommend the following practices:
- To provide accurate environmental data to the cable manufacturers in order to take this information into account in the cable system and installation design and inform them of any relevant variation all over the cable life-time. The circuit owner should monitor and inform the cable supplier when any relevant change of the environmental conditions occurs. For new installations, optical fibers may provide a useful means to provide punctual information on the thermal conditions relating to the environment. To be more general, since it is more than complex to anticipate all the potential evolution of operational parameters, monitoring of key parameters is identified so far as the best way

to record in real time thermal conditions, acoustic disturbances, current in vital components and be able to react before we are beyond boundaries of operations conditions.
- To identify new crossings, heat water pipes, new roads or asphalt-thermal conditions, etc.
- For both the TSO and the cable manufacturer to undertake a temperature monitoring - data analysis together and any other relevant monitoring.

3.2.3 Cable end-termination faults

These options for improvement and mitigation apply to both submarine and land cables.

3.2.3.1 Flashovers

Overall considerations	Easy solution	Complex solution	Full scope solution
It is very important to have a realistic knowledge of the environmental parameters (pollution, moist, wind…). In this respect, understanding the effect of local environmental conditions to DC insulators may require long-time monitoring.	To specify a slightly higher voltage withstand level and creepage distance for the HVDC insulation than standards require.	To collect realistic environmental parameters at design stage in order to determine the optimum insulator profile and to set up regular maintenance activities.	Indoor solutions, even though more expensive, improve significantly the availability with reference to adverse atmospheric conditions at high risk environments.

ENTSO-E and Europacable recommendations

In order to avoid and/or reduce flashovers, ENTSO-E and Europacable recommend the following:

- To give this issue the necessary consideration. Although this may seem a minor issue, consequences if ignored may be considerable.
- Add safety margins: To specify a slightly higher voltage withstand level and creepage distance for the HVDC insulation than standards require.
- Advanced solution: to put equipment indoors (significantly more expensive).

3.2.4 Cable laying

These options for improvement and mitigation refer to submarine cables.

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Overall considerations	Easy solution	Complex solution	Full scope solution
A proper marine cable installation, a comprehensive planning, engineering and a sustainable installation methodology are highly recommended.	Not applicable	Not applicable	- A proper marine route survey (a geophysical investigation to be combined with a geotechnical approach for a better understanding of the sedimentary content); - A detailed engineering phase contemplating cable landing at shore-sites or onto platforms as well as offshore cable installations; - A burial assessment study leading to optimized installation tools concerning underground conditions (i.e. Burial Protection Index); - In-situ measurements of thermal resistivity leading to an optimized burial depth between the maximum protection and the maximum ampacity of the system; - Cable route preparation (pre-lay grapnel run, route clearance, pre-trenching, obstacle removal, sea-floor intervention); - Selection of installation tools with less impact (shear-strength, compression and pulling forces) on the cable; - Selection of post-lay burial or simultaneous lay and burial methodology depending on the underground situation and the available installation spreads; - Sustainable bundling of cable systems if required; - A proper mechanical monitoring of the cable during the cable laying (touch-down monitoring, slack management in front of ploughs, etc.)

ENTSO-E and Europacable recommendations

In order to avoid and/or reduce faults, ENTSO-E and Europacable recommend the following practices:
- To require high quality marine survey activities (with focus on the accuracy & quality of soil/marine data) and to ensure that those high-quality data are interpreted by highly skilled and experienced professionals. - To plan and perform the cable laying from fully reliable & relevant data points, notably for extreme conditions. - To perform a proper cost and risk assessment also for the cable laying process. - To pay special attention in the burial process and to perform sufficient post-laying inspections. - To have the best possible coordination between the cable manufacturer and the installer at any given point in the process to reduce / mitigate any possible risk of cable damage.

3.2.5 J-Tube challenges

These options for improvement and mitigation apply to submarine cables.

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3.2.5.1 Swinging

Overall considerations	Easy solution	Complex solution	Full scope solution
In principle, both pre-rock dumping and/or cable protection could prevent scour effects on the cable. However, cable protection systems could be more cost effective.	Not applicable	Not applicable	- A proper scour modelling/analysis and early engineering of planned scour protection methodology (passive or active protection); - Engineering of suitable cable protection system taking into consideration all metocean data, swinging analysis, and lifetime calculations for the cable inside the cable protection system as well as inside the J-Tube; - Cable swinging damping methods in J-Tube; - An intensive and sustainable coordination and co-operation between the foundation or the offshore substation developers and the cable manufacturers.

ENTSO-E and Europacable recommendations

In order to avoid and/or reduce swinging faults, ENTSO-E and Europacable recommend this issue to be given the necessary consideration. Although this may seem a minor issue, consequences if ignored may be considerable. In this respect both Associations recommend the following practices:

- A proper scour modelling/analysis and early engineering of planned scour protection methodology (passive or active protection);
- Engineering of suitable cable protection system taking into consideration all metocean data, swinging analysis, and lifetime calculations for the cable inside the cable protection system as well as inside the J-Tube;
- An intensive and sustainable coordination and co-operation between the owner, the offshore substation developers and the cable manufacturers, incl. data exchange to be done in good time;
- Cable pull-in considerations.

3.2.5.2 Hotspots

Overall considerations	Easy solution	Complex solution	Full scope solution
This is a design issue.	- Planning of ventilation or breathing holes inside the J-Tube to allow water exchange; - Installation of ‘sun shields’ on the outer side of the J-Tubes; - An appropriate sizing of the cables should also be considered during the engineering phase. - To tackle corrosion vs. thermal issues.	Not applicable	Any hotspot may be detected by online temperature monitoring and real-time temperature rating.

ENTSO-E and Europacable recommendations

In order to avoid and/or reduce faults in hotspots, ENTSO-E and Europacable recommend the following practices:

- To plan ventilation or breathing holes inside the J-Tube to allow water exchange;
- The installation of ‘sun shields’ on the outer side of the J-Tubes;
- Co-operation between the different engineering, i.e. data exchange to be done in good time;
- To tackle corrosion vs. thermal issues.

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3.2.6 Cable crossings

These options for improvement and mitigation refer to both submarine and land cables.

Overall considerations	Easy solution	Complex solution	Full scope solution
Need for proper crossing design selection taking into account the thermal properties of soil and protection method, including also the effect, when the crossing is sinking in the seabed. In case fiber optic temperature measurement gives unwanted overheating alarms, the system may need calibration over a longer distance.	Not applicable	Not applicable	- Pre-crossing survey; - Analysis of the as-laid data of the crossed cable (depth of burial); - In situ measurement of the thermal resistivity of the sedimentary layers up to the targeted burial depth for optimized ampacity calculations and temperature modelling; - Realization of cable spacing between crossing and crossed cable systems considering the electrical characteristics of the crossed cables and the power it is transmitting and/or rated for; - Sustainable protection of the crossing cable at the surface between grade-out and grade-in point, like grout bags, mattresses, PE (Polyethylene) impact protection, rock berm, etc.

ENTSO-E and Europacable recommendations

In order to avoid and/or reduce cable crossings impacts, ENTSO-E and Europacable recommend the following practice:

- Companies planning an HVDC system should take early care of in situ measurements of the thermal resistivity of the surrounding sediments including, if appropriate, consideration of soil stability in area of crossing and technical data of the crossing infrastructure;
- Early design of the crossing solution and definition of a crossing agreement (where applicable);
- Installation of the cable, including in the crossing area all the protections and mitigations as identified by design.

4. Procedures to further improve HVDC cables and systems reliability and availability

Further to the list of recommendations set up in the previous chapter to tackle HVDC cable and system faults experienced by TSOs, ENTSO-E and EUROPACABLE recommend the following practices to further improve the reliability and availability of HVDC cables and systems installed in Europe.

4.1 Preparations for rapid fault location

Overall considerations	Easy solution	Complex solution	Full scope solution
Availability of all relevant information is key.	Need for rapid communication of data via formerly standardized forms and communication channels.	Not applicable	Installation of an automatic, real-time warning and messaging system and set-up of a preventive maintenance program including long term service contracts

ENTSO-E and Europacable recommendations

In order to rapidly locate a fault, ENTSO-E and Europacable recommend the following practices:

- To set up proper preparation plans and procedures for communication and channels between all parties from operators to manufacturers in order to efficiently manage emergency situations which may arise and minimize any delays in the fault clearance process;
- To collect common experiences, 'success stories' and good practices together with TSOs.

4.1.1 Methods for immediate location / pin-pointing / accurate location

To detect immediate location / pin-pointing / accurate location is possible to use the existing pre-location method on new HVDC cables technology. Furthermore, it is also possible for the cable manufacturers and the fault location material manufacturers to cooperate to test and check the different configurations.

Overall considerations	Easy solution	Complex solution	Full scope solution
Availability of fault location equipment on-site. In general, it is up to the owner to assess the relevance and the importance of the line and to set up the appropriate solutions. Such a risk analysis in fact applies to several other aspects of this listing.	- Fault location equipment units to be kept and maintained ready at both terminal stations; - Internal or external experts to be trained to perform fault location for the various expected scenarios.	Online monitoring system including fault location capability.	To set up long term service contracts

ENTSO-E and Europacable recommendations

In order to detect immediate location / pin-pointing / accurate location, ENTSO-E and Europacable recommend the following practices:

- To conduct a risk assessment to identify the appropriate solution level, namely in relation to:
  - high resistance faults;
  - the applicability of current well-proven pin-pointing methods with higher voltages and thicker insulation;

- The CIGRE WG B1.52 describes the process of fault location systematically. They describe a variety (9) of different pre-location technologies and 5 pin pointing technologies. It is recommended to study in advance what technologies are the most suitable for the particular cable system design and system layout of the project at hand. A particular chapter is dedicated to this end describing design factors affecting fault location capability covering amongst others cable construction, circuit configuration and installation design factors. It is a good document to read and for planning purposes.
- Particularly and due to the focus on repairs of expensive outages new fault locating and pin-pointing methods are evolving. It is recommended to follow these new developments and read about them in the CIGRE WG B1.52 brochure as some of them might be applicable to the challenges of locating faults in long length cables. They are categorized into three: Fibre Optic Fault Location Methods, Electrical/Conventional Fault Location Methods and Pinpointing Using Marine Based Methods. Especially the idea of on-line fault location methods is interesting as this might potentially cut down the time to locate the fault.

4.1.1.1 Submarine cables

Regarding submarine cables, the length of the cable reduces the accuracy of Time Domain Reflectometry (TDR) method. Moreover, for TDR on long links it is important to focus on how to determine the velocity of the signal all along the cable length and provide customers with the exact wave speed shape.

ENTSO-E and Europacable recommendations

In order to detect immediate location / pin-pointing / accurate location for submarine cables, ENTSO-E and Europacable recommend the following practices:

- A description of the TDR method for obtaining a fingerprint of the pulse wave propagation characteristics of HVDC cables with particular reference to submarine cables is provided in CIGRE TB 496 “Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV” cl. 7.3.
- TDR fingerprint measurements be carried out on the cable after production and also after installation are recommended in CIGRE TB 713 “Designing HVDC grids for optimal reliability and availability performance” with reference to submarine cables in cl. 6.3 as an appropriate method for an initial indication of fault location facilitating subsequent pinpointing of fault.
- The CIGRE document comes with a number of considerations to be made for fault locating. Although no specific heading for submarine DC cables is found some of the heads-up are given here.
  - A basic requirement is that as much as possible and accurate data concerning the cable system design and the route design, as for instance As Laid Records, should be available.
  - It is important to perform a fingerprint of the cable system for later comparison (joint locations, transition to different conductor sizes, sheath/armour connections) and deducing the wave velocity. It is recommended to perform these fingerprints on a regular basis because unknown variations may develop over time.
  - Metallic connections between armour and sheath are used in long submarine cables. These might give rise to false position indications. And in case a submarine cable design is used for a land section, sheath testing will be difficult. A fingerprint will be a good tool for later reference and avoid misinterpretation.
  - Metallic return cables sometimes lack a metallic sheath. This makes the TDR method more difficult to use. Other methods might then be required.
  - Mechanical protection of submarine cables will influence pin-pointing techniques.

- Fault location on long cables is difficult due to attenuation effects. Different strategies and technologies are discussed in the WG B1.52 document. It is therefore important to have in depth knowledge of fault location technologies in theory and practice. It is therefore also recommended to let fault location and pinpointing be performed by specialists.

4.1.1.2 Land cables

For TDR Method on links with lots of sheath breaks at joint pits, it is important to identify how to avoid the sheath break joint impact.

ENTSO-E and Europacable recommendations

In order to detect immediate location / pin-pointing / accurate location for land cables, ENTSO-E and Europacable recommend the following practices:

- The short overview of the previous clause is also applicable here with the addition that concerning the implementation of the method to systems with cable joints, CIGRE TB 680 'Implementation of long AC HV and EHV systems" cl. 6.1 outlines the fault location procedures often adopted for fault location of long underground cable systems including initial TDR fingerprinting procedure and comparison after fault-in principle also applicable to DC cable systems- and in cl. 5.7 provides a case study of fast fault location by comparing initial TDR fingerprint with TDR after the fault, on a system comprising both submarine and land cables including joints.
- The CIGRE WG B1.52 highlights especially the topic of joints that influence the fault location process. Methods based on any type of pulse reflection will get readings due to the fact that a joint is a discontinuity in an otherwise smooth coaxial cable structure. These readings can falsely be interpreted as a fault location, it is recommended to perform fingerprinting such that the location of the joints is known in the TDR trace in advance. Also, geographical information on joint location (As Laid Records) is of importance and will speed up the process.
- Sheath sectionalized joints are sometimes used. Such joints where the sheaths of adjacent cables are interrupted can lead to false interpretation of reflection signals when using TDR methods or alike. It is recommended to perform fingerprinting in order to learn in advance where such interruptions are located in the reflection trace. A method to avoid these reflections is to short-circuit the interruptions during the fault locating process.
- Cables in tunnels and galleries might in some cases need special attention.
- Cables installed in ducts need special consideration too as they by nature are physically less easy accessible. Also from an electrical fault location point of view such burial techniques might be more challenging. Pinpointing with acoustics becomes challenging too.

4.1.1.3 Combined cable systems with both long land and submarine cable sections (fault on submarine cables)

Regarding the TDR method, it is important to focus on how to allow a fast pre-location of a submarine fault in case of presence of a lot of sheath breaks on land parts. Moreover, it has to be understood how to allow a quick discharge of cable after the test.

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ENTSO-E and Europacable recommendations

In order to detect immediate location / pin-pointing / accurate location for combined systems with both long land and submarine cable sections, ENTSO-E and Europacable recommend the following practices:

- Examples of adopting TDR method for rapid pre-location of faults in cable systems with both land and submarine cable section are provided in CIGRE TB 680 cl. 5.7 and CIGRE TB 610 "Offshore Generation Cable Connections "cl 8.8.1 referring to fault localisation. In addition TB 610 cl. 8.8.1 refers to CIGRE WG B1.52, "Fault location on land and submarine links (AC and DC)", which is investigating fault localisation methods and recommends to consult the Technical Brochure from this working group, when it is ready
- The WG B1.52 does not specifically deal with this situation. However, the in-depth description of fault location technologies and cable and system design aspects cover the basic aspects of the land and submarine cable as a common system. The main specific aspects to consider are (and covered in the two previous sections):
  - Long cable.
  - At least two designs (submarine and underground cable), often with two different conductor cross sections, giving rise to a reflection at the connecting point, or affecting bridge measurements.
  - The many joints in the land cable section with possible sectionalizing of the sheaths.
  - It is recommended to make it possible to quickly decide with measurements whether the fault is located in the submarine part or the land part. When in doubt, and if a TDR method does not give a clear decisive answer, then the transition joint is a suitable location for a local measurement.

4.1.1.4 Combined OHL + cable systems

ENTSO-E and Europacable recommendations

In order to detect immediate location / pin-pointing / accurate location for combined OHL and cable systems, ENTSO-E and Europacable recommend the following practices:

- Apart from the underground / submarine cable system fault location methods referred to earlier, CIGRE TB 713 "DESIGNING HVDC GRIDS FOR OPTIMAL RELIABILITY AND AVAILABILITY PERFORMANCE" also addresses maintenance aspects- including fault location -of overhead, land and submarine cable sections HVDC systems but separately.
- The WG B1.52 does not specifically deal with this situation. However, the in-depth description of fault location technologies and cable and system design aspects cover the basic aspects of the land and OH lines as a common system. The main specific aspects to consider are (and covered in the two previous sections):
  - A strong electrical discontinuity will be seen in all methods at the transition point from cable to OH-line. This will be very helpful.
  - The cable will also be easily accessible at the connection point.
- Also, special on-line monitoring systems (base on e.g. travelling waves) can be adopted for distinguishing whether the fault is on the OHL or the cable sections of the transmission line.

4.2 Root cause analysis

4.2.1 Reaction to faults, namely finding solutions for repair and replacement

ENTSO-E and Europacable recommendations

ENTSO-E and Europacable recommend the following practice:
- Always make proper root cause analysis (by owner and manufacturer) of any cable failure without delays in order to learn from the case and to improve reliability in the future / avoid similar failures to re-occur. Each fault should be reviewed also in relation to the FMECA (Failure Mode, Effects and Criticality Analysis) or other methodologies the manufacturers use in their quality assurance processes - If needed, to include experts also from independent third parties in order to improve and/or speed up co-operation and root cause analysis in relation to solutions for repair and replacement.

4.2.2 Co-operation between manufacturer and cable owner

ENTSO-E and Europacable recommendations

ENTSO-E and Europacable recommend the following practice:
- Co-operation between manufacturers and cable owners is essential in ensuring quick reaction and openness. - Improved co-operation activities can provide useful feedback for future solutions and design.

4.3 Repair preparedness

4.3.1 Preparedness of contracts and availability of different items.

Overall considerations	**Easy solution**	**Complex solution**	**Full scope solution**
In some cases, outage time has been significantly affected by permitting time to access the site and execute the repair.	Not applicable	Not applicable	Long term service contracts which would include among others regular "return on experience" meetings

ENTSO-E and Europacable recommendations

In relation to contract preparedness, ENTSO-E and Europacable recommend the following practices:
- To regulate co-operation at contract level. Co-operation between manufacturers and cable owners is essential in ensuring quick reaction for repair and openness to third parties. - Improved co-operation activities can provide useful feedback for future solutions and design. Permits: At the commissioning of the link, to identify on the cable route: • Public places which need a permit delivery. • Private places, which need a defined procedure • The procedures to access within the converter station and run tests

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Describe the procedures of repair with the equipment and tools needed. This could help to pre-obtain permit, or obtain it within a short time line.

4.3.1.1 Availability of jointers, vessels and tools

Overall considerations	Easy solution	Complex solution	Full scope solution
- Cable handling and installation, particularly for HV and EHV cables, represent a critical activity for the reliability of the cable system. - Burial tools to protect the repair cable must be fit for purpose.	Preparedness plan. Communications plan	Not applicable	To set up long-term service contracts

ENTSO-E and Europacable recommendations

In order to promote the availability of vessels, ENTSO-E and Europacable recommend the following practices:

- To select only experienced installation companies in the field of power cables and have the best possible coordination between the cable manufacturer and the installer at any given point in the process to reduce / mitigate any possible risk of cable damage. This would contribute to faster response times, the availability of crews and vessels and a maximum quality;
- To opt for long term service contracts which may further serve this purpose;
- To identify the cable manufacturer requirements on the repair vessels;
- To identify the characteristic of the burial tools which will protect the repair bight (i.e. the extra length or loop of the cable, which needs to be laid on the seafloor for a cable repair), depending of the affected area of the fault.

4.3.1.2 Re-testing needs

ENTSO-E and Europacable recommendations

In order to fulfill re-testing needs, ENTSO-E and Europacable recommend the following practices:

- To consider keeping the vessels mobilized until post-burial cable tests - also after energization - are fully completed, depending on whether the business case justifies this additional cost for an extension of the vessel mobilization time.

4.3.1.3 Weather restrictions

ENTSO-E and Europacable recommendations

In relation to weather restrictions, ENTSO-E and Europacable recommend the following practices:

- To be aware that weather conditions for installation differ from repair activities and those need to be considered in the contract.

4.3.2 Spares

It is important to be aware of the challenges that might arise in tendering framework agreements among various suppliers.

Overall considerations	Easy solution	Complex solution	Full scope solution
- Spare availability needs to be ensured in the long term by taking into account the shelf life of the repair kits components. HVDC systems are often including custom made components which would require long lead time. - Obsolescence of some designs may represent an issue.	Spare parts to be kept and maintained ready.	Centralised spare parts management system to be operated by TSO.	To set up long term service contracts, including the maintenance & management of the spares and possibly also the replacement of obsolete & expired spare parts.

ENTSO-E and Europacable recommendations

In order to promote the availability of spare parts, ENTSO-E and Europacable recommend the following practice:

- All design information (including Global Positioning System - GPS) to be constantly available.
- To do a periodical inspection of spare part in order to check the obsolescence.
- Keep the spare (submarine) cable long enough and as one whole piece if possible, especially considering the uncertainty of possible future failure location(s).

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4.3.3 Cable route survey

Overall considerations	Easy solution	Complex solution	Full scope solution
The quality of project phase surveys are essential. However, cable burial conditions may also change over time due to sea bed soil movements or external reasons.	- To do proper survey at installation phase. - To undertake a cable route survey looking for exposed cable sections and possible changes in the route.	- To undertake a cable route survey focusing on measuring cable burial conditions. - For the land section, it is important to check if the access to the cable route is ensured.	Full on-line monitoring system to be able to record all the service history as well as to detect changes in thermal conditions (trends, alarms). This may provide an indirect indication of burial conditions.

ENTSO-E and Europacable recommendations

In order to promote to ensure cable route surveys at regular intervals, ENTSO-E and Europacable recommend the following practice:
- To conduct a risk assessment to identify the appropriate solution level.

4.4 Preventive measurements

It is important to identify the technologies which are available to continuously test the condition of the cables.

Overall considerations	Easy solution	Complex solution	Full scope solution
On-line condition monitoring to reduce risk and regular maintenance	- To carry out regular off-line checks as per maintenance plan. - To provide adequate warning on load cable presence along the land route to minimize risk of mechanical damage.	Online thermal monitoring system, if available, would provide warning on changing thermal conditions.	Full on-line monitoring systems are able to record all the service history, to detect thermal, mechanical and electrical dangerous conditions.

ENTSO-E and Europacable recommendations

In order to promote preventive measurements, ENTSO-E and Europacable recommend the following practice:
- To conduct a risk assessment to identify the appropriate solution level.

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5. Conclusions

HVDC transmission links will be a vital part of Europe's future electricity networks. High reliability and system availability will be crucial to secure Europe's electricity supply.

Interruptions in HVDC system transmission still occur rather frequently, although a slight decrease can be detected over the decades. Most of the HVDC system faults that cause outages do occur on converter stations, and although HVDC cable faults are quite rare, any such can be challenging to locate and time consuming to repair.

ENTSO-E and Europacable have therefore taken this joint initiative to analyze a selected set of experienced major failure types and to develop recommendations to minimize future outages. Our technical experts have mutually identified measures to be applied to prevent future failures or to reduce downtime, should they still occur.

We call upon Transmission System Operators and manufactures to follow the recommendations outlined in this document to ensure maximum system availability.

ENTSO-E and Europacable aim at keeping up a close co-operation and exchange of information to further mitigate any reliability issues like those identified in this document, as HVDC projects are rolled out across Europe.

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Glossary

HVDC	High Voltage Direct Current
ENTSO-E	European Network of Transmission System Operator for Electricity
TYNDP	10-Year Network Development Plan
MI	Mass Impregnated
TSO	Transmission System Operator
AC	Alternating Current
EU	European Union
EHV	Extra High Voltage
XLPE	Cross Link Polyethylene (Extruded)
TRL	Technology Readiness Level
CIGRE	Council on Large Electric Systems
SC	Study Committee
AG	Advisory Group
OHL	Overhead Line
TB	Technical Brochure
HVAC	High Voltage Alternating Current
PQ	Pre-qualification
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
IEC	International Electrotechnical Commission
CENELEC	European Committee for Electrotechnical Standardization
TOV	Transient Overvoltage
UXO	Unexploded (Explosive) Ordnance
MV	Medium Voltage
PE	Polyethylene
WG	Working Group
TDR	Time Domain Reflectometry
FMECA	Failure Mode, Effects and Criticality Analysis
GPS	Global Positioning System

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