Systèmes de câbles HT à courant continu

Sélection d'articles présentés au symposium Jicable HVDC'17

LUCIEN DESCHAMPS,
PRÉSIDENT DU COMITÉ D'ORGANISATION DE HVDC'17

PAUL PENSERINI
ASSET MANAGER, RTE

Les systèmes à courant continu sont des précurseurs des solutions qui seront apportées aux défis énergétiques rencontrés par les grands projets de réseaux. Il y aura de plus en plus de connexions, à la fois terrestres et maritimes, notamment pour les liaisons à longue distance et le raccordement des parcs éoliens en mer. Les systèmes de câbles à courant continu sont donc désormais des éléments clés de la transition énergétique vers les énergies renouvelables. Les progrès techniques récents dans les systèmes de câbles et les convertisseurs intéressent tout particulièrement les connexions de 400 à 700 kV, jusqu'à des puissances de 3 GW.

C'est pourquoi, en plus des conférences Jicable qui se tiennent tous les quatre ans en étroite collaboration avec le CIGRE, un premier colloque Jicable HVDC a été réalisé à Perpignan en 2013 pour traiter spécifiquement des systèmes à courant continu. Puis un atelier Jicable HVDC'16 a été organisé à Paris en 2016 ; il a permis de préparer le symposium 2017 Jicable HVDC'17 qui vient de rassembler près de 250 experts de 25 pays. Ce symposium a notamment traité :
- des innovations concernant les matériaux et les systèmes haute tension de pointe ;
- de la coordination entre les systèmes de câbles et les convertisseurs ;
- de la fiabilité des liaisons terrestres et maritimes longue distance ; des problèmes d'installation et de maintenance.

Une table ronde a permis aux exploitants de présenter leurs retours d'expérience sur les défauts et les réparations des câbles sous-marins, ainsi que leurs recommandations.

Ce symposium Jicable HVDC'17 s'est tenu à Dunkerque, là où la première liaison France-Angleterre a été réalisée en 1961. Cette liaison historique était limitée à 100 kV DC et à une capacité de 160 MW ; une réussite pour cette époque.

Cette connexion a été remplacée en 1986 par une liaison 270 kV DC de 2 000 MW appelée "HVDC Cross Channel - IFA 2000". Depuis 2012, une partie des anciens câbles souterrains à huile fluide a été remplacée par des câbles extrudés à isolation synthétique.

En 2017, une nouvelle liaison à courant continu est en construction : "Eleclink" ; elle utilisera des câbles à isolation synthétique posés dans le tunnel sous la Manche. Cette liaison de 1 000 MW sera mise en service en 2020. Il convient de mentionner aussi le projet d'interconnexion IFA2 de 1 000 MW entre la France et l'Angleterre qui portera à 4 000 MW la capacité totale d'échange en 2020. La liaison IFA2 est constituée de deux câbles 320 kV DC à isolation synthétique et de convertisseurs de technologie VSC. Elle relie par un tracé de 200 km en sous-marin et de 25 km sur terre deux postes 400 kV, l'un près de Caen en Normandie et l'autre près de Southampton en Angleterre.

Avant d'en venir aux articles rassemblés dans ce dossier, nous voudrions souligner quelques conclusions qui se sont dégagées du symposium Jicable HVDC'17 :

- **technologies extrudées :** les travaux se poursuivent sur de nouveaux matériaux, maîtrise nécessaire de la conduction, de l'évolution des charges d'espace et des interfaces avec les accessoires ;
- **de nouveaux systèmes de câbles à des tensions de 400 à 640 kV DC** sont en cours de qualification ;
- **coordination d'isolement :** de nouveaux phénomènes transitoires sont liés aux nouvelles technologies de convertisseurs. Quelle stratégie d'élimination des défauts ? Quels essais de qualification ?
- **fiabilité et disponibilité des liaisons HVDC de grande longueur.** Les exploitants de réseaux s'interrogent sur les actions à mettre en place : essais de conformité ; essais de routine : à quelle fréquence ? Contrôles de production et d'installation, etc.

Des réalisations innovantes en termes d'installation de câbles sous-marins HVDC, notamment en milieux hostiles, ont été évoquées. De nombreux retours d'expérience sur des défauts ainsi que sur les méthodes pour les localiser et les réparer efficacement ont été partagés.

Cinq communications ont été sélectionnées pour le présent dossier :

Challenges and opportunities with interfaces and materials for HVDC cable systems

Cet article rappelle les progrès réalisés sur les systèmes d'isolation extrudés, qui ont notamment permis une spectaculaire augmentation des niveaux de tension (jusqu'à 640 kV). Il décrit ensuite une méthode par simulation pour évaluer la faisabilité de tensions encore plus élevées, ouvrant la voie vers une nouvelle génération de systèmes d'isolation des câbles.

Surge and extended overvoltage testing of HVDC cable systems

Cette communication présente un point d'avancement des travaux du groupe CIGRE JWG B4/B1/C4.73, qui étudie les essais de choc et de surtension de longue durée des systèmes de câbles HVDC :
- aperçu historique de l'état de normalisation des systèmes de câbles HVDC ;
- récapitulatif des retours d'expérience ;
- résultats préliminaires de simulations.

Reliability on existing HVDC links feedback

Cette communication présente les travaux d'un groupe créé au sein d'ENTSO-E à la demande des GRT européens, ayant pour objectif d'améliorer la fiabilité et la disponibilité des systèmes HVDC. Elle évalue les solutions permettant de réduire la fréquence et la durée des déclenchements de liaisons, qui sont des événements graves nécessitant la mise en œuvre de moyens très lourds.

Asset management of submarine cables and lessons learned from a repair

Cette communication traite de l'amélioration de la fiabilité de câbles sous-marins. On y décrit et on y discute, du point de vue d'un GRT, les politiques de gestion des actifs y compris la maintenance préventive, la préparation des chantiers de réparation et la gestion des pièces de rechange. Celle-ci s'appuie notamment sur les enseignements tirés par RTE

Lucien Deschamps *a été conseiller scientifique à Electricité de France. Ses travaux ont porté sur les matériaux pour l'électrotechnique, les câbles de transport d'énergie, les énergies nouvelles et la prospective technologique. Il a également travaillé sur l'énergétique spatiale et le concept de centrale solaire spatiale. Lucien Deschamps a créé et organisé de nombreux événements internationaux dont les congrès Jicable, Espace, Mer, Agriculture, Énergie, Foudre... Il est aujourd'hui président de l'association Grands projets 21, AGP 21, et président de la commission Astronautique de l'Aéro-club de France.*

Paul Penserini *a rejoint EDF R&D en 1990, après une agrégation en génie civil et une thèse en calcul des structures. Ses travaux ont porté sur l'évolution des matériels de réseaux électriques de distribution et de transport par l'intégration de nouvelles technologies. Il a dirigé les laboratoires d'études et d'essais électriques d'EDF aux Renardières jusqu'en 2007. A RTE, il a dirigé le département d'expertise et de recherche dans le domaine des liaisons de puissance et à fibres optiques. Il est actuellement en charge d'une mission de coordination des activités de gestion des actifs de RTE. Paul Penserini est membre émérite de la SEE.*

des réparations des câbles sous-marins HTCC de l'interconnexion IFA2000 (FR-UK) durant l'hiver 2016-2017.

Fault Location on Land and Submarine Links (AC & DC)

Cet article est issu des travaux entrepris par le groupe de travail B1.52 du CIGRE sur le sujet de la localisation des défauts sur les liaisons terrestres et sous-marines (CA et CC). Il présente des recommandations sur la mise en œuvre des différentes techniques disponibles. ■

Figure 1 : Liaisons existantes et en projet entre le Royaume Uni et le continent.
en projet existantes

LES ARTICLES

Challenges and opportunities with interfaces and materials for HVDC cable systems

Gian Carlo Montanari; University of Bologna, (Italy), giancarlo.montanari@unibo.it
Alun S. Vaughan; University of Southampton, (UK), asv@ecs.soton.ac.uk
Peter Morshuis, Solid Dielectric Solutions, (The Netherlands), peter.morshuis@dielectrics.nl
Gary C. Stevens, Gnosys Global, (UK), g.stevens@gnosysgroup.com

ABSTRACT *HVDC cable technologies will play a critical part in integrating renewable generation sources into the electrical power systems of the future. Here, we first consider how HVDC cables have evolved to the present time, with reference to the adoption of extruded insulation systems. In particular, we discuss the advances by which recently reported dramatic increases in rated voltage (up to 640 kV) have come about. We then describe a simulation approach for assessing the feasibility of developing cable systems for use at even higher voltages; this suggests that existing insulation materials may be approaching their performance limit, when both the internal electric field and thermal factors associated with heat dissipation in the conductor are jointly considered. Finally, some potential next-generation cable insulation systems are described, which address the performance gaps identified in the simulation.*

KEYWORDS : Materials design; crosslinked polyethylene; numerical simulation; thermoplastic insulation.

introduction

It is now widely accepted that the combustion of fossil fuels results in changes in atmospheric chemistry that are having an increasing impact on the climate of our planet. Nevertheless, the demand from both developed and developing economies for energy continues to grow, with the U.S. Energy Information Administration's International Energy Outlook 2016 (IEO2016) reference case projecting that global generation of electricity will increase from 2.2×10^{13} kWh in 2012 to 3.7×10^{13} kWh in 2040 [1]. While fossil fuels will, for the foreseeable future, continue to make a major contribution to meeting this demand, the role played by renewable sources will grow, which will require electrical power systems to evolve to accommodate them.

Increased reliance on renewable sources of electricity generation will, for a number of reasons, require the adoption of new power transmission technologies. First, renewable generation will in general need to be located at sites that are remote from major centers of demand (e.g. off-shore wind farms; hydro-generation in mountainous areas). Second, many renewable sources of generation (e.g. wind and solar) are intrinsically intermittent, which will lead to the interconnection of national power systems to form international supergrids, whereby massive power flows over long distances will become, increasingly, the norm. High voltage direct current (HVDC) transmission will be essential in facilitating this and, while overhead lines have much to recommend them in many circumstances, such a solution is impractical where connections involve crossing the sea or where the perceived environmental impact of overhead lines is unacceptable. This problem is well illustrated in Germany, where low public acceptance of overhead power lines means that the Südlink project will require the installation of a 700 km, 500 kV underground HVDC link from the northern seaboard to demand centers in the center and south of the country, in order to integrate offshore wind generation. Indeed, in total, TransnetBW GmbH has estimated that Germany will require new HVDC transmission corridors with a total length of between 2600 and 3100 km and with a total transmission capacity 12 GW [2]. While many HVDC subsea systems have been installed successfully, such underground systems on land pose many challenges, many of which relate to the design of the cable and the choice of the insulation system.

Evolution of HVDC cables

Many different HVDC cable technologies have been developed in preceding decades and have been successfully deployed around the world. Although the majority of well-established HVDC cable systems currently in service are based on paper/oil or mass impregnated insulation systems, the complexity of manufacture, weight and limited operating temperature of such systems are contributory factors in driving the current interest in HVDC cables based upon extruded polymeric insulation.

Project	Country	Year	Voltage *[kV]*	Submarine *[km]*	Land *[km]*
Gotland	Sweden	1998	80	0	140
Directlink	Australia	1999	84	0	390
Murraylink	Australia	2002	150	0	360
Cross Sound	USA	2002	150	83	0
Troll A	Norway	2004	60	284	0
Estlink	Estonia-Finland	2006	150	150	62
BorWin1	Germany	2009	150	266	155
EWIP	Ireland-UK	2012	200	372	152
DolWin1	Germany	2013	320	170	187
SouthWest link	Sweden	2014	300	0	797
NordBalt	Sweden-Lithuania	2015	300	800	100
Aland-Finland	Finland	2015	80	318	0
DolWin2	Germany	2015	320	99	183

Table 1: Extruded DC (HVDC Light) cable systems from ABB submarine and land based installed cables [km] and country and year of installation (adapted from [3]).

It is generally acknowledged that the world's first HVDC transmission system using cable designs based on extruded polymeric insulation (crosslinked polyethylene – XLPE) was used to connect the Swedish island of Gotland (50 MW; 80 kV; 70 km) in 1999. Incremental advances in the following years led to incremental increases in both the rating and operating voltage of such systems. Table 1 illustrates this progressive evolution in terms of ABB's HVDC Light technology [3]. However, recent years have witnessed a remarkable acceleration in the development of such systems, with companies such as ABB, and latterly NKT, reporting major advances in HVDC XLPE technology. In 2014, ABB reported on a new 525 kV HVDC extruded cable system with a power rating range of up to 2.6 GW for use in both subsea and underground applications [3]. In 2017, the same basic material technology was used by NKT to produce a 640 kV XLPE-insulated HVDC cable which, NKT indicates, differs from its 525 kV ABB predecessor only in terms of design optimization, process parameters and through the implementation of more sophisticated quality assurance measures [4].

From materials to cables

The radical advances in XLPE-insulated HVDC cable designs introduced above that have emerged in recent years are based upon novel material systems, which include both insulation and complementary semiconducting (semicon) screen systems. As such, it is worth posing the question: what is innovative about these systems that has led to such rapid progress? A key factor appears to be Borealis' development of their BorlinkTM materials, which are described as exhibiting an optimized combination of chemical, mechanical and electrical properties, with ABB highlighting high breakdown strength and very low DC conductivity as being key characteristics.

Space Charge and Impurities

XLPE has been widely used for many decades as the insulation in high voltage cables, because of the thermo-mechanical benefits that result from crosslinking. Crosslinking of low density polyethylene (LDPE) with dicumyl peroxide (DCP) has been studied for many years [5], as having the impact to retain crosslinking by-products on key electrical characteristics. For example, Hirai et al. [6] considered the impact of a number of DCP decomposition products on charge transport dynamics in PE and concluded that cumylalcohol acts as a trap for charge carriers while acetophenone and α-methylstyrene act to assist carrier transport. Conversely, a complementary theoretical study of the effect of such impurities on charge trapping in PE suggested that α-methylstyrene should be most strongly related to trapping phenomena. While the detailed results of such studies may differ, the key conclusion is nevertheless equivalent: retention of the small molecular by-products of DCP decomposition will affect space charge formation which, in turn, must increase the local field and thereby reduce service life.

While the crosslinking process itself is a source of impurities, it is not alone in this regard and a number of studies have considered the influence that changes in semicon formulation exert on electrical characteristics of the neighboring insulation. In 2010, Nilsson and Boström [7] described an important study of the influence of semicon formulation on space charge accumulation. Specifically, this work involved formulations that differed with respect to both the base polymer used and the cleanliness of the carbon black. Elemental analysis indicated that while their furnace black contained 100 ppm of sulfur (total impurities ~160 ppm), this was not present in the acetylene black (total impurities ~40 ppm – ~3 ppm sulphur). While replacement of the furnace black with acetylene black was found to reduce space charge accumulation, replacement of the polar ethylene/butyl acrylate (EBA) base polymer with non-polar systems was found to yield more significant benefits. Based upon Fourier transform infrared (FTIR) data, it was suggested that this was linked to migration of low-molar mass species from the polar semicon into the insulation. This conclusion is in line with earlier work [8] in which peelings, ~100 μm in thickness, were cut from an XLPE-insulated cable sample and analyzed by FTIR, such that the chemical composition as a function of radial position could be obtained. Variations in the concentration of carbonyl groups from ester groups originating in the copolymers used in the semicon, was used to infer diffusion of low molar mass molecular fractions from the semicon into the XLPE; DC breakdown testing of the peelings showed a good correlation between reduced DC breakdown strength and the intensity of the absorbance peak at 1735 cm-1.

Advances in XLPE Insulation

While it would be unreasonable to ascribe the recent dramatic advances in XLPE-insulated HVDC cable technology to a single factor, it is evident from material published by both ABB and Borealis that a major, if not dominant, contributory factor is the LDPE resin itself. Reference to the patent literature reveals a number of significant changes that relate to the active design of the molecular architecture, specifically to generate material systems that are targeted at HVDC cable applications. The Borealis patent EP3190152 (*A Cable and Production Process Thereof* – published in July 2017) [9] is one such. A key element of this appears to be the inclusion of a degree of unsaturation within the molecular architecture, an innovation which would seem to be related to increasing the ease of peroxide crosslinking. Certainly, such a strategy is consistent with the notion of minimising unwanted peroxide crosslinking by-products and, therefore, would be consistent with the requirements of advanced HVDC cable insulation systems.

Advances in Semicon Formulation

It is apparent from the above discussion that the semicon is also a potential source of impurities that can migrate into the insulation with adverse consequences. As such, a number of steps can be envisaged to minimise such effects, which include the use of high purity carbon blacks and replacement of conventional polar co-polymers with appropriate non-polar systems. This strategy is well exemplified in patent WO2017089201 (*Semiconductive Polyethylene Composition*, Borealis AG, published June 2017) [10], where one of the stated aims is the formulation of a semicon system that will lead to "excellent space charge performance to ensure good DC properties in a cable". The innovation described is to base the semicon on very low density copolymers of ethylene and an α–olefin (so-called plastomers), where the required combination of electrical, mechanical and rheological properties is achieved by suitable selection of the carbon black loading level combined with blending of different plastomer grades.

Towards higher voltage cables

Although the advances made in recent years in increasing the voltage and ampacity of XLPE-insulated HVDC cables are impressive, current HVDC overhead lines are operating at up to 1.1 MV and, as such, cables still lag some way behind. While it is possible to approach this through an incremental approach in which design considerations, material processing and polymer characteristics are iteratively refined, here, we describe a fundamentally different approach to the problem, which is based upon three distinct steps:
- Numerical simulation is used to explore the available parameter space.
- Required material characteristics and performance gaps (relative to current materials technologies) are identified.
- Material systems are explicitly designed to address these deficiencies.

HVDC cable simulation studies

The feasibility simulation described here was based on algorithms for electric field calculations in DC cable insulation, using considerations relating to failure statistics obtained from laboratory accelerated life testing on cable models, combined with the relevant dimensional effect expression needed to convert from sample testing to full-size cable design.

The cable insulation design was divided into two steps, which interact one with the other:

a) Electrical-statistical design, aimed at defining the insulation geometry that is necessary to ensure the required electrical performance;

b) Thermal design, which is aimed at verifying that the maximum temperature inside the insulation does not lead to overheating (thus life reduction through Arrhenius law) or even thermal runaway.

Electrical-statistical Design

The major issue here concerns the electric field profile in a DC cable, which can change significantly with the

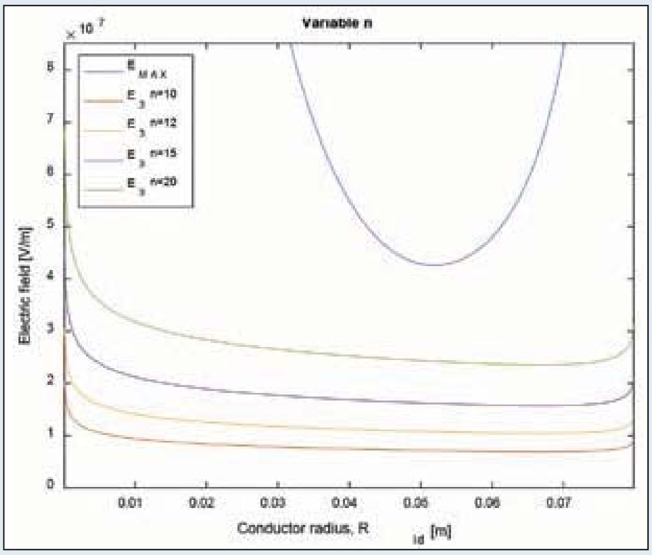

Figure 1: Example contour (feasibility) plots for E_{MAX} and E_3 for different values of the voltage endurance coefficient, *n*.

temperature gradient that evolves across the cable insulation during operation. Consequently, designing the cable insulation thickness based on a mean field (as under a uniform field distribution) may bring a level of approximation that poorly describes the likely effect of the actual spatial distribution of field on cable life. Secondary issues are (a) that a statistical approach is needed to estimate design life from a given failure probability and (b) dimensional effects associated with extrapolating from laboratory specimens to full-size cable must be taken into consideration.

If E_{MAX} is the maximum field, which depends on ΔT and R_{id} (temperature drop and internal insulation radius, respectively), the limiting electrical condition for cable feasibility is:

$$E_{MAX}(\Delta T, R_i) = E_3(R_{id}) \qquad (1)$$

where E_3 is the expected design field providing the desired life at the chosen failure probability. This equation allows the internal radius of the cable insulation to be determined. To be solved, eq. (1) needs to be coupled with an equation correlating the temperature drop, ΔT, with the internal radius, R_{id}, which is the Fourier thermal equation. This is considered below.

Thermal Design

The aim of the thermal design is to verify if the temperature distribution inside the cable is acceptable given the requirements. Under DC conditions, we assume that the only heat source is represented by the Joule losses of the internal conductor, $R_{cc}I^2$. Depending on the insulating material's maximum operating temperature and the temperature of the cable's environment, the cable ampacity can be obtained, the maximum ΔT estimated and the maximum electric field in the insulation calculated.

Feasibility

Feasibility concerns the need of a design to conform to eq. (1). If an internal radius, $R_{id,}$ able to satisfy eq. (1), exists, then cable manufacture is feasible and it is possible to start the thermal design. Otherwise, it is necessary to restart the design with a larger size of extruder and/or different insulation parameter values.

Fig. 1 contains exemplar contour plots summarizing a design feasibility exercise for a polymeric DC cable of 800 kV and 3 kA, using typical parameters valid for high voltage alternating current (HVAC) grade XLPE. The variable parameter is the voltage endurance coefficient, *n*, which is the inverse of the life line slope. As can be seen, for none of the n values considered does the consequent curve intersect with the curve indicating E_{MAX}; thus, eq. (1) is not satisfied. This means that the cable is not feasible with the chosen parameter values and the performance-rating specifications.

Based on the results of the simulations, it appears that the feasibility of extra high voltage DC (EHVDC) polymeric insulated cables may be questionable considering the technologies and the characteristics and properties of the insulation materials that, currently, are most commonly used in extruded polymeric cables, XLPE in particular.

There is a need for a very high breakdown strength and large value of *n*, also, in relation to the cable length (dimensional effect). In order to increase cable length, a major issue is the value of the shape parameter of the Weibull distribution of breakdown strength and failure times, which must be as high as possible. This reflects the need to have maximum homogeneity of the insulation, placing demands on both the material and the extrusion process.

The extruder for an EHVDC cable would have a larger diameter than those currently used to cover the voltage range up to 400-500 kV, because the maximum electrical field is a challenge that materials cannot cope with at present. Regarding this, the activation energy of the conduction process in the insulation has to be lowered as much as possible, to reduce the dependence of the conductivity on the temperature gradient (thus on cable ampacity).

Also, the space charge accumulation threshold will become an issue, because if the cable has to run with the required design reliability, the maximum electrical field must be lower (at the operating temperature) than the threshold for space charge accumulation. Therefore, the capability of the insulating material to store space charge at very high field will be a fundamental issue for the development of EHVDC cables.

The above considerations may introduce the need to investigate nanostructured materials and/or polymeric materials different from XLPE (such as thermoplastic materials). In addition, if the operating temperature can be raised above the present limit established by the thermal characteristics of XLPE, i.e. 90° C, an increase in ampacity will be favored. In this case, even more, the need to control the activation energy of the conduction process (to reduce the variation of conductivity as function of thermal gradient in the dielectric and, thus, the maximum field value) will become critical for the insulating polymer candidates chosen for HVDC applications. Addressing all these requirements can only be achieved through the development of new materials, some of which are currently emerging.

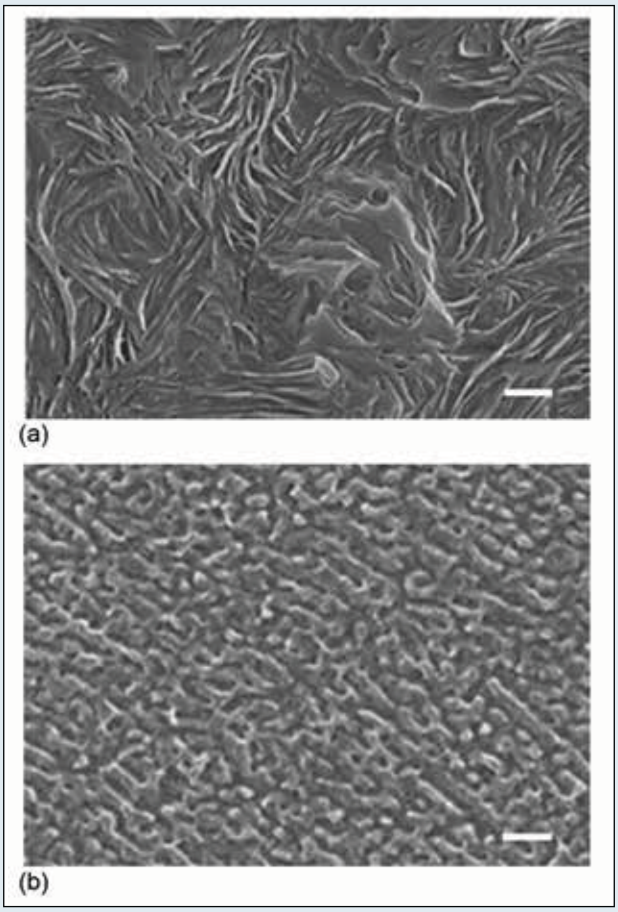

Figure 2: Scanning electron micrographs (scale bars 1 µm) comparing the designed morphology of two blend systems: (a) 20% HDPE and 80% LDPE; (b) 50% isotactic polypropylene and 50% of a propylene/ethylene copolymer.

Thermoplastic HVDC insulation

In 2016, Prysmian issued a number of announcements relating to the use of its thermoplastic P-Laser technology in HVDC applications, which culminated in September with the launch of a 600 kV HVDC cable system. As described in the related CIGRE publication [11], this material facilitates an increase in cable operating temperature up to 130° C, which provides increased flexibility to network operators. Also, by eliminating the need for crosslinking, the insulation system is intrinsically free of the crosslinking byproducts discussed above. Although complete details of the P-Laser insulation system have not been published, it is described as being a high performance thermoplastic elastomer [12], of which related patents also indicate that the concept is based upon a combination of propylene-based polymers plus a dielectric liquid [13].

Designing Cable Insulation Systems

Cable insulation materials are required to meet a range of properties, that include electrical, mechanical and thermal factors. As such, designing systems to meet the requirements of particular applications is far from trivial. However, from the HVDC perspective, the importance placed upon reduced impurity levels makes thermoplastics highly attractive; while only Prysmian has, thus far, brought a thermoplastic-insulated cable to market, it is very clear from the patent literature that many other cable companies are active in this space.

A key feature of thermoplastic polymers is their morphological complexity, which involves the formation of complex hierarchical microstructures that generally include electrically weak regions [14]. The nature of the materials design challenge is well illustrated in a number of publications published by Hosier et al. [15, 16], which considered the effect of changes in morphology on the short-term breakdown strength of polyethylene. In this study, high density polyethylene (HDPE) was added to LDPE and the blend composition, combined with different thermal treatments, were used as a means of varying the microstructure of the system. This work showed that systems in which crystallization results in a space-filling array of thick lamellar crystals (here, primarily composed of HDPE) can exhibit attractive combinations of electrical and mechanical properties, which include increased breakdown strength, good low temperature flexibility and high temperature mechanical integrity. Such a morphology is shown in Fig. 2a.

While HDPE/LDPE blends such as those described above illustrate basic principles well, extending the concepts to polypropylene in order to exploit the higher melting temperature of this polymer – as in the case of Prysmian's P-Laser – is not that simple. Nevertheless, the Suscable I collaborative project, involving the University of Southampton, Gnosys Global, Dow Chemicals and National Grid, successfully built on earlier academic work on blends of isotactic polypropylene (iPP) and various propylene-based copolymers [17] to develop novel blend systems that exhibited excellent combination of properties obtained from laboratory plaque samples, which were retained when extruded into mini-cables (see Fig. 2b). Progressive DC stress testing of 6 m lengths showed that, while XLPE insulated mini-cables all failed at applied DC voltages in the range 168-224 kV, none of the mini-cable specimens based on the designed propylene-based blend failed before the maximum voltage of 400 kV was reached, which corresponds to maximum electric field within the insulation of more than 120 $kV.mm^{-1}$ [18]. Subsequent work has sought to extend these concepts by up-scaling to a pseudo-commercial medium voltage cable design (Suscable II); it resulted in increased thermal conductivity for increased cable ratings (CableSure).

Suscable II was conceived to produce a medium voltage AC (MVAC), high operating temperature cable system, based upon polypropylene blends. Such systems would not require crosslinking and, consequently, would be very clean with no-crosslinking by-products. This development has now been achieved and it will be used to support HVAC and HVDC cable development based on the same technology. More complex polypropylene blend formulations have been developed beyond those patented in Suscable 1 [19]. These materials have excellent HVAC and HVDC performance and are expected to feature in a new HVDC cable insulation system, which combines a new semicon system that works effectively with the insulation system. The additional attraction of this development is that the polymer components required for the insulation system can be sourced from multiple suppliers provided they are appropriately qualified.

However, an intrinsic issue with any cable insulated with polypropylene is the reduced thermal conductivity of this polymer. Indeed, Pilgrim et al. [20] analyzed the impact of different insulation properties on cable rating and overall power losses for a high voltage AC cable design and concluded that thermal conductivity was of most significance in determining these. As such, increasing thermal conductivity can be of great practical significance and, therefore, a massive body of research exists in this area, the majority of which has involved the addition of particulate fillers. While this strategy has been shown to be a viable means of producing significant increases in thermal conductivity, this invariably appears to require the formation of percolating filler structures. While this is very reasonable in that it is explicable in terms of minimization of phonon scattering at particle/matrix interfaces, the consequences, from a dielectric perspective, are severe. For example, the problem is well illustrated in the recent publication by Chi et al. [21], who used applied magnetic fields to induce ordering in iron oxide/polyethylene nanocomposites. While the result was a maximum increase in thermal conductivity of 46% on including 7 vol.% of magnetically ordered nanofiller, the addition of just 1 vol.% of the filler resulted in an increase in electrical conductivity of three orders of magnitude. To increase thermal conductivity whilst maintaining excellent insulation characteristics is a major challenge.

Nevertheless, recent work at the University of Southampton has revealed a previously unreported form of behavior for systems based upon hexagonal boron nitride (hBN), where an increase in thermal conductivity of more than 60% has been accompanied by an increase in breakdown strength in excess of 20% [22]. These preliminary results are currently being refined in the CableSure project, involving the University of Southampton and Gnosys Global, through optimization of the hBN surface chemistry both to enhance dispersion within the polymer and to minimize phonon scattering at matrix/filler interfaces. Combining these concepts with those described above in connection with our Suscable II developments will produce a new generation of HVDC cable insulation systems characterized by increased breakdown strength, reduced electrical conductivity and space charge accumulation, increased maximum operating temperature and increased thermal conductivity compared with current state-of-the art systems.

Conclusions

The need for long-distance transmission of large quantities of electrical power as remote sources of renewable generation are incorporated into national power systems, combined with the need to connect these together to form trans-continental supergrids, is driving the need for novel HVDC technologies, including cables that are able to operate at higher voltages and ampacities. In recent years, two competing approaches have begun to emerge and, while these employ very different polymer systems, a critical feature of both the ABB/NKT/Borealis XLPE and Prysmian P-Laser HVDC strategies for cables capable of operating above 600 kV, is minimization of the impurities that lead to space charge accumulation and electrical conduction. That is, both of these strategies are based upon advances in materials. Looking forward, we propose that future advances will need to continue to embrace a unified approach in which cable design is used to identify material performance gaps and, based upon this, novel material solutions will need to be actively designed. This approach has been exemplified here through an initial feasibility evaluation of a prototype 800 kV, high ampacity EHVDC cable. This simulation suggests that established materials technologies may be close to their ultimate performance ceiling and that radically new systems will shortly be needed, such as the propylene-based blend and hBN nanocomposites that we describe.

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Glossary

DCP: Dicumyl peroxide
EBA: ethylene/butyl acrylate
EHVDC: Extra high voltage direct current
FTIR: Fourier transform infrared
hBN: Hexagonal boron nitride
HDPE: High density polyethylene
HVAC: High voltage alternating current
HVDC: High voltage direct current
iPP: Isotactic polypropylene
LDPE: Low density polyethylene
MVAC: Medium voltage alternating current
PE: Polyethylene
XLPE: Crosslinked polyethylene

Surge and extended overvoltage testing of HVDC cable systems

JWG B4/B1/C4.73

Markus Saltzer; ABB Switzerland Ltd., (Switzerland), markus.saltzer@ch.abb.com
Minh Nguyen-Tuan; SuperGrid Institute, (France),
minh-2.nguyen-tuan@edf.fr
Alessandro Crippa; CESI S.p.A., (Italy), alessandro.crippa@cesi.it
Simon Wenig, Max Goertz; Karlsruhe Institute of Technology (KIT), (Germany), simon.wenig@kit.edu;
max.goertz@kit.edu
Hani Saad; RTE, (France), hani.saad@rte-france.com
Carsten Bartzsch, Pritam Chakraborty, Luigi Colla, Yujun Fan, Mingli Fu, Vincent Joubert, Jon Ivar Juvik, Tanumay Karmokar, Bahram Khodabakchian, Amit Kothari, Willem Leterme, Jérôme Mathot, Sören Nyberg, Amit Kumar Saha, Antonios Tzimas, Roland D. Zhang

ABSTRACT *In this contribution a short status update of the Cigré JWG B4/B1/C4.73 is presented. The focus of joint working group is to investigate the surge and extended overvoltage testing of HVDC cable systems, since standard test levels for HVDC are at present not available. In this paper, a historic overview of the standardization status for HVDC cable systems is presented. This is followed by summarizing some findings and trends from data of the HVDC project collection, which are used for prioritization of the work tasks. Moreover, preliminary simulation results on the topic are presented. Since the JWG B4/B1/C4.73 is still in operation mode, no firm conclusions on standardization should yet be drawn by the investigations presented here. Instead the relating brochure and/or Electra publication should be awaited.*

KEYWORDS: High Voltage Cables, HVDC Transmission systems, Temporary overvoltages in HVDC systems, Symmetric Monopole, Bipole, Asymmetric monopole.

Introduction

Cigré JWG B4/B1/C4.73 held its kick-off meeting in March 2016. It has the task of looking into surges and extended overvoltages testing for HVDC cable systems. More specifically, the goal is to reconsider temporary overvoltages experienced by the cable within HVDC transmission systems, given various converter configurations, respectively system topologies, i.e. monopole, symmetrical monopole, bipole etc. Furthermore, a method for lightning impulse (LI) level determination in mixed OHL-cable systems based on project specific parameters should be considered. Based on these studies, recommendations on testing schemes and levels for HVDC cable systems shall be concluded. Beyond point-to-point, multi-terminal and DC/AC mixed grids could also lead to new types of overvoltage shapes, and should, if possible, be considered by the JWG. However, since this topic might not be relevant in the immediate future, it is considered as optional. The driver for these requests has been the way temporary overvoltages are defined in today's standards and recommendations, where specific test levels are not provided, but left for customer-supplier negotiations. Moreover, the switching impulse (SI) wave shape has been more and more challenged in recent discussions. Instead, impulses on longer timescales have been considered relevant, motivated by changes in converter configurations compared to earlier standardization work.

In this paper the status of the ongoing work is shared. This is done by providing a summary on today's practice as well as drawing some conclusions from the market development by looking on commissioned and to be commissioned projects. A major focus for the work of this JWG are simulation HVDC system tools, as respective data is rare. Therefore, preliminary simulation results are summarized.

Technology status and todays practice

Present Practice for Impulse test on HVDC Cables

Nowadays the main reference adopted for testing an HVDC cable system for electrical purpose are the following. Electra 189 (2000) "Recommendations for tests of power transmission DC cables for a rated voltage up to 800 kV", and relevant addendum from TF B1-16. The document is a revision of the previous Electra 72 (1980) "Recommendations for tests of power transmission DC cables for rated voltage up to 600kV". Electra 189 applies to cables and accessories, either submarine cables or land cables, and is intended for use in DC power transmission systems with rated voltages up to 800 kV. The recommendations are applicable to paper insulated cables (mass impregnated, oil filled, gas pressure and lapped insulation, e.g. PPL) and cover routine tests, type tests and after laying tests. There is no indication regarding the HVDC schemes considered, but taking into account the year of publication, it is assumable that the recommendations are applicable to HVDC system with LCC schemes. The other main reference is TB 496 (2012) "Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV''. The document is a revision of the previous TB 219 (2003) "Recommendations for DC extruded cable systems for power transmission at a rated voltage up to 250 kV". TB 496 applies to HVDC extruded cable systems for land or submarine application and includes recommendations for electrical testing of HVDC system for long duration testing (PQ test), type testing, sample testing routine testing, and tests after installation of HV and return cables. The test program proposed in TB 496 follows the same principles as in TB 219 and includes testing programs for VSC and LCC application.

Considering the impulse test, publication Electra 189 includes a test program with switching and lightning impulse superimposed to DC voltage of the opposite polarity. Other overvoltages of short duration and relatively lower amplitude are omitted with reference to results of JWG 33/21/14-16 (1994). A test factor of 1.15 for impulse amplitude (peak value) is suggested with reference to JWG 15/21/33. The following parameters apply for switching impulse wave shapes: a time to crest of 250 μs ± 20% and a time to half value of 2500 μs ± 60%. For lightning impulse the time to crest is 1-5 μs and the time to half value: 50 ± 10 μs. Values come from IEC 230 (1966) "Impulse test on cables and their accessories" which is a very old standard and is today under revision. This standard contains conditions and procedure for carrying out impulse tests on cables and their accessories. This standard applies solely to the methods of carrying out the tests as such, independently of the problem of selecting the test levels to be specified. Testing programs proposed in TB 496 are somewhat different between LCC and VSC application. Specifically, for the case or transient overvoltages relevant in this paper, the wave shapes suggested for LCC in Electra 189, are applied in a similar way to VSC. However, additionally switching impulses superimposed to DC voltage U_0 of the same polarity are foreseen and required for VSC application. The required wave shapes for impulse tests suggested in TB 496 are shown in Figure 1. TB 496 does not include technical explanations regarding the typologies of switching impulses to be applied for VSC and LCC scheme; the following note is reported at paragraph 1.5.3. *"[…] Due to the constraints within the DC system design, $U_{P2,S}$ does not necessarily equal $U_{P2,O}$, i.e. the same polarity impulse is limited by surge arresters, but the opposite polarity impulse may be limited by the converter"*. TB 496 and 219 do not deal with the evaluation or characterization of this overvoltage.

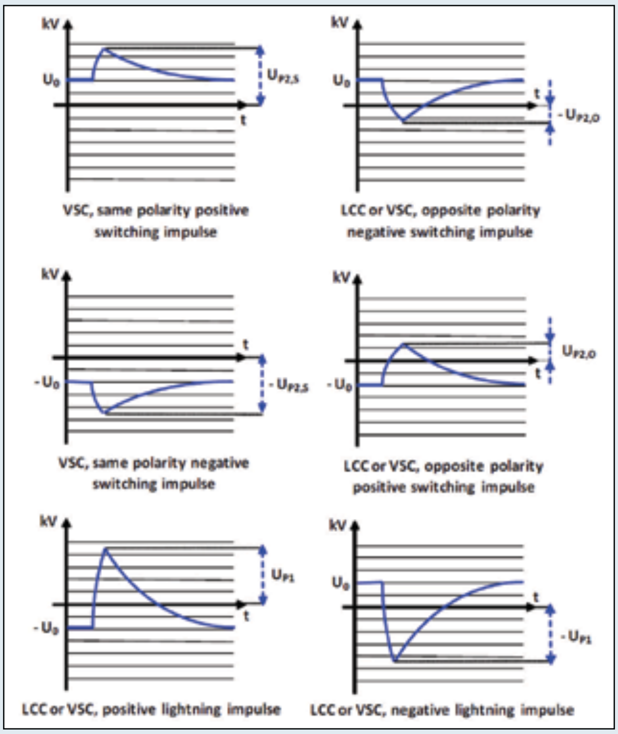

Figure 1: Required wave shapes for impulse tests for VSC and LCC systems suggested in TB 496.

As for lightning impulse TB 496 does not differentiate between VSC and LCC: lightning impulses superimposed to DC voltage with opposite polarity must be applied. TB 496 suggests a test factor of 1.15 for impulse peak value (type test), this is based on previous works in light of the good experience gained in the past (explanation in Appendix A of TB 496). TB 496 refers to the same procedure given in Electra 189 for application of superimposed impulse voltage (same wave shapes and number of impulses for each series).

Beside Cigré publications, there is a new standard for HVDC cable testing: IEC 62895 (2017) "High Voltage Direct Current (HVDC) power transmission cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications - Test methods and requirements". This International Standard specifies test methods and requirements for transmission power cable systems, cables with extruded insulation and their accessories for fixed land installations, for rated voltages up to and including 320 kV.

	HVDC-LCC	HVDC-VSC
Paper insulated cables	Electra 189	?
Extruded insulated cables	TB496 / IEC62895	TB496 / IEC62895

Table 1: Reference for HVDC cable testing.

Requirements for impulse tests follow in general the recommendations of TB496, as for wave shapes, number and type of impulses and test factors.

Table 1 summarizes the references for HVDC cable testing; it should be noted that for paper insulated cable intended for HVDC-VSC application there is no specific document.

Apart from the recommendation for testing there is a Cigré document, which deals with overvoltage in HVDC cables: TB No. 86 (1994) "Overvoltage on HVDC cables" (JWG 33/21/14-16). The focus of the JWG 33/21/14-16 was to evaluate the influence of transient overvoltages on DC cable insulation, compare the overvoltages with the DC cable test voltages and investigate the applicability of overvoltage limiting device. The work deals with paper cables (MI and Oil filled) and HVDC-LCC system. Typical topics addressed in TB No. 86 are a collection of data and type test information for DC cables in operation/planning stage, analysis of the insulation capability of DC cables (MI and Oil filled), analysis of internal and external overvoltages occurring on DC cable schemes, means of reduction of overvoltages, determination of typical values for withstanding of lightning overvoltages, internal overvoltages and long duration overvoltages, suggestion for safety margins between protective level and insulation withstand. However, discussion on alternatives for cable tests have not been addressed from JWG 33/21/14-16 but suggested for a future special WG.

Technologies and statistics from projects

In the following, a summary deduced from collection of HVDC projects in operation and tendering phase is given. Preliminary priorities for the work in the JWG are defined, based on the analysis on existing HDVC projects.

About 100 HVDC cable systems are in operation or planned worldwide. The first modern HVDC transmission systems were installed in the 1950's. These systems are based on LCC technology (Line-Commutated Converter). Working on the principle of bridge rectifiers, early LCC converters used mercury arc valves. A significant technical advance was made in the 1970's with the introduction of thyristor valves. At the beginning of the 21st century, VSC technology (Voltage-Source Converter) was introduced, thanks to the development of higher rated valves, such as IGBTs (Insulated-Gate Bipolar Transistors). MMCs

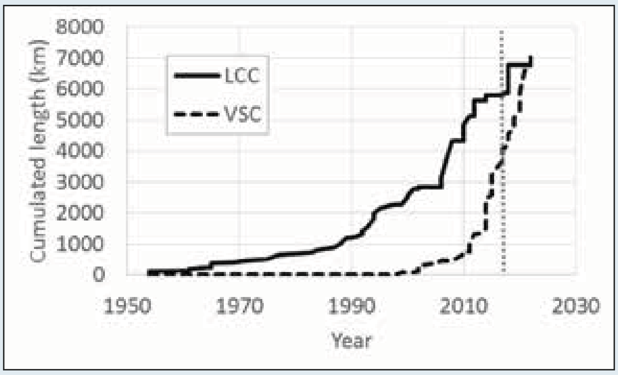

Figure 2: Cumulated route length of HVDC cables world wide relating to converter technology. Numbers beyond 2017 include also tendering phase project, which might change in the future.

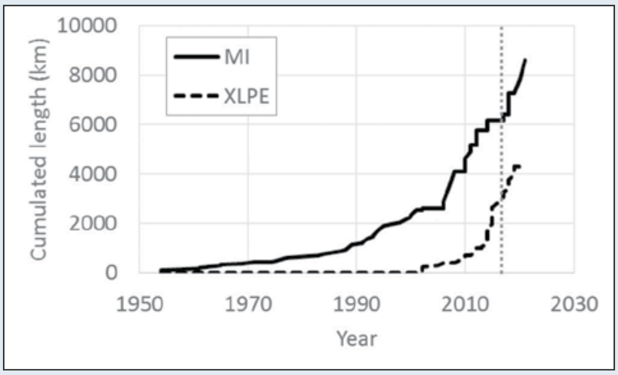

Figure 3: Cumulated route of HVDC cables relating to insulation technology. Numbers beyond 2017 include also tendering phase project, which might change in the future.

(Modular Multilevel Converters) then appeared as the most cost effective VSC converter concept, as these topologies practically eliminate filtering needs. Today, the number of VSC systems has almost reached the number of LCC systems, and the amount of cumulated kilometers of cables connected to VSC systems will soon reach parity to LCC systems (cf. figure 2).

HVDC cables are mostly used for submarine applications, but they are also used for land applications. The two main technologies available today are mass impregnated (MI) cables and extruded cables mostly with XLPE as the main insulating material. In *mass impregnated cables* conductors are insulated by paper layers, which are impregnated with a high viscosity fluid. MI cables have proven to be highly reliable in service and are qualified up to 500 kV. Recent developments introduced 600 kV cables and potentially higher using Polypropylene Laminated Paper (PPLP) insulation. MI cables are today widely used in LCC systems as they are less sensitive to polarity reversal than polymeric cables. Polymeric *Extruded cables* nowadays are mainly XLPE based. The development of VSC converters, which allows to reverse the power flow without polarity reversal, encouraged the use of polymeric cables. XLPE cables have

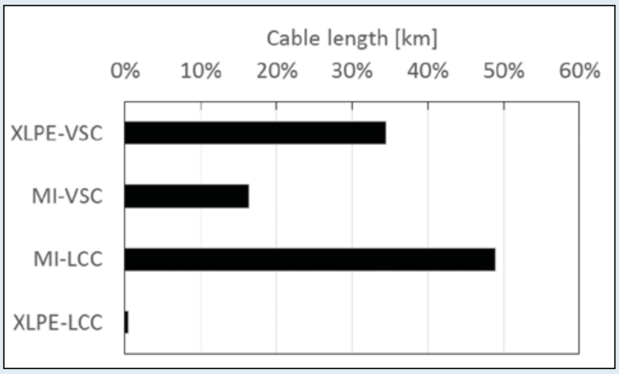

Figure 4: Cumulated route of HVDC cables relating to converter technology. Numbers beyond 2017 on a tendering phase are included, but add uncertainty to this figure.

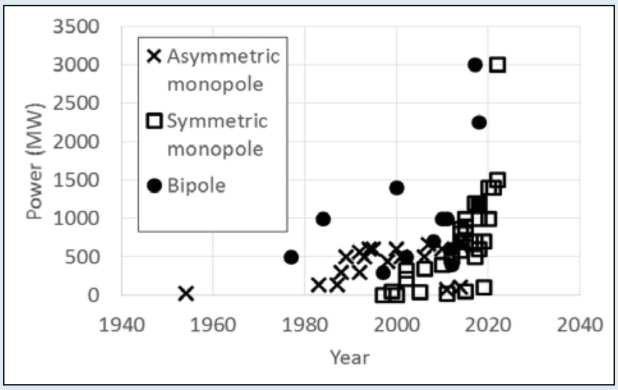

Figure 5: Evolution of the power for the different system configurations.

been into service at voltages up to 320 kV with a project also being awarded at 400 kV. Although service experience is still limited, the rated voltage of extruded cables in service is expected to increase in near future up to 525 kV, whereby potentially higher voltages might be available. Figure 3 shows the length of installed (and to be installed) cumulative cable lengths related to insulation technology. Recent development suggests that there is no clear separation of converter technologies and cable insulation technologies. It is envisaged that a considerable part of VSC links will be operated with MI cables. This is visualized in Figure 4, which summarizes the amount of cable in kilometers, installed or to be installed in near future, related to converter technology in combination with cable insulation technology. As a conclusion, if one considers MI-LCC as historical basis, VSC-XLPE is the major technology at the moment from the HVDC transmission systems. However, there is also a considerable amount of cable lengths in MI-VSC systems to be considered in near future.

From the system perspective, there are basically three converter station topologies: asymmetric monopole, symmetric monopole, and bipolar configurations. In Figure 4 their evolution in power with time is shown, indicating also the amount of realizations in time. The *Asymmetric mono-pole* configuration requires only one HV cable. The current returns through a neutral cable (rated for the load current but only lightly insulated) or through the ground. Asymmetrical monopoles represent roughly 30% of the links, but they are not considered as the preferred choice for future links. In Figure 4 this is reflected by very little project realized and planned in the recent years. For the *symmetric monopole* configuration two HV cables are required. Compared to an asymmetric monopole, no DC stress is imposed on the converter transformer. Symmetric monopoles are uncommon for LCC systems, but have found wide acceptance for VSC systems. They represent more than 50% of all links. The *bipolar* configuration can be seen as two asymmetric monopoles connected in series on the DC side and in parallel on the AC side. The benefit of a bipole is that the loss of any major element leads only to the loss of half of the transmission capacity. Bipoles are used when high power is sought (Cf. Figure 5). They represent about 20% of the links.

Based on those considerations and the assumption that MI-LCC systems are the historic basis on which today's standards are based, the JWG has decided on prioritizing VSC systems with XLPE an MI cable technology in symmetric monopole configurations for intermediate power levels and todays 320 kV voltage level. For the highest power however the focus will be shifted towards bipolar configurations.

Simulative evaluation approach

In this section a first glimpse of our work is shown by representing first calculation results on overvoltage type that differs considerably from those described in the summarized past standardization activities in a 320 kV symmetric monopole configuration.

As of today, the highest share of high voltage DC projects is realized in symmetrical monopolar configuration utilizing state-of-the-art modular multilevel converter topologies (MMC-HVDC). Simulations presented within this chapter highlight results to obtain characteristic overvoltage shapes and verify these in different EMT-type software tools. Finally, selected parametric sensitivities supplement initial investigations.

System Parameters and Modeling

Following the framework provided by previous working groups [1], an exemplary MMC-HVDC point-to-point connection based on half-bridge technology has been determined (Table 2). The transmission corridor has a length of 300 km, is realized with an extruded DC cable, and is modeled using a frequency dependent model. The pre-fault power flow at

Description	Parameter	Value
Rated power	P^r	$1\ GW$
Nominal DC voltage (pole-to-ground)	V_{dc}^r	$\pm 320\ kV$
Nominal AC voltages (converter-/grid-side)	v_{ac}^r	$330\ kV$, $400\ kV$
AC short circuit level	SCL	45 GVA
Line frequency	f	$50\ Hz$
Number of submodules per arm	N_{SM}	320
Arm sum capacitor voltage (each arm)	$\sum v_{C,i}$	$640\ kV$
Arm inductance	L_{arm}	$70\ mH$
Average submodule voltage	$v_{C,i,avg}$	$2\ kV$
Submodul capacitor size	C_{SM}	$8.1\ mF$
Converter control sample time	t_s	$50\ \mu s$
Protection system delay	t_p	manually triggered
Protection level surge arrester	V_p	$1.7\ pu$ @ 3 kA

Table 2: Half-bridge MMC-HVDC system specification.

the point of common-coupling of MMC 1 is +1 *GW* ac in-feed and +300 *MVAR*. The control strategy considers an active/reactive power flow control on MMC 1 and a DC voltage/reactive power control on MMC 2. Control system details are reported in [1].

Impact of Simulation Environment

In order to obtain typical overvoltage levels of MMC-HVDC, a large number of time domain simulations needs to be carried out considering related system layout and relevant fault locations. Besides these project specific parameters, the impact of state-of-the-art commercially used EMTP-type software on obtained overvoltage levels needs to be addressed and quantified first. A comparison of occurring transients subsequent to common faults is performed using two exemplary EMT-type software tools namely EMTP-RV [2] and PSCAD/EMTDC [3]. Therefore, the first task is to validate and benchmark both models used for this working group. A symmetrical monopolar MMC-HVDC link is set up in both EMT-type software tools considering identical system parameters, as stated in Table 2 and Figure 6. The implemented half-bridge submodule stacks are classified as a *Type 4* model according to [3] in the PSCAD/EMTDC and EMTP-RV.

A first benchmark between the two EMTP-RV is performed for a positive pole to ground fault at MMC 1 (Figure 6). The obtained transients are depicted in Figure 7. Apparently, there are some minor differences in the voltage curve, whereby the absolute peak value of the pole to ground voltage at the healthy (negative) pole as well as the rise time of the voltage are close (Figure 7 (b) and Figure 7 (d)). The pole to ground voltage at the faulted pole shows a damped oscillation due to reflections and negative pole discharge (Figure 7 (c)). Investigations have shown that the differences in the obtained voltage oscillations at the faulted pole are mainly due to different damping properties of the underlying cable representation in EMTP-RV and PSCAD. Nevertheless, differences in modeling of ideal branches, e.g. very low impedance faults, as well as representation of power electronic devices in both EMT-type software tools can also have impact on these discrepancies.

A second benchmark is given in Figure 8 for a phase to ground fault at the transformer of MMC 1 (converter side). The pole to ground voltage at the DC side shows the typical characteristic due to the converter operating as a diode rectifier after submodule blocking. Again, it can be observed that almost similar system behaviour in both EMT-type software tools does occur.

Even though slight differences exist between the results obtained using EMTP-RV and PSCAD/EMTDC models, the general system behavior and overvoltage levels are in a good

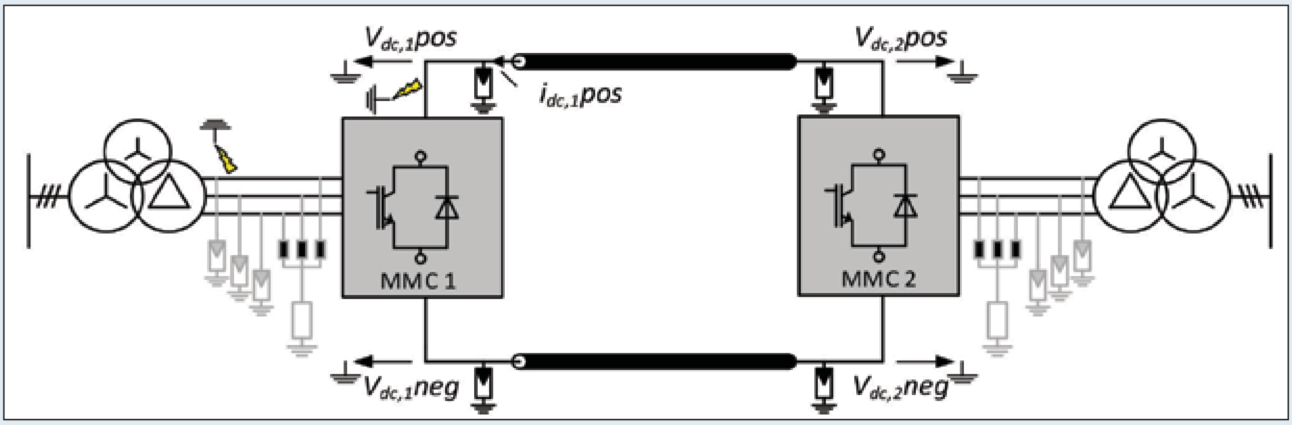

Figure 6: Schematic overview of investigated monopolar MMC-HVDC link including relevant quantities as well as fault positions.

agreement. Therefore, it is concluded to consider the achieved accuracy as sufficient and to proceed with a detailed parametric sensitivity study to deal with varying converter design parameters as well as different transmission system configurations.

Parametric Sensitivity

To address the impact of project specific parameters such as cable length and AC short circuit level on overvoltage shapes, a brief parametric sensitivity study is shown within this section.

First, the cable length is varied between 200 km and 50 km. Presented results within this section are performed using EMTP-RV. However similar results are expected with the PSCAD/EMTDC model. The system behaviour after a phase to ground fault at the converter transformer (Figure 6) and after a pole to ground fault at the DC side of MMC1, this time on the negative pole, including two different cable lengths, are depicted in Figure 9. The red curves are for a HVDC system with a cable length of 200 km while the blue dotted curves are with a cable length of 50 km. It can be seen in Figure 9 (a), that for the phase to ground fault at the converter transformer, the rise time of positive pole to ground voltage, as well as the voltage level after current interruption through AC circuit breaker, is of major difference for the different cable lengths. Similar variation can be also observed for a negative pole to ground fault, see Figure 9 (b) and (c).

As another example in a parameter sensitivity analysis, the short-circuit level (SCL) of the AC network has been varied. Overvoltage results for both faults of Figure 6, i.e. one phase to ground fault on the converter transformer and one pole to ground faults, negative pole, with the variation of the SCL are depicted in Figure 10. For this specific test case, it can be noticed in Figure 10 (a) that for a one-phase-to-ground fault at the converter transformer, the varying SCL has an impact on the overvoltage shape. However, for the negative pole to ground fault, Figure 10 (b), the impact of the SCL variation on the occurring overvoltage (on the healthy pole) is minor.

It should be noted that these results are based on the generic HVDC-MMC model of the working groups [1]. Therefore, depending on the circuit configuration, the wave shape of these overvoltages can differ and it remains the task of the JWG to agree on the most severe type relevant for the cable performance.

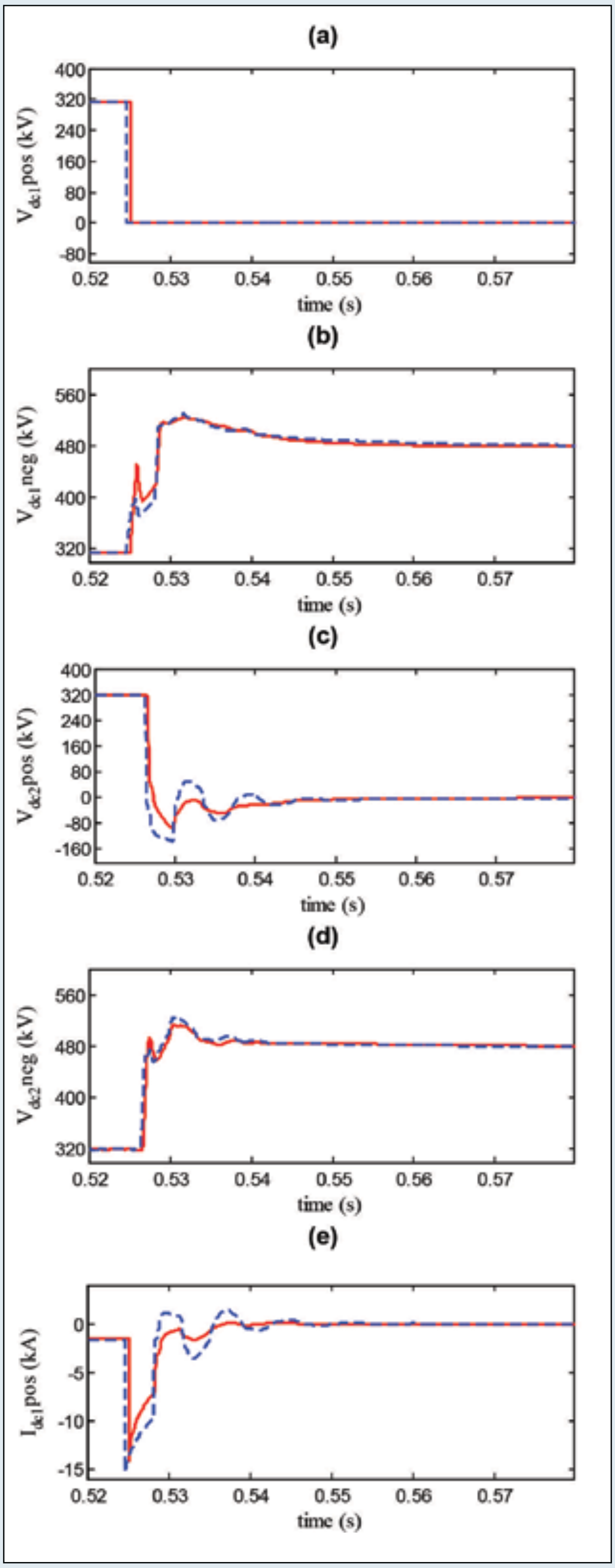

Figure 7: Selected transients subsequent to a positive pole to ground fault at MMC 1 obtained using EMTDC (blue) and EMTP (red) software.

Summary and outlook

In this paper we presented a status summary of ongoing work in Cigré JWG B4/B1/C4.73. We summarized today's practice and elaborated on the limited guidance of today's testing recommendations for temporary overvoltages of HVDC cable systems. By evaluating data based on installed and to be installed projects, we prioritized VSC systems with

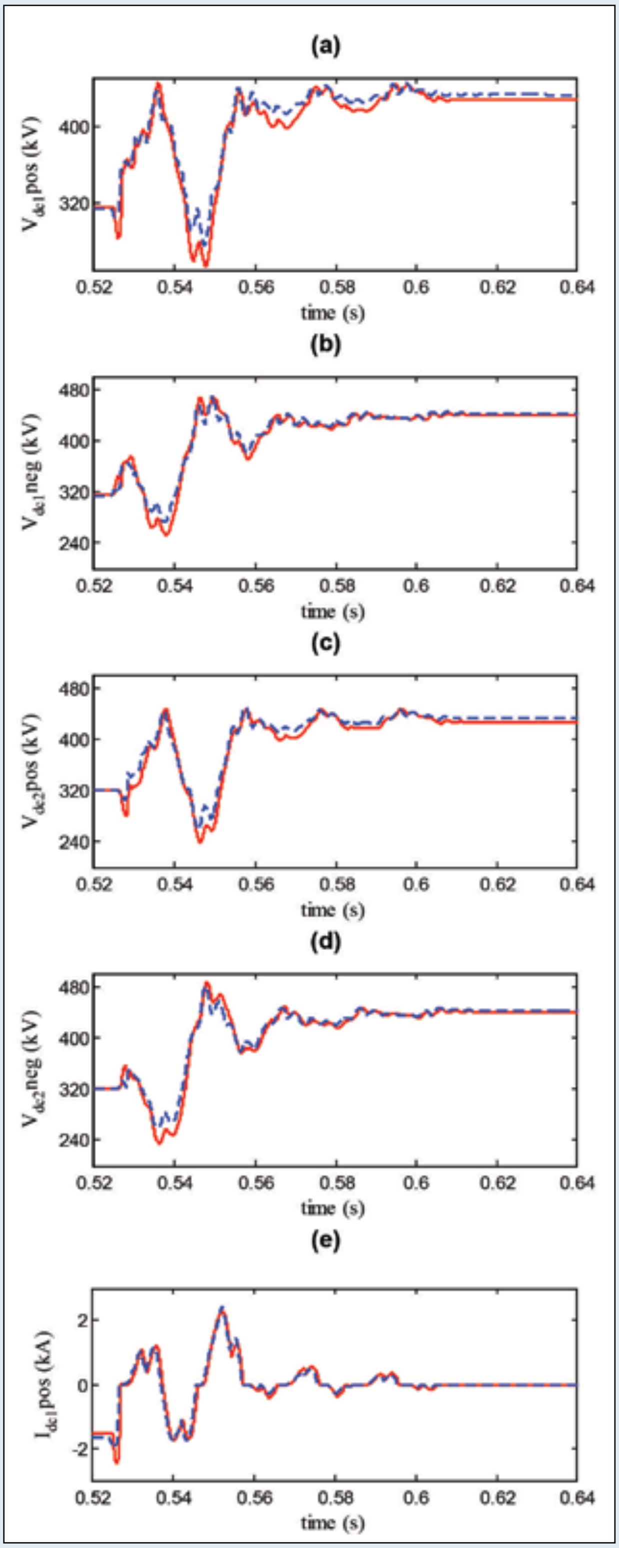

Figure 8: Selected transients subsequent to a phase a to ground fault at the converter transformer of MMC 1 obtained using EMTDC (blue) and EMTP (red) software.

XLPE and MI cable technology in symmetric monopole configurations for intermediate power levels up to todays 320 kV voltage level. For the highest power however the focus is shifted towards bipolar topologies. Moreover we compared EMT-type software tools to be used as a fundamental part for reaching conclusions in the JWG. A demonstration of a temporary overvoltage on the 320 kV on symmetric monopole configuration was presented and parameter evaluation was exemplified. No conclusions on worst case scenarios or severity on temporary overvoltages are to be made yet as these are ongoing discussions in the JWG. The further objective of the JWG should then go beyond the simulative evaluation approach and also give a guidance whether extended testing of HVDC cable systems is recommended, i.e. the response of the cables insulation system should also be considered. Based on necessity and if possible first direction of testing schemes shall be mentioned.

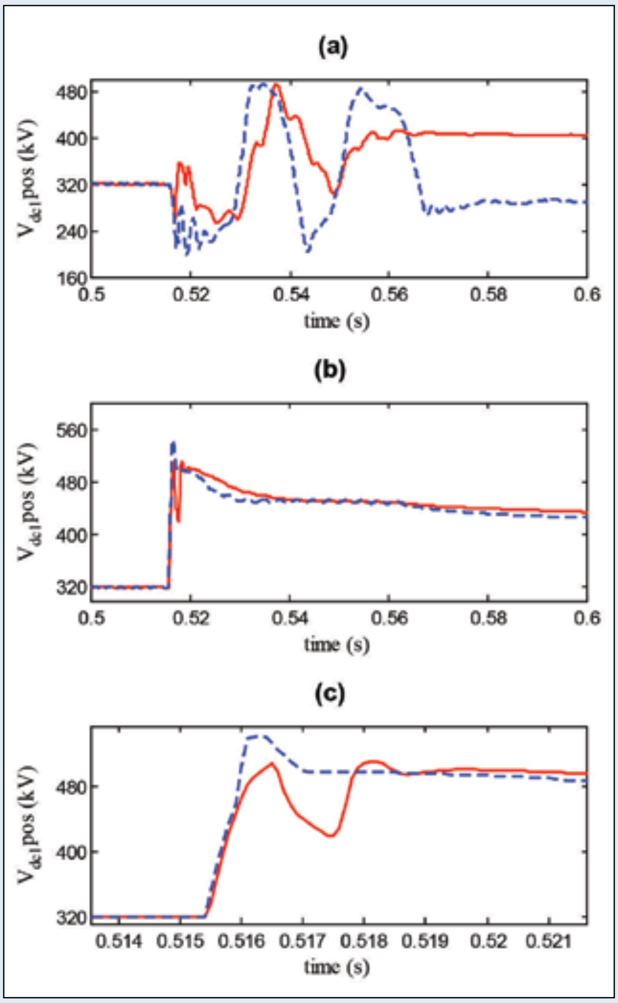

Figure 9: Sensitivity with respect to two cable lengths (red=200 km, blue=50 km) in EMTP on voltage transients subsequent to: (a) one-phase to ground fault at the converter transformer of MMC 1, (b) negative pole to ground fault at MMC 1, (c) zoomed waveform of negative pole to ground fault at MMC 1.

Moreover, it is a task of the JWG to evaluate mixed OHL-cable systems and recommend an approach for determining LI testing levels based on project specific paramters.

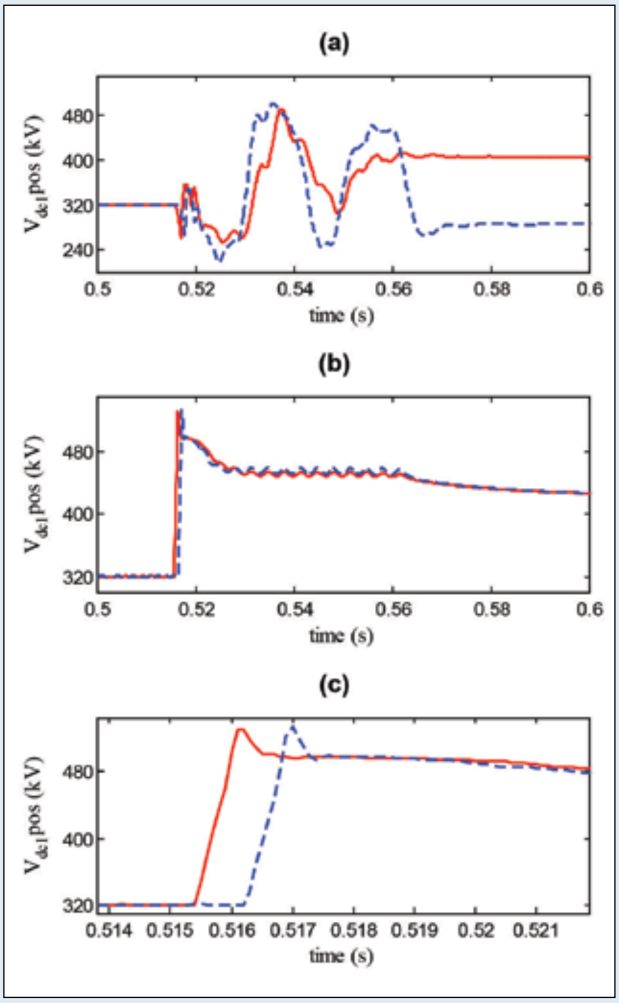

Figure 10: Sensitivity with respect to two AC short circuit levels, red=3 GVA, and blue= 50 GVA, on the overvoltage transients subsequent to: (a) phase to ground fault at the converter transformer of MMC 1, (b) negative pole to ground fault at MMC 1, (c) zoomed waveform of pole to ground fault at MMC 1.

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Reliability on existing HVDC links feedback

Patrik Lindblad; ENTSO-E Task Force HVDC Reliability, (Finland), patrik.lindblad@fingrid.fi

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 according to CIGRE and 4.4 according to the Nordic statistics. Only 49% of all reported links have experienced less than 5 forced outages/year. Even if outliers like the three worst cases per year is removed from the 10-year Cigré statistics, the number of trips were 4.9 in average. 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. The average FEU level was as high as 2.6% according to Cigré statistics. Without the three worst cases per year, average FEU level was still 1.1%.

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 levels 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 October 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 trip/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 h outage (0.9/year). Most submarine cable faults are expected to be in this category.
- Worldwide ≈ 16 faults with 100-1000 h outage (1.6/year). This category is expected to include e.g. land cable faults.
- Worldwide 10...15 faults with 50-100 h outage (1-1.5/year). This category may include also cable faults.
- 60...70% of the faults are very short outages (< 8 h). 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 was 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 fault/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 sea cable fault types and 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.

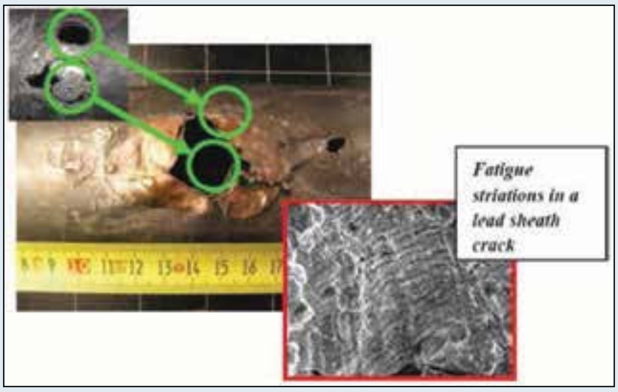

Figure 1: Internal failure of Fenno-Skan 1 MI-cable.

Cable crossings may be another challenge. They must be designed with care. EstLink 2 output power had to be limited to 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.

Figure 2: Crossing PPL-duct principle.

The lessons learned were:

• The fibre optic temperature measurement system may need calibration over a longer distance. There was an error:

Figure 3: Crossing PPL-duct of EstLink2.

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. 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.

Figure 4: Damage in joint failure of GRITA.

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.

Figure 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.

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.

Figure 6: Moisture damage in EstLink 2 joint failure.

- 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 February 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 restart 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.

Figure 7 : Flashover marks on cable end termination.

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 leads 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 faulty 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

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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

Asset management of submarine cables and lessons learned from a repair

JEAN CHARVET, RTE (FRANCE), JEAN.CHARVET@RTE-FRANCE.COM

ABSTRACT *Provided that submarine cable are correctly designed and installed, failures are rare but do happen on some occasions. Consequent repairs can be very costly and cause long unavailabilities. This article aims to identify the levers to improve reliability of submarine cable assets by limiting occurrence of failures and induced losses. Asset management policies including preventive maintenance, repair preparedness, and spare parts are described and discussed from a TSO perspective. Finally, lessons learned are shared from repairs managed by RTE on HVDC submarine cables of the IFA2000 interconnector (FR-UK) during the winter 2016-2017.*

KEYWORDS : Submarine cables, Service experience, Preventive Maintenance, Repair Preparedness, Offshore Repair, Spare parts.

Context

Service experience of HVDC submarine cables

CIGRE brochure TB379 – Update of service experience of HV underground and submarine cable systems, December 2009 – presents a failure rate for HVDC cables of approximately one failure per year per 1000 km of circuit, mostly caused from external damage.

However, this figure is to be taken with great care because it is based on rather old service experience between 1990 and 2005, while in the past ten years, a lot of improvements has been achieved in marine engineering and routing, cable design, installation, protection and preventive maintenance.

TB379 is currently being updated by CIGRE Working Group B1.57 with more recent data but results will not be published before end of 2018.

In the meantime, RTE carried out a similar survey on the following sample:

- HVDC submarine links in Europe, ranging from 250 kV to 500 kV;
- Service experience from 2006 to 2016;
- Failures known from public sources, counted per circuit (one failure may affect one or two cables) and after commissioning.

Results of this survey is that for MI insulation technology, there is an average of **less than one failure per year per 3000 km of circuit**, while no failure has been reported for XLPE technology (so far on a very limited sample).

Even if those figures seems reassuring (a trend of decreasing failure rates), it is worth mentioning that HVDC submarine links are being built on increasingly long length, and thus can be more vulnerable to faults.

Unavailability and cost of repair

Submarine cables generally don't need any planned unavailability, but can suffer from unplanned availabilities due to faults or the need for remedial protection works.

Even with low failure rates, the fact that HVDC submarine cable failures takes a long time to repair can lead to significant impact on interconnector business models and security of electricity supply.

For a single fault, two to three months is a typical time to be considered for repair, excluding hazards, while cost of repair and losses of revenue can be in the order of tens of million euros.

For a long interconnector of 500 km for instance, supposing a failure rate of one failure per year per 3000 km would mean that, as an average, 2 to 3 months unavailability can be expected on a 6 years period. This corresponds to an average of 3 to 4% of the time which is significant to impact profitability of the interconnector.

IFA 2000 experience

On 20th of November 2016, four out of eight cables of the IFA2000 interconnector failed offshore, leading to 1000 MW lost capacity. After consequent mobilization of resources to perform repair as quickly as possible, the interconnector recovered 500 MW capacity (two first cables repaired) on 17th of February 2017 and it was fully operational (repair of the two remaining cables) on the 2nd of March 2017.

Lesson learned:

> It took slightly more than three months in total to repair four cable damages,

> Considering the extent of works, this good performance was made possible by hiring two repair vessels and two jointing teams working in parallel.

Design measures

Fault causes and preventive design measures

Risk mitigation regarding fault occurrence and induced losses starts from the design phase of submarine links.

Type of faults and design measures to prevent them are described below.

External faults may be caused either by human activities, natural phenomena or a combination of those:
- Seabed movements linked to seismic activity or currents and waves;
- Abrasion or fatigue on non-buried cables and free spans,
- Impact or hook by anchors, fishing gears;
- Damage caused by works in the seabed (dredging, cable or pipeline laying, extraction of aggregate);
- Falling objects, shipwreck;
- Ordnance explosion in the vicinity.

To prevent external faults, the cable route and the level of protection shall be carefully designed depending on the above mentioned risks.

> ***IFA2000 experience***
>
> Since it has been commissioned in 1986, the submarine part of the interconnector has experienced two simultaneous external faults in 2016, affecting four cables, presumably caused by anchors although cables were well buried at approx. 1.5 m in relatively stiff soil, 5 km away from English coast and relatively far from shipping lanes.
>
> **Lessons learned:**
>
> \> Emergency anchoring is probably more likely to happen in nearshore areas and not inside a shipping lane.

Figure 1: IFA 2000 cable damage.

Internal faults may be caused by:
- Error or defect during manufacturing or assembly of joints and termination;
- Mechanical design parameters exceeded during transport, storage or installation;
- Bad thermal environment leading to exceed temperature design values;
- Overvoltage or overloads above design values.

To prevent internal faults, it is consequently recommended to select properly tested materials, have a robust inspection and test plan during every step from design, manufacturing and installation of submarine cables, have a robust thermal design based on on-site measurements, and put in place proper protections against overvoltage and overloads.

> ***IFA2000 experience***
>
> Since it has been commissioned in 1986, the submarine part of the interconnector has experienced one internal fault in 2003, affecting one cable, caused by mishandling during installation which created a weak point.
>
> **Lesson learned:**
>
> \> Not all defects can be detected during commissioning tests, neither warranty period, which means that controls during all steps from cable design to cable installation are crucial.

Maintenance friendly designs

In order to allow an effective preventive maintenance and a quick repair the following key points must be considered:
- Integration of FO unit inside power cables, or alternatively bundled, is beneficial to allow FO based cable monitoring and fault location;
- Cable must be easily accessible in case a repair is needed : this may be contradictory to preventive protection measures against external threats and should be carefully balanced;
- Limiting the number of different cable designs and accessories or making sure they are compatible between each other in order to rationalise spare parts storage.

Preventive maintenance

The purpose of preventive maintenance policies is to decrease the probability of failure.

Cable awareness

It is obvious that precise cable position shall be reported on every relevant marine charts.

It is also recommended to work with fishermen to define good practices when they work in the vicinity of the cables.

Moreover, it is also possible to monitor vessels positions and movements in the vicinity of cable routes using real time AIS[1] data. A detected risk situation can then lead to contact the vessel captain or marine authorities in order to prevent unauthorized activities in the vicinity of the cable.

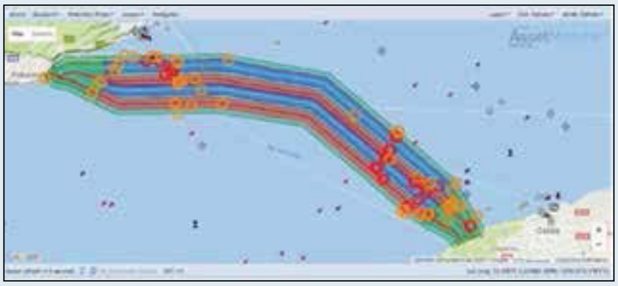

Figure 2: AIS monitoring on IFA2000.

Cable monitoring

Standard practice for newly built HVDC links is to monitor temperature along the link by implementing DTS systems. Development of local hotspots could indicate an internal defect or an unfavourable thermal environment, while local "cold spots" could reveal deburial.

It is also recommended to install DAS systems that could help locating deburials or external aggressions but experience is still very limited and signals are not easy to interpret. Partial discharge measurement are also sometimes considered but its interpretation can also be tricky.

Those systems have a limited range and only a part of the submarine link may be monitored for long interconnectors, although technology is constantly improving.

In order to ensure the efficiency of FO based systems, best practice is that FO units are either bundled, or directly integrated to each power cable. This sometimes lead to install an extra FO unit when a pair of power cable is unbundled (which is often the case at landfalls).

The way of interpreting data from those monitoring systems can vary from regular checks with analysis reports to continuous check with pre-defined levels of alarm. A learning phase in the first month or years of operation may be necessary to fine tune the interpretation of monitoring data.

In case an anomaly occurs and depending on its severity, it may be decided to launch surveys and/or remedial works.

[1] AIS: Automatic Identification System, système d'échanges automatisés de messages entre navires par radio VHF qui permet aux navires et aux systèmes de surveillance de trafic de connaître l'identité, le statut, la position et la route des navires se situant dans la zone de navigation (NDLR).

Geophysical marine surveys

Minimum frequency and extent of surveys are often part of regulatory or insurance obligations, which can vary depending on the asset.

The data to collect which are project specific generally include multi-beam bathymetry and sometimes side-scan sonar, measurement of cable position and burial depth, environmental monitoring, etc..

Because marine survey operations on long links are very costly activities, the best practice is to adapt the frequency and the extent of planned surveys depending on risks, notably seabed mobility and external threats (anchors, fishing).

Moreover, unplanned surveys may be decided upon occurrence of extreme meteorological event or anomaly detected on monitoring systems.

Great care shall be taken on format of GIS data, in order to be able to compare each survey data from the previous surveys, and make the data usable for potential future works on or next to the link.

Repair preparedness

The purpose of repair preparedness is to reduce the time for a repair, and thus the induced losses.

Organisation and emergency contingency plans

Elaborating and maintaining an up-to-date emergency contingency plan for each submarine link is a key point for a quick response after a fault.

IFA2000 experience

Immediately after fault happened in November 2016, and based on its experience of emergency situation, RTE put in place an operational project team involving local personnel from project management and maintenance departments, relying on the support from internal cable expertise and offshore project departments, procurement and legal departments and outsourced marine and legal experts.

Lessons learned:

> Having RTE qualified personnel on board of repair vessels allowed to handle interfaces between different contractors on board, which were sometimes critical and it surely has saved time and participated to quality and safety;

> Experience from repairs is valuable to improve contingency plans.

Such a plan would typically include
- Description of internal organisation to put in place including human resources, role and responsibilities, decision making;
- Repair procedures for different plausible fault scenarios;
- List of relevant contacts and providers;
- Interface management;
- Safety, Environment and Regulatory requirements.

Periodic revision of contingency plans shall be performed and it is also recommended to perform regular crisis exercises.

Fault location

Fault location is on the critical path of a repair. It is generally performed in two steps:
- Pre-location from land using TDR based methods on the power cables,
- Pin-pointing using magnetic field or acoustic measurements at sea, and/or with fibre optic when available.

Reliability and reactivity of those operations is of paramount importance and thus it is recommended either to have an internal expertise or frame agreement with a specialised provider.

IFA2000 experience

In November 2016, pre-localization and pin-pointing of faults on the four cables with 50 m accuracy were completed within 9 days after faults occurrence, and later double-confirmed by surveys showing anchor scars on the seabed.

RTE has an internal expertise in fault pre-location (TDR based systems) and owns specific offshore pin-pointing fault location equipment (magnetic field based) developed internally and patented.

Lesson learned:

> Having internally the equipment ready for mobilisation together with regularly trained maintenance teams proved to be very efficient.

Figure 3: Offshore pin-pointing equipment.

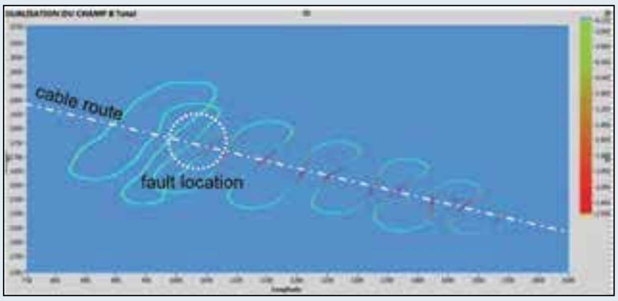

Figure 4: Pin-pointing based on magnetic field measurements.

Marine operations

Mobilization of an adapted marine spread to allow the repair needs to be done as soon as possible after fault location is confirmed.

In addition to vessels that are necessary for fault location and surveys, type of marine vessels to mobilize depends mainly on water depth, and are generally:
- Jack-up barges and tugs for repairs at landfalls
- Anchored barges and tugs for repairs in shallow waters < 15 m WD
- DSV or DP vessels for repairs in deep water > 15 m WD

Because it is very costly to keep in standby all those type of potentially necessary vessels for repairs, it is general practice, upon a failure, to hire vessels that are available on the market, through a specialized broker for example.

Moreover, repair operations need specific equipment to be installed onboard which can vary depending on the situation. Some of the critical equipment which can be project specific are listed below.
- Tools for deburial and re-burial, mainly depending on the type of soil and cable diameter
- Turntable or basket, mainly depending on cable coilability, length and weight of spare and cable MBR
- Cable chute and quadrant, mainly depending on cable MBR

Figure 5: one of the vessels hired for IFA2000 cable repairs, at mobilization site.

• Tensioner, mainly depending on cable weight and water depth

Having pre-contractual arrangements or frame agreement for mobilization of marine spread, personnel and equipment with a specialized contractor is a common practice in order to save time for negotiations and engineering after occurrence of a fault.

IFA2000 experience

RTE and National Grid Interconnector Ltd share a frame agreement for mobilization of marine spread.

Considering that failures happened on two distinct locations for each pair of cables, it has been decided to work as much as possible in parallel in order to save time.

Two repair vessels and one support vessel were hired within one month and ready before the jointer teams. The support vessel was dedicated to prepare cables (cable cuts, deburials, expertise of damages, checks and tests on cables, sealing ends) while the two others were dedicated to jointing operations.

Lessons learned:

> Having a frame agreement made possible to hire and mobilize a consequent fleet within a short time.

Jointing operations

Know-how of specialized jointing teams is a key point for a successful and reliable repair, especially in very high voltage ranges.

IFA2000 experience

Because of the extent of the repairs to be done and limited availabilities of jointing teams, RTE contracted those operations to 2 different suppliers who were both competent to perform the cable jointing operations on the RTE IFA2000 submarine cables (MI technology), but still needed rehearsal on a piece of spare cable before going offshore.

Those operations appeared to be on the critical path of the repair, as marine spread was ready before jointing teams.

Lessons learned:

> Having the possibility to install compatible joint from a different supplier than the original cable was beneficial and saved time.

Spare parts storage

The purpose of spare part storage is to make sure that reliable spare materials of the cable system is immediately available in case a repair is needed without waiting for remanufacturing.

Quantity of spares is project specific and mainly depends on:
• Risks and failures scenarios to cover;
• Water depth;
• Presence of areas where jointing will have to be avoided (for e.g. HDD and possibly rock berms);
• Lead times and minimum quantities to refill the stock after it is used;
• Hazards to consider.

Storage site is usually:
• Nearby a quay in a port with direct and permanent access to sea;
• In a controlled and secure area, aired and protected from UV and rain.

IFA2000 experience

Tests confirmed that spare cable that was stored for more than thirty years in cable tanks were still in good condition.

Two cable joints from the spare parts have been used for training of jointers, prior to perform the offshore repairs.

Lesson learned:

> Regular inventory and maintenance on the spare parts is valuable.

Conclusion

Lessons learned from submarine cable repair experience makes possible to improve asset management policies.

Sharing of service experience and collaboration for more standardization of repair solutions must be encouraged.

Glossary

AIS: Automatic Identification System
DAS: Distributed temperature Sensing
DTS: Distributed Acoustic Sensing
DP: Dynamic Positioning
DSV: Diving Support Vessel
FO: Fibre Optic
GIS: Geographic Information Systems
MBR: Minimum Bending Radius
MI: Mass Impregnated
TDR: Time-Domain Reflectometry
XLPE: Crossed-linked Polyethylene Close and Return

Fault Location on Land and Submarine Links (AC & DC)

Robert Donaghy; ESB International (Ireland) robert.donaghy@esbi.ie

ABSTRACT *The increasing number of land and submarine cable assets globally has created a focus on cable fault location capabilities. All faults in cable systems are different and cable fault location depends to a great extent on applying the appropriate technique or combination of techniques. The methods for locating power cable faults require competent engineers and service providers. Guidance is therefore required for engineers on the correct application of the various techniques available. This paper outlines the work that is being undertaken by CIGRE Working Group B1.52 on the topic of Fault Location on Land and Submarine Links (AC & DC).*

KEYWORDS : Fault Location, Submarine Cable, Underground Cable.

Introduction

In 2014, CIGRE SC B1 established WG B1.52 to develop a Technical Brochure on "Fault Location on Land and Submarine Links (AC & DC)".

The terms of reference for the working group are as follows:

- To cover fault location on the following installed cable types: MV/HV/EHV; AC/DC; land and submarine cable systems; single core, 3-core and pipe type cables.
- Focus on main insulation & sheath faults
- Provide overview of existing fault location techniques and underlying principles
- For land and submarine cable systems, provide guidance and strategies for effective fault location for a variety of installation types including but not limited to:
  - Direct buried cable systems
  - Ducted land cable systems
  - Cables between GIS bays
  - Cables installed in horizontal directional drills and tunnels
  - Cables at large burial depths
  - Cable systems with different bonding types
  - Very long cables
- Examine the different methods of pre-location and pinpointing from an accuracy and suitability viewpoint
- Prepare a flowchart to assist in selecting appropriate methods according to fault type and cable type
- Design factors (cable design and installation method) affecting fault location capability
- Safety considerations
- Marine vessel and support requirements for finding submarine cable faults
- Collect case studies of fault location experiences
- Training requirements for fault location personnel
- Assess applicability of on-line methods to support fault location
- Review new and innovative fault location techniques & future developments

The brochure should not cover:

- Leak location in fluid filled cables
- Gas leak location on gas compression cables
- Diagnostic testing
- Defects in cathodic protection systems

For leak location in fluid filled cables, refer to CIGRE TB 652 by CIGRE Working Group B1.37 [1].

Fault location steps

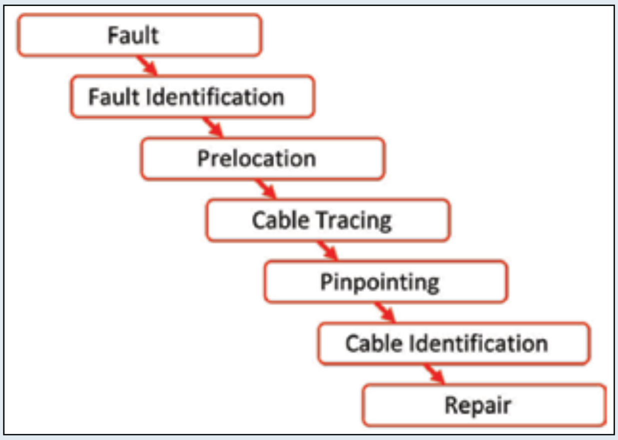

Figure 1: Fault Location Steps.

Fault types

Open Circuit Fault

Also known as a series fault or conductor continuity fault, the current path is broken resulting in the current being completely or partly hindered. They are generally uncommon in submarine cables and land cables. Some open circuit faults have been reported in submarine cables cut by anchors and underground cables in earthquakes where joints connectors are pulled apart.

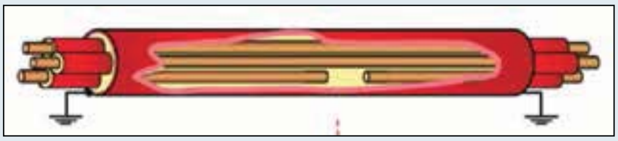

Figure 2: Open Circuit Fault.

Shunt Fault

Also known as insulation fault or short circuit fault, two or more main conductors come into contact with each other or with earth. Intermittent shunt faults are nonlinear voltage dependent faults with high resistance until the insulation breaks down. During arcing, they are low resistance.

In XLPE land cables, faults are often high resistance or intermittent. In submarine cables, the arc often penetrates all watertight layers resulting in sea water ingress, resulting in low fault resistance, making the fault a persistent shunt fault.

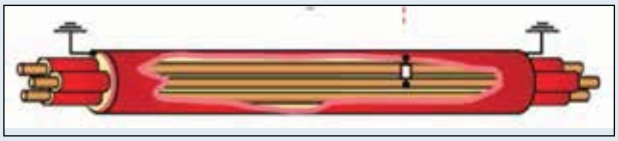

Figure 3: Shunt Fault.

Sheath Fault

In cable oversheath & metallic sheath, damage usually opens a current path from the metallic sheath to earth due to water ingress. It often causes metallic sheath corrosion, leading to further damage in the metallic sheath or eventually in the main insulation. Sheath faults can be low or high resistance.

Figure 4: Sheath Fault.

Cable fault location techniques

Prelocation

Prelocation involves testing the circuit from the cable terminations to estimate distance to the fault. It can determine the fault position to within a few percent of the cable length. On very long cables, the margin of error can be significant. Sometimes the fault has to be conditioned to make it detectable e.g. burned to a low resistance fault.

The main prelocation techniques considered are:

- Time Domain Reflectometry (TDR)
- Burn Down Techniques
- Arc Reflection Methods (ARM/SIM/MIM)
- Decay Method and Differential Decay Method
- Impulse Current Method (including Comparison and Differential Modes)
- Frequency Domain Reflectometry
- Bridge Methods

Pinpointing

Pinpointing is a test to confirm the exact position of the cable fault following prelocation. It is carried out directly over the cable.

The main pinpointing techniques considered are:

- Acoustic Method
- Step Voltage Method
- Magnetic Field Methods
  - Impulse magnetometry (primary faults)
  - DC magnetometry (sheath faults)
  - Audio frequency methods
- Sectionalising Methods

Guidelines and examples of the application of these prelocation and pinpointing techniques are provided in the technical brochure.

Design factors affecting fault location

Fault location capability is not always a primary concern in system design. Some effective actions can be taken at the design and project implementation stage to enhance fault location capability including:

- Ensure that a good set of as laid records and cable system information is compiled. This information must be properly stored and readily available to fault location personnel.
- Use link boxes at joints and terminations to enable the circuit to be split into sections to narrow down the fault and to give additional access points to conductor or screen. Ensure link boxes are readily accessible.
- Avoid using cables without an outer semiconducting or graphite sheath as detecting and locating faults requires current flow from the metallic screen or sheath through the fault to earth.
- In the case of hybrid circuits, provide a means of disconnecting cable from the overhead line.
- Some installation types pose particular challenges for fault location:
  - Cables terminated into GIS at both ends
  - Cables in ducts
  - Cables in tunnels

Emergency planning

Attention given to emergency planning aspects of fault location will enable a more efficient fault location campaign to be undertaken, particularly in the case of offshore submarine cable faults. The brochure identifies the key elements of emergency planning which operators should consider in advance of any fault occurring:

- Cable System Records
- Permits
- Preparatory works
- Marine logistics
- Cooperation arrangements if there are different TSO's involved
- Aspects of Repair Preparedness Plans relevant to fault location
- Fault Location Manual:
  - Safety procedures and risk analyses to be performed prior to fault location
  - Steps to follow for fault location (flowchart)
  - Chronological overview of tests and measurements to be performed in different scenarios
  - Testing and measuring equipment needed for fault location which is adapted to the characteristics of the cable connection

Political and legal aspects can have the potential to interfere with fault location activities, but it is vital for successful fault location that that fault location is carried out methodically in an evidence-based and forensic manner.

Innovation and future developments

The brochure describes some of the innovative methods which are currently emerging and being developed within the industry. These methods are covered under three categories:

1. Fibre Optic Fault Location Methods
- Distributed Temperature Sensing (DTS)
- Distributed Acoustic Sensing (DAS)
- Distributed Vibration Sensing (DVS)
- Brillouin Strain Measurements

2. Electrical/ Conventional Fault Location Methods
- Partial Discharge Measurements
- Advances in conventional fault location Methods
- Online Fault Location Methods

3. Submarine Pinpointing Techniques Using ROVs
- Visual, tone tracing, step voltage method, use of hydrophones
- Submersible habitat technique
- Multibeam equipment

Fibre optic cables enable a wider range of fault pinpointing methods to be applied including Distributed Temperature Sensing, Distributed Vibration Sensing and Distributed Acoustic Sensing through the application of Raman and Brillouin spectroscopy. In Raman spectroscopy, the scattered magnitude is temperature dependent; In Brillouin spectroscopy, the Brillouin shift is temperature and strain sensitive.

The fibre optic cable can be installed externally, directly attached to the cable, or contained in a separate duct. For best fault location results, the fibre optic cable should be installed as close as possible to power cable core. An example of an integrated fibre optic cable is shown in Figure 5.

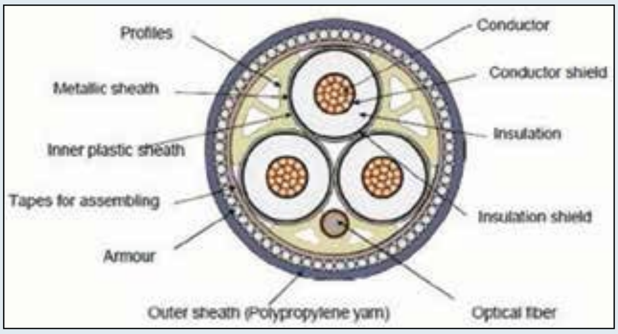

Figure 5: 3-core cable with integrated fibre optic.

Some failures of submarine cables with embedded fibre optic cables have been reported, so particular attention should be paid to the integrity of the overall cable design in such cases.

Distributed Temperature Sensing (DTS)

With DTS, the fibre acts as a linear sensor to detect hot spots along the cable with high accuracy over long distance. The accuracy of DTS is independent of the laying depth, it is insensitive to electromagnetic interference and can be used from the shore.

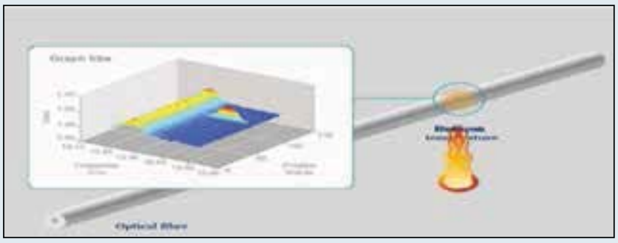

Figure 6: Distributed Temperature Sensing.

Distributed Acoustic Sensing (DAS)

Thumping high resistive faults with surge generator creates vibration at the fault. Localised vibrations are captured on the DAS interrogator (onshore) and compared with the initial surge vibration detected at the fault location.

DAS can be undertaken by laying a temporary external fibre optic cable adjacent to cable near the fault. Single mode fibre is generally preferred for DAS applications.

Distributed Vibration Sensing (DVS)

With DVS, the single mode fibre optic cable acts as vibration sensor. A disturbance on the fibre generates a microscopic elongation or compression of the fibre which causes a change in the phase relation.

If there is no integrated FO element, DVS can be undertaken by laying external fibre adjacent to the cable.

Safety considerations

The highest priority should be set for the safety of the fault finding personnel. Fault location should be performed according to the relevant national, international and company safety regulations. Personnel performing fault location shall have appropriate training and authorisation to carry out the works.

Before the execution of cable fault location, it is recommended that a risk assessment is carried out and method statements for the fault location techniques are prepared. Some particular risks apply in fault location, for example:

Particular Risks in Fault Location:

- Maximum allowed test parameters and test voltages
- Stored energy in long and extra-long cables
- Return voltage in DC cable systems
- Induced and impressed voltages
- Impulse voltages
- Touch and step voltages
- Re-energizing the cable

Training considerations

Training requirements for working in the high voltage environment are registered in international standards national regulations for electrical operations and company standards. It may also occur that fault location must be performed on industrial plants or other specific areas each with their own specific training and certificates requirements depending on the circumstances. Some examples of general training requirements are listed below.

- General training
  - Electrical safety training
  - Basic safety training
  - Working at height
  - First aid training
  - Fire awareness training
  - Offshore training requirements where necessary
- Specific training
  - Safety rules
  - Understanding fault types and fault behaviour
  - Connection methods
  - Understanding the various pre-location and pinpointing methods
  - Equipment specific training

Accuracy and suitability of prelocation methods

The suitability of the prelocation and pinpointing methods are described in Tables 1 and 2 respectively. The colour codes indicates the suitability.

	Fault Type				
Method	Low Resistance	High Resistance	Open Circuit	Intermittent	Sheath Fault
TDR	Land & Submarine 1-3 % accuracy Fingerprint reference helpful Limitations for X bonded & screen interrupted systems	Fault Burning Required	Land & Submarine 1-3 % accuracy Fingerprint reference helpful limitations for X bonded & screen interrupted systems	Fault Burning Required	
Arc Reflection Methods	No need as TDR will work	Land & Submarine 1-3 % accuracy Length limited limitations for submarine cables (water ingress). Limitations for X bonded & screen interrupted systems	No need as TDR will work	Land & Submarine 1-3 % accuracy Length limited limitations for submarine cables (water ingress). Limitations for X bonded & screen interrupted systems	
Decay	No need as TDR will work	Cable cannot be charged to a DC voltage due to low resistance fault.	No need as TDR will work	Land & Submarine 1-10 % accuracy Propagation velocity unknown, no reference points available. Limitations for X bonded & screen interrupted systems	
Differential	No need as TDR will work	Land & Submarine 1-3 % accuracy Access to ref. conductor required	No need as TDR will work	Land & Submarine 1-3 % accuracy Access to ref. conductor required	

Impulse Current	No need if TDR works	Land & Submarine 5-10 % accuracy Limited by breakdown voltage & distance to fault. Limitations for X bonded & screen interrupted systems	No need as TDR will work	Land & Submarine 5-10 % accuracy Limited by breakdown voltage & distance to fault. Limitations for X bonded & screen interrupted systems	
Bridge Methods	Land & Submarine ~ 1 % accuracy Need 1 healthy return conductor	Land & Submarine ~ 1 % accuracy Up to few MW fault resistance, Need 1 healthy return conductor			Land ~ 1 % accuracy Need 1 healthy return conductor
Voltage Drop	Land & Submarine ~ 1 % accuracy Need 1 healthy return conductor	Land & Submarine ~ 1 % accuracy Up to few MW fault resistance, Need 1 healthy return conductor			Land ~ 1 % accuracy Need 1 healthy return conductor
Fibre Optic Methods	Land & Submarine 1-3 % accuracy Vibration from fault spot or magnetic force along route needed	Land & Submarine 1-3 % accuracy DAS & DTS	Land & Submarine 1-3 % accuracy Already OTDR will work	Land & Submarine 1-3 % accuracy Sound/heat needed at fault	Land & Submarine 1-3 % accuracy Vibration from fault spot needed

Table 1: Accuracy and Suitability of Prelocation Methods.

applicable not applicable possibly

	Fault Type				
Method	**Low Resistance**	**High Resistance**	**Open Circuit**	**Intermittent**	**Sheath Fault**
Acoustic	Land & Submarine Limited application. A solid short circuit will not create noise. Can be used for submarine faults with water ingress	Land & Submarine 1-3 m accuracy Not for cables in ducts	Land & Submarine 1-3 % accuracy Earthing of disconnected sections needed Cables in ducts	Land & Submarine 1-3 m accuracy Not for cables in ducts	
Step Voltage	Land 1-3 m accuracy Fault needs soil contact Not for cables in ducts	Land 1-3 m accuracy Fault needs soil contact Not for cables in ducts	Land 1-3 m accuracy Fault needs soil contact Not for cables in ducts	Land 1-3 m accuracy Fault needs soil contact Not for cables in ducts	Land 0.1 m accuracy Fault needs soil contact Not for cables in ducts Galvanic contact of neutral conductor to grounding systems
Audio Frequency	Land & Submarine Land: 1-3 % accuracy Submarine: 10m - several hundred meters accuracy		Land & Submarine Land: 1-3 % accuracy Submarine: 10m - several hundred meters accuracy		Land Audio frequency measurement with capacitive probes Step voltage usually preferred
Fibre Optic Methods	Land & Submarine 1-3 % accuracy Vibration from fault spot or magnetic force along cable route needed	Land & Submarine 3-5m accuracy Up to few M ohms fault resistance, Need at least one healthy return conductor	3-5m accuracy	3-5m accuracy Sound or heat production in fault spot needed	Land 1-3 % accuracy Vibration from fault spot needed

Table 2 – Accuracy and Suitability of Pinpointing Methods

applicable not applicable possibly

CONCLUSIONS

This paper has outlined the work that is being undertaken by CIGRE Working Group B1.52 on the topic of Fault Location on Land and Submarine Links (AC & DC). There are many well established techniques available for fault location in cables particularly for buried underground cables. Guidance is provided on the application of different techniques in various scenarios. New and innovative techniques are also being developed which increase the toolkit for fault location.

Many of these techniques use fibre optic cables integrated or in close proximity to the power cable. Appropriate safety measures should be put in place for fault location activities and fault location personnel must be competent and adequately trained for the work being undertaken.

The technical brochure for Working Group B1.52 will be published in 2018.

Acknowledgments

The contribution of the members of CIGRE Working Group B1.52 is hereby acknowledged.

References

[1] CIGRE B1.37, Technical Brochure 652 "Guide for the Operation of SCFF Cable Systems"

Glossary

DAS: Distributed Acoustic Sensing
DTS: Distributed Temperature Sensing
DVS: Distributed Vibrations Sensing
FO: Fibre Optic
GIS: Gas Insulated Switchgear
ROV: Remotely Operated Vehicle
TDR: Time Domain Reflectometry