Design aspects on HVDC cable joints

Original
Design aspects on HVDC cable joints / Ye, H.; Han, Z.; Luo, Y.; Zhuang, Q.; Fechner, T.; Wang, H.; Lei, X.. - STAMPA. - (2018), pp. 300-304. (Intervento presentato al convegno 12th IEEE International Conference on the Properties and Applications of Dielectric Materials - Xi'an - China) [10.1109ICPADM.2018.8401269].

Publisher:
IEEE

Published
DOI:10.1109ICPADM.2018.8401269

Design Aspects on HVDC Cable Joints

[1]Hanyu Ye, [1]Zhengyi Han, [1]Yi Luo, [1]Qikai Zhuang, [1]Tobias Fechner, [2]Xi Lei
[1]Global Energy Interconnection Research Institute Europe GmbH
Markgrafenstr. 34, 10117 Berlin, Germany
[2]State Key Laboratory of Advanced Power Transmission Technology (Global Energy Interconnection Research Institute Co., Ltd)
No. 18 Binhe Avenue, Future Science Park, Changping District, Beijing, 102211, China

***Abstract* - Today's power utilities are evolving towards a more environment-friendly form. Particularly, in undersea power transmission, offshore renewable energy integration, and urban power transmission, HVDC cable systems play a significant role. As an essential part of the cable systems, cable joints are often the weakest and the most critical point. Hence, the safe operation of cable joints under different operational stages is one of the key issues to make the cable systems reliable. In this paper, the development of HVDC cable joints has been reviewed. The design aspects, including geometry, insulation materials, and interfaces are briefly discussed.**

I. INTRODUCTION

Recently, the demand for power increases dramatically in developing areas, and the energy supply transits towards low carbon and clean sources. Both increase the demand on the long-distance power transmission, the interconnection of asynchronous AC-grids and the integration of renewable energy in the main power networks [1][2][3]. Therefore, High-Voltage Direct Current (HVDC) power transmission becomes more and more competitive compared to High-Voltage Alternative Current (HVAC) power transmission.

Submarine cables are often utilized for long-distance HVDC power transmission across the sea and/or towards offshore wind farms [4]. For the onshore HVDC power transmission, underground systems may be more favorable to the public than overhead lines despite the latter is much cheaper, due to the public's aesthetic sensibilities and living environment [5]. Hence, HVDC cable systems become more and more widely applied nowadays.

For the development of HVDC cables systems, several aspects must be considered. In view of the electrical design, the electric field distribution in HVDC cable components under DC operation is affected not only by temperature and electric field dependent electrical conductivity but also by space charge effects in the insulation materials [6]. Therefore, the following points should be considered in the development:

- The temperature and electric field dependent electrical conductivity
- Space charge behavior in insulation materials and interfaces
- DC and impulse breakdown strength of the cable and accessories.

Cable joints are often the weakest and the most critical link of a cable system due to the high complexity of their electrical, thermal and mechanical designs as well as the high possibility of environmental pollution and insulation defects. These factors make the joints more challenging to design than other components in the HVDC cable system.

In this paper, the governed physical background for the calculation the electric field distribution of HVDC cable systems are introduced. Based on the introduction, we discuss our main concern on the selection of insulation materials of joints, as well as on the main aspects of the geometric design of HVDC cable joints. These principles guide our future work of developing cables joints up to 500 kV level.

II. GENERAL PHYSICAL BACKGROUND

The electric field distribution in an HVDC cable and its accessories (joints and terminations) are governed by the following equations:

$$\vec{E} = -\nabla\varphi \tag{1}$$

$$\vec{J} = \kappa \cdot \vec{E} \tag{2}$$

$$\rho_e = \nabla \cdot (\varepsilon_0 \varepsilon_r \vec{E}) \tag{3}$$

$$\nabla \cdot \vec{J} = -\frac{\partial \rho_e}{\partial t}\,, \tag{4}$$

where $\vec{E}$ is the electric field, φ is the scalar potential, $\vec{J}$ is the current density, κ is the electrical conductivity, ρ_e is the space charge, ε_0 is the vacuum permittivity and ε_r is the relative permittivity. The following equation can be derived from eqn. (1) to (4):

$$\rho_e = -\frac{\varepsilon_0\varepsilon_r}{\kappa}\frac{\partial \rho_e}{\partial t} + \vec{J} \cdot \nabla\left(\frac{\varepsilon_0\varepsilon_r}{\kappa}\right). \tag{5}$$

The first term $-\frac{\varepsilon_0\varepsilon_r}{\kappa}\frac{\partial \rho_e}{\partial t}$ in eqn. (5) indicates the rate at which the long-term steady state is achieved. This is determined by the dielectric time constant $\tau = \frac{\varepsilon_0\varepsilon_r}{\kappa}$. When the first term equals zero, which means the charge and the electric field becomes steady, the eqn. (5) can be simplified to

$$\rho_e = \vec{J} \cdot \nabla\left(\frac{\varepsilon_0\varepsilon_r}{\kappa}\right). \tag{6}$$

This implies the accumulated charge in the insulation materials due to the discontinuities of permittivity and conductivity. It should be noted, that this charge does not account for the charge stored locally at trapping centers associated with insulation microstructure, which can only be measured with diverse measurements techniques [7].

The electrical conductivity $\kappa(T,E)$ of the insulation materials for HVDC cable systems highly depends on temperature and, to a less extent, on elethe ctric field [4]. Such dependence is often described using the following equation [8]:

$$\kappa(T,E) = \kappa_0 \cdot e^{\left(\alpha(T-T_0)+\beta(E-E_0)\right)} , \tag{7}$$

where κ_0 is the electrical conductivity at the reference temperature T_0 and at the reference electric field E_0, α and β are the temperature and electric field coefficient respectively.

To estimate the electric field distribution in an HVDC cable system, the distribution of the temperature should be known as well. This can be calculated by solving the heat conduction equation:

$$\rho_m \cdot C_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \cdot \nabla T) + S_{heat} , \tag{8}$$

where ρ_m is the mass density, C_p is the specific heat capacity and λ is the thermal conductivity. The term S_{heat} represents the ohmic losses in the conductor and in the insulation materials, which is given by

$$S_{heat} = \kappa \cdot E^2. \tag{9}$$

III. DIFFERENT OPERATIONAL STAGES

There are several operational stages of HVDC cable systems. To ensure the cable system works reliably, the developer should estimate electric fields under different operational stages and ensure them to be lower than the threshold values in each stage. For example, when raising the DC voltage, the distribution of the electric field is at first capacitive, i.e. determined by the permittivity of the insulation materials:

$$\nabla \cdot \left(\varepsilon \cdot \vec{E}\right) = 0 . \tag{10}$$

Then the transition from a capacitive to a resistive field occurs. In this stage, the electric field distribution is time- dependent, which is governed by equations (1) – (5). After a sufficiently long time, usually 10τ, the electric field does not vary anymore and becomes steady resistive. The governed equations in this stage can be simplified as the following:

$$\nabla \cdot \left(\kappa(T,E) \cdot \vec{E}\right) = 0 \tag{11}$$
$$\nabla \cdot (\lambda \cdot \nabla T) + S_{heat} = 0 . \tag{12}$$

In this case, the accumulated space charge in the insulation materials is given by equation (6).

In CSC (Current Source Converter) systems power flow direction reversal is accomplished via inverting the voltage polarity. It is known that high electric field may occur at the cable conductor immediately after reversing the polarity of the voltage [9]. The insulation is especially vulnerable if the cable is loaded and there is a temperature gradient, which leads to space charge accumulation in the insulation materials. Immediately after the polarity reversal, the electric field can be calculated according to

$$E(t=0^+) = E(t=0^-) - 2E_{capacitive} , \tag{13}$$

in which $E(t=0^+)$ is the electric field just after the polarity reversal and $E(t=0^-)$ is the field just prior to it. $E_{capacitive}$ is the capacitive field given by equation (10). In VSC (Voltage Source Converter) systems, the current flow direction is reversed when a power flow direction reversal occurs. In this case, the voltage polarity reversal is not required anymore.

After polarity reversal, the electric field gradually changes from the field calculated via equation (13) to a stable field gained by the reverse voltage source. In this progress, the electric field is time-dependent and can be determined by equations (1) - (5).

In operation, DC cable systems have to endure switching over-voltages and, in the case of a cable-overhead line hybrid system, lightning over-voltages from the overhead line. In these cases, the impulses are superimposed on the DC operating voltage. Suppose the peak value of the superimposed voltage is U_p and the DC operating voltage is U_{DC}, the superimposed electric field $\vec{E}_{superimposed}$ can be divided into two parts as follows:

$$\vec{E}_{superimposed} = \vec{E}_{DC} + \vec{E}_{impulse} , \tag{14}$$

where $\vec{E}_{DC}$ is the steady resistive DC field under the operating voltage U_{DC} and $\vec{E}_{impulse}$ is the capacitive field of the applied impulse voltage $U_P - U_{DC}$. More information about how to numerically calculate the electric field distribution at various operational stages can be found in [10].

IV. HVDC CABLE JOINTS

Cable joints are devices which connect two cable segments with each other.

A. *Types of cable joints*

There are various types of cable joints. For oil-impregnated and mass-impregnated cables, cable joints and terminations are wound by paper and impregnated in oil [11]. At sea, the length of a cable segment can exceed 100 km because heavy cable drums can be transported on boats. In this case, factory joints are most common for extruded submarine cables. For land applications, the longest cable segment is less than 1 km because of the limited transport capacity on land. Hence, prefabricated joints are mostly used for the land application.

The main advantage of factory joints is that they can be installed on the cable in a well-controlled environment. In this case, the pollutants entering the joint can be minimized. Furthermore, the joint is made of the same insulation materials as the cables. Therefore, problems such as matching different dielectric materials on the interface can be avoided. Nevertheless, the time for installing a factory joint on the cable is much longer than the time needed for a prefabricated joint.

Prefabricated joints made of elastomeric materials, such as ethylene propylene diene monomer (EPDM) or silicone rubber (SiR), can be slipped on or shrank onto the cable insulation. According to different technologies, the insulation body of cable joints can be classified into the following ones:

- Cold shrink elements
- Three-piece slip-on elements
- One-piece slip-on elements

The cold shrink elements and the three-piece slip-on elements are mostly used at medium voltage levels. For high voltage levels, one-piece slip-on elements are most commonly used. The main advantage of the one-piece slip-on elements lies in their design. On one hand, they are prefabricated and can be produced in a clean surrounding in the factory, which results in higher quality. On the other hand one-piece, slip-on elements can be pre-tested in the factory.

B. Basic Design

Although a variety of different types of joints exists, the basic design of joints for extruded cables is very similar and consists of the following components (see fig. 1):

- Conductor clamps connecting both conductor ends of the cables. The main methods to connect two cable ends are pressing, welding and screw-fastened connections.
- Insulation body consisting of semi-conductive deflectors, a semi-conductive middle electrode, a solid insulation compound and a conductive layer outside the insulation compound. The materials used for the insulation compound are usually EPDM or SiR.
- A metallic shield covering the polymeric insulation for moisture protection. The metallic shield is often made of a copper or aluminum corrugated sheath, lead sheath or copper and aluminum-laminated sheath.
- Cover for mechanical protection. Depending on different applications, diverse designs for the mechanical protection are available.

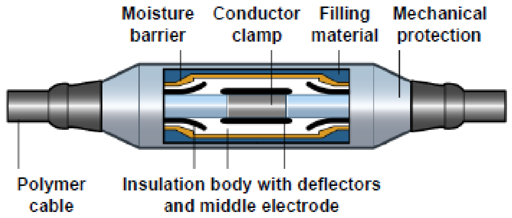

Fig. 1: Basic design of a joint for polymeric cables [12]

C. Insulation material

SiR and EPDM are the two most used materials for the insulation body of cable joints. A comparison of these two materials is summarized in table 1.

Table 1: Some properties of EPDM and SiR [13]

	EPDM	SiR
Chemical Structure	C-chain as basic	O-Si chains as basic
The range of temperature at which electrical and mechanical properties remain stable	-40°C ~ +100°C	-50°C ~ +180°C
Corona and ozone stability	None	High
Elasticity	Limited	High
Mechanical strength	High	Medium
Lifetime factor n[1]	≈ 20	>40
Breakdown Strength	≈ 20 kV/mm	>23 kV/mm

The comparison shows that SiR has advantages over EPDM in high voltage applications. Specifically, SiR has higher electric breakdown strength, prolonged lifetime and a considerably wider temperature range at which electrical and mechanical properties remain stable. Furthermore, SiR materials can fit the joint insulation better to the surface of the extruded cables than EPDM, which ensures the appropriate pressure on this interface. For these reasons, SiR is the most widely used material for high voltage AC joints. However, for HVDC joints, EPDM is more common, since it is much more challenging to compound SiR materials than EPDM materials to achieve the desired electrical properties.

D. Interfacial Behaviors

For designing HVDC cable joints, a key issue is the charge dynamic at the interface of the cable insulation and the joint body insulation. As important is the understanding of the charge dynamics at the interface of different insulation materials. This is usually modeled via the Maxwell-Wagner-Sillars (MWS) polarization [14] [15]. Assuming a voltage U_0 is applied across two dielectrics, the charge on the interface is given as follows

$$\rho(t) = \frac{\varepsilon_A\kappa_B-\varepsilon_B\kappa_A}{\kappa_A d_B+\kappa_B d_A} U_0\left(1-e^{\left(-\frac{t}{\tau_{MWS}}\right)}\right), \qquad (15)$$

where ε_A and ε_B are the permittivities of the dielectrics A and B; κ_A and κ_B are the respective conductivities; d_A and d_B are the thickness; the polarization time constant τ_{MWS} is given by

$$\tau_{MWS} = \frac{d_A\varepsilon_B+d_B\varepsilon_A}{d_A\kappa_B+d_B\kappa_A}. \qquad (16)$$

From the equation (15) it can be concluded that the charge will accumulate at the interface in proportion to the divergence of the permittivity/conductivity ratios in the two dielectrics. Obviously, the ratio depends on the temperature, thus any changes of the cable load will change the interfacial charge and

---

[1] Tested under AC. Corresponding values under DC are not available in literature.

hence the electric field distribution. Accordingly, the insulation material of the joint should be compatible with that of the cable, primarily in terms of the temperature dependence of the insulation resistivity. To avoid local electric field enhancements, a proper grading of the electric field can be realized if the two insulation materials are carefully selected and tuned.

III. CONCERNS OF DESIGNING HVDC CABLE JOINTS

In previous sections, the physical background for HVDC cable systems and the important points of cable joints are introduced. In this section, two aspects, which we believe to be critical in future designs of HVDC cable joints are discussed.

A. Selection of the insulation material for the joint body

For AC joints, SiR is the most widely used insulation material for high voltage applications. However, in the case of DC joints, this material can cause problems. One solution is using EPDM, which, due to lower volume resistivity, reduces accumulation of space charges in HVDC joints, especially at higher voltage levels. Another solution which has been applied in 320 kV HVDC joints is the treatment of silicone with nano-scale fillers [16].

Moreover, special attention needs to be paid to the tangential field along the insulation materials of joint body and cable under different loads of the cable. To achieve a reasonable tangential field distribution along the interface, the temperature and field dependent conductivities of both insulation materials should be matched. Ideally, the temperature and field dependence of both materials should be equal. However, this is quite difficult to achieve. This effect is shown in fig. 2. Two simulations are performed to evaluate the tangential electric field distributions in a simplified 150kV HVDC joint with different joint body materials respectively. Material 2 has a temperature dependence more similar to XLPE than material 1. The results show that the joint with the material 2 has a better tangential electric field distribution along the interface compared to material 1.

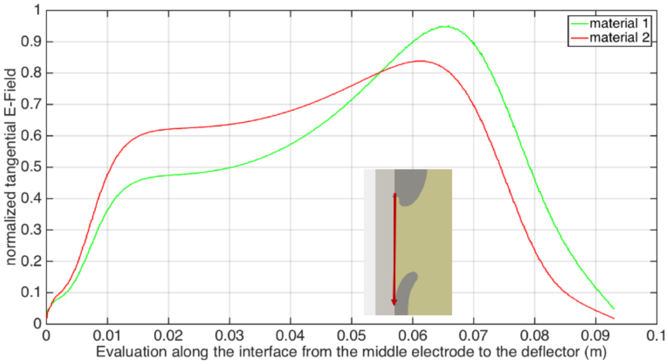

Fig. 2: Comparison of the normalized tangential electric field distributions along the interface in a simplified HVDC joint with two different materials.

It is clear, that a matching of the dielectrics and a reduction of the temperature dependence of the conductivity will lead to a better design. Besides, an increase in the thermal conductivity of the insulation material seems to be beneficial for two reasons. On one hand, it will lead to a reduction of the temperature gradient in the insulation and consequently to a more uniform electric field distribution (see fig. 3). On the other hand, it will reduce the probability of the thermal instability.

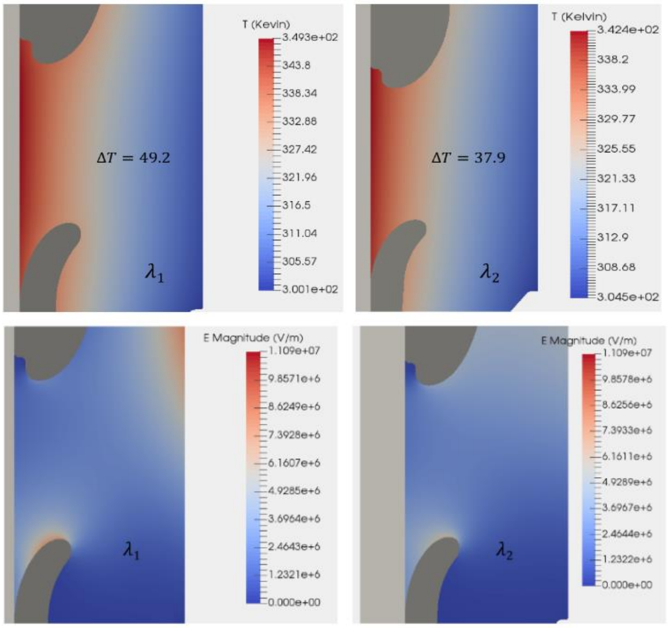

Fig. 3: Comparison of temperature and electric field distributions in a simplified 150kV HVDC joint with two different materials. The conductor temperature is set to 363 Kelvin. The material with the thermal conductivity λ_1 has a better distribution than the material 2 with the thermal conductivity $\lambda_2 > \lambda_1$.

B. Deflector Design

To achieve a qualified design, the electric field distribution under a transient voltage must be acceptable. In transient states, the shape of the deflector plays a vital role in the field grading. The deflector is made of semi-conductive rubber material and its outer shape serves to guarantee homogenous field distribution. The shape can be studied in finite-element-method simulations and determined in a way that the electric field inside the insulation material and along the interface between the cable and the joint is under a threshold value, which is proven to be reliable based on long-term experience.

For cable joints, a stress cone has to be installed on a cable with an expansion to generate the surface pressure, so that the electric field between the stress cone and the cable surface can be withstood. However, it should be noted, that the stress cone loses its original shape when being expended. As a result, the wall thickness is reduced, and the deformation changes the outline of the deflector surface, as shown in fig. 4 [17]. In this case, the installed joints may perform worse than predicted by the simulation.

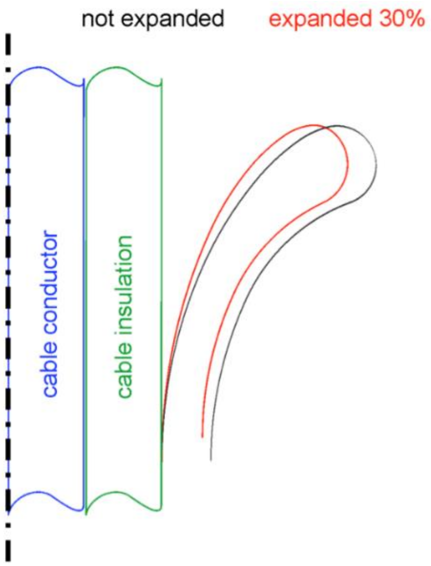

Fig. 4: Illustration of the deformation of a semi-conductive deflector with and without the expansion [12].

IV. CONCLUSIONS

The demand on HVDC cable systems keeps growing. A large amount of knowledge has been gained on designing various types of cable joints, as this is the most vulnerable link in cable systems. As a preparation work, the most critical aspects of HVDC cable joint design are reviewed and two aspects were further discussed as the guide to future work. The first is the comparison between EPDM and SiR as the main dielectric for the joint body. The second are the main concerns in geometric design, namely the transient states and the deformation of the deflector.

ACKNOWLEDGMENT

This work was supported by the National Key Research and Development Program of China in its project entitle “Critical Technologies for Designing and Manufacturing ±500 kV DC Cables and their Accessories” (No. 2016YFB0900703); Science and Technology Project of SGCC (Research on Key Technologies for ±500kV Direct Current Cable：Research on Key Technologies for the Preparation of DC Cable Accessories).

REFERENCES

[1] De Clercq, B, et al, “Towards a governance model for the European electricity transmission network in 2050”, e-Highway 2050 milestone D5.1, 2015.
[2] U.S. Department of Energy, “A national offshore wind strategy: creating an offshore wind energy industry in the United States”, 2011.
[3] China National Energy Administration, “Development plan (2014-2016) for national offshore wind power”, 2014.
[4] T. Worzyk, “Submarine power cables: design, installation, repair, environmental aspects”, Springer Science & Business Media, 2009.
[5] M. Byggeth, K. Johannesson, C. Liljegren, L. Palmqvist, U. Axelsson, J. Jonsson, and C. Tornkvist, “The development of an extruded HVDC cable system and its first application in the Gotland HVDC Light project”, in Proceedings of Fifth International Conference on Insulated Power Cables, JICABLE, 1999, pp. 538–542.
[6] G. Chen, M. Hao, Z. Xu, A. Vaughan, J. Cao and H. Wang, "Review of high voltage direct current cables", in CSEE Journal of Power and Energy Systems, vol. 1, no. 2, pp. 9-21, June 2015.
[7] N. H. Ahmed and N. N. Srinivas, “Review of space charge measurements in dielectrics”, IEEE Trans. Dielectr. Electr. Insul., Vol. 4, No. 5, pp. 644-656, October 1997.
[8] M. S. Khalil and A. Gastli, "Dependence of DC insulation resistivity of polyethylene on temperature and electric field," IEEE 1997 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Minneapolis, MN, 1997, pp. 296-299, vol.1.
[9] CIGRE Working Group 02 of Study Committee No. 21, “Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 600 kV”, Electra No. 72, pp. 105-114, 1980.
[10] M.J.P. Jeroense and P.H.F. Morshuis, “Electric fields in HVDC Paper-Insulated Cables”, IEEE Trans. Dielectr. Electr. Insul., vol. 5, No. 2, pp. 225-236, April 1998.
[11] Andreas Küchler, “High voltage engineering”, ISBN 978-3-642-11992-7, Springer Vieweg Verlag, 2017.
[12] Ruben Vogelsang, Hans-Jörg Winter, Hansjörg Gramespacher, Martin Grunwald, „Silicone technology for reliable performance of joints and terminations for high voltage polymer power cables”, 8th International Conference on Insulated Power Cables, Versailles, France, 2011.
[13] Hansjörg Gramespacher, Ruben Vogelsang and Matthias Freilinger, “Application guide for high voltage accessories”, 2nd edition, a publication of the Brugg Cables Academy. ISBN: 978-3-033-04936-9.
[14] Wagner K W, “Erklärung der dielektrischen Nachwirkungsvorgänge auf Grund Maxwellscher Vorstellung”, Archiv für Elektrotechnik, vol. 2, no. 9, pp. 371-387, 1914.
[15] Sillars R W, “The properties of a dielectric containing semiconducting particles of various shapes”, Journal of the insulation of electrical engineers, vol. 80, no. 484, pp. 378-394, 1937.
[15] Sillars R W, “The properties of a dielectric containing semiconducting particles of various shapes”, Journal of the insulation of electrical engineers, vol. 80, no. 484, pp. 378-394, 1937.
[16] K. D. Haim, “HVDC cable insulation & accessory designs”, INMR Article, June 2016.
[17] Stefan Zierhut, Thomas Klein, Eckhard Wendt and Lutz Zühlke, “Influence of expansion on electric field distribution of stress cones for high voltage cable accessories”, 9th International Conference on Insulated Power Cables, Versailles, France, 2015.