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Qualification testing of synthetic cable systems

Pierre Hondaâ; RTE, (France),
pierre.hondaa@rte-france.com,

ABSTRACT

HVDC XLPE cable is recent and feedback in terms of experience is limited. Furthermore, towards the end of the 90s, demand from TSOs for new high-power HVDC links was high, while at the same time HVDC activity regarding R&D by the cable-layers or big laboratories was either stopped or put aside. As this activity needed boosting, laboratories had to be built, leaving little time to work on the still little known laws of ageing. Very aware of these deficiencies, TSOs were pressing for qualification tests to check the specific functionalities of HVDC cable systems and to guarantee the long-term reliability of these materials.

Development of HVDC XLPE technology is complex, forcing manufacturers to carry out numerous development tests to design their cable system. In addition, once these tests have been validated, qualification tests are carried out in order to verify all the functionalities required by the TSO on the cable system. Thus this article suggests more advanced development on the functionalities verified by a HVDC cable system via four points:

- *The functionalities of HVDC cables in comparison with HVAC cables*
- *The main functionalities of a HVDC cable systems*
- *The qualification tests used to verify the expected functionalities*
- *The qualification tests which contribute to standardisation and innovation*

KEYWORDS

Qualification testing, functional analysis.

INTRODUCTION

HVDC XLPE cable is recent and feedback in terms of experience is limited. Furthermore, towards the end of the 90s, Transmission System Operator (TSO) demand for new high-power HVDC connections was high, while at the same time HVDC activity regarding R&D by the cable-manufacturers or big laboratories was either stopped or put aside. R&D activity needed boosting and new laboratories had to be built to approve the new technical functionalities which are: 1) mass-impregnated paper cable with a voltage increase and 2) new XLPE cable technology. So, there is not much time left to study the laws of ageing, particularly for XLPE cables. In addition, this lack of knowledge of the laws on electric, thermal and thermo-mechanical ageing has led to the recommendations by CIGRE for applying the electric ageing law for AC cables with a safety factor to size the voltage values for the DC cable tests.

There are currently three types of HVDC cable technology as shown in the figure below. There are extruded cables, mass-impregnated paper cables and fluid-filled cables.

Figure 1: Presentation of different HVDC cable technology

Within this family of HVDC cables, XLPE cable is a recent technology and consequently, feedback in terms of experience is limited. The number of links made or at project stage over the last 15 years typifies the immaturity of this technology. The following two figures show that:

- The first link is only 15 years old
- Of 18 projects, 10 are in progress, half of which have less than 10 years operation and the other 8 are in the process of installation
- Of 18 projects, 11 (61%) are or will be operated at voltage levels of 250 kV or below
- There are only two links currently being operated at a voltage of 300 kV or above; one link at 300 kV and one link at 320 kV

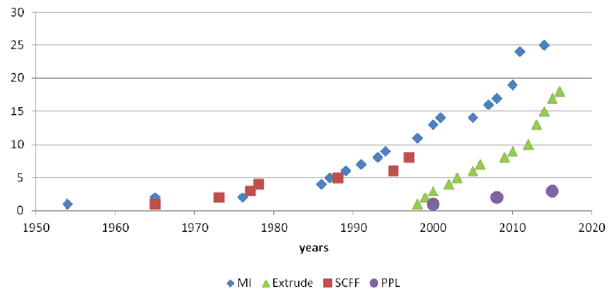

Figure 2: Number of HVDC projects accumulated in the word by technology

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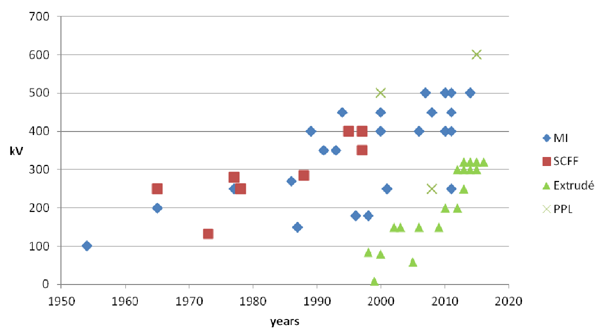

Figure 3: Evolution of the levels of voltage per technology

The first observation is that HVDC extruded cable technology is new and feedback in terms of experience is limited.

Well aware of these deficiencies in respect of the ageing laws of HVDC technology and limited feedback of experience, the utilities are requesting that qualification testing is carried out for each project. Qualification extensions can not be applied as they are for AC cables.

PROBLEM

Development of HVDC XLPE technology is complex, forcing cable-manufacturers to carry out lot of development tests to size their cable system. Once these tests are validated, additional qualification tests are needed to verify all the functionalities required by the TSO on a cable system.

But which functionalities are required on XLPE insulated cable and which tests are used to check them?

This paper proposes to develop the functionalities verified for a HVDC cable system more accurately through four points:

- HVDC cable functionalities in comparison with HVAC cable
- The main functionalities of a HVDC cable system
- The qualification tests used to check the expected functionalities
- The qualification tests that contribute to standardisation and innovation

For the first point, we will just demonstrate the behaviour or physico-chemical reactions of an XLPE cable insulator under stresses from different electric fields for HVDC and HVAC, and also under thermal stress. These "laws" of dielectric, thermal, electro-thermal or physico-chemical behaviour give the main functionalities of a HVDC cable system which will be further expanded in the second point. Then, for the third point, we will develop the qualification tests needed to check the expected functionalities. Lastly, for the fourth point, we will provide elements which demonstrate that qualification tests contribute to standardisation and innovation.

HVDC CABLE FEATURES IN COMPARISON WITH HVAC CABLE

A first important feature of HVDC cable is the distribution of the electric field in the insulation. Taking a AC 2500 mm² cable fitted with a 20 mm thick insulation as a dimensional hypothesis, and a DC cable of the same section proposed by the cable-manufacturers for large interlinking projects with a similar thickness, if we apply voltage to this same cable design at industrial power frequency (AC) and direct current (DC), the distribution of the electric field in the insulation is very different as shown on the graph curves in Figure 4.

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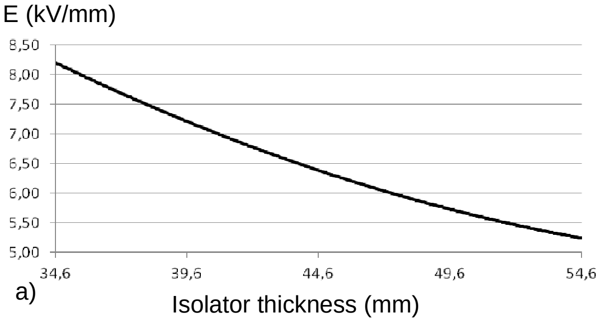
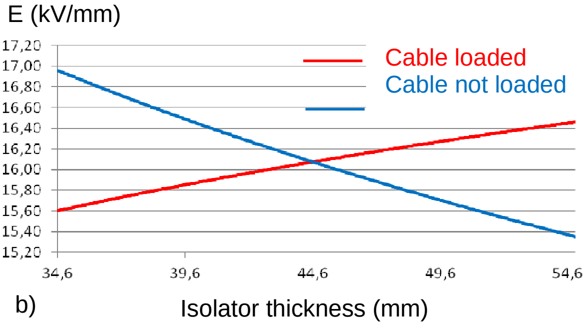
<table>
<tr><th>AC</th><th>DC</th></tr>
<tr><td>Law of distribution

$$E(r) = \frac{V}{r \ln(r_2/r_1)}$$


In this case, the field inside the insulation depends only on the dimensional size of the cable.</td>
<td>Law of distribution

$$E(r)\exp[\beta_e E(r)] = -\frac{I}{\sigma_0 \times 2\pi r}\left(\frac{r}{r_1}\right)^m \exp[-\alpha\theta(r_1)]$$
With: $m = \frac{\alpha\Delta\theta}{\ln(r_2/r_1)}$


$$\sigma(r) = \sigma_0 \exp[\alpha\theta(r) + \beta_e E(r)]$$
The field depends on the:
• Dimensional size;
• Temperature gradient inside the insulation;
• α and β, which are respectively the insulation temperature coefficient and the electric field coefficient.</td></tr>
</table>

Figure 4: Comparison of electric field distribution in the insulation supplied with- a) AC voltage and- b) DC voltage

For HVDC the internal gradient of a cable at ambient temperature is higher than that of a cable in operation. For the external gradient, it is the reverse.

<u>In conclusion:</u>

It is necessary to evaluate a cable system when cold (with no current flow in the core) to determine the highest electric gradient at the interface between the internal semi-conductor/insulation, and also at hot (with maximum current in the core) to determine the highest external gradient at the interface between the external semi-conductor/insulation and these without stressing the accessories.

A second important feature of HVDC cable is the problem of space charges. AC cables also have space charges which are quite uniformly arranged in the insulation. But inverting the periodic field (50 Hz) does not promote displacement and accumulations that are dangerous to the dielectric strength of the insulation. If the quality (number of impurities and defects) of the AC insulation remains high, the problem of space charges remains of secondary importance.

HVDC space charges are problematical because they accumulate inconsistently in the insulation under combined thermal, mechanical and electric field stresses at particular locations. These locations are the interfaces with the semi-conductors, the interfaces between amorphous and crystalline areas in the insulation and around defects or impurities (areas particularly prone to trap of charges). This accumulation of charges increases the electric field when the charges are heterocharges or reduces the electric field in the case of homocharges.

There is also another constraint: the different materials that make up the triplex cable (internal and external semi-conductor and insulation) are potential generators of positive or negative charges in insulation. It is therefore very important to choose the various materials and additives carefully in order to minimise the production of charges or to produce homocharges to counteract the heterocharges.

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Finally with respect to space charges, there is a very important point and this concerns cables that are chemically cross-linked. To improve the mechanical properties of polyethylene and for it to be used at higher temperatures, a chemical reaction takes place between the polyethylene base and the peroxide creating cross-links between the polyethylene molecular chains. This chemical reaction generates by-products such as water, methane, acetophenone and cumyl alcohol. Methane escapes quickly at ambient temperature, but this is not the case for other products. As a result, a degassing procedure must be carried out to remove most of these by-products that have **a direct effect on the amount of heterocharges in the insulation**. The amount of by-products depends on the peroxide content, the duration and the degassing temperature.

In conclusion:

The physical phenomena linked to space charges are complex and are combined in different fields which are electric, thermo-mechanical and chemical. Controlling the concentration of by-products from peroxide decomposition is an essential component for the quality of the cable. Their classification must be verified through physico-chemical testing to guarantee sufficient quality. Final produced cable must have equal or higher quality than the cable used during the qualification tests.

A final important feature of HVDC cable compared to AC cable is its law of electric ageing which is not well-known. Consequently, for the purposes of developing networks, HVDC cable systems must be qualified on the basis of an AC electric law of ageing. Voltage levels are defined by the Weibull Law for electric ageing of 40 years for short and long-term test.

$$\boxed{V^n \times t = \text{constant}}$$

Where V is the voltage applied between the conductor and the sheath, t is the application time of this voltage and n is the coefficient that classifies the quality of the cable insulation and whose value is taken as 10 by default, corresponding to a very average quality but compensates for lack of knowledge of the law for HVDC.

There are two tests to age the cables and accessories and to check their performance. Short-term and long-term tests.

The short-term test imposes a high electric field to verify the different breakdown strengths:

- Electric, this is a trigger to electronic avalanche effect,
- Thermal, this is an increase in the resistive currents causing thermal runaway,
- Electro-mecanical, this is the action of compression forces due to the electric field F=qE which causes cracks in the insulation and breakdown

The long-term test imposes a thermal stress which causes oxidation of the insulation then the appearance of cracks which, under the stress of the electric field stress, lead to a breakdown.

Thermal and thermo-mechanical stresses in the short and long-term promote the injection, displacement and accumulation of charges. This being the case, the impact of space charges on ageing in the short-term is likely to differ from the long-term due to a higher Coulomb's force.

In conclusion:

We do not activate the same phenomena for short and long-term ageing tests. The issues relating to interfaces, like the injection or extraction of charges that depend on the temperature and the electric field are visible in the short-term because the field is high and also in the long-term. The chemical compatibility between materials can be observed over the long-term. The stability of peroxide by-products at high temperature must also be assessed over the long-term.

The main functionalities of a HVDC cable system/ Qualification tests to verify the expected functionalities

The main functionalities expected of a HVDC cable system can be divided into three areas, which are:

- Electric
- Thermo-mechanical
- Chemical

Limiting our observations to the functionalities of the internal and external semi-conductors and the insulation based on the areas mentioned above. The tables below give the functionalities and the tests used to verify them.

Area	Functionalites	Assessment criteria	A. Tests on core Or Material tests	B. Non-electric functional tests	C. Short-term electric functional tests	D. Long-term electric functional tests
Electric (I)	Allow capacitive currents to flow up to the screen throughout the life of the cable (AC)	Low electric resistivity	Measurement of electric resistivity			
	Avoid DP at the interface with the screen during operation	No DP detectable				
Thermo-mechanical (II)	Resistance to laying and bending, during manufacture and on site	Deformability		Bending test	Lightning impulses when hot + resistance to DC voltage after bending test	
	Limit overheating in transient operation	Thermal diffusivity (high)				
	Dissipate losses by joule effect	Thermal resistivity (low)				
	Durability of mechanical properties in operation	Deformability			Lightning impulses when hot + resistance to DC voltage	
Chemical (III)	Compatibility with the insulation	Chemical inertia		Compatibility test measurements on insulation		Long-term
	Conservation of electric properties in the event of short-circuit	Conservation of electric properties after VA			Short-circuit test	
	Compatibility with oil from terminations if in contact	Conservation of electric and mechanical properties				Long-term
	Compatibility with the semi-conductor joints					Long-term

Table 1: Functional analysis of internal and external semi-conductor screens

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Area	Functionalites	Assessment criteria	A. Tests on core or Material tests	B. Non-electric functional tests	C. Short-term electric functional tests	D. Long-term electric functional tests
Electric. (I)	Insulate the core throughout the life of the material	Electric gradient at ambient temperature				Long-term test
	Minimise dielectric losses	tan δ (when hot)	NA		NA	
	Produce a low capacitive current	Low dielectric constant				
	Conservation of dielectric properties in the event of short-circuit	Breakdown gradient at temperature	Elongation tests when hot			
	Minimise space charges	Profile of electric field in the thickness of insulation			Testing by Pulse Electro-Acoustic method (PEA) or Thermal Step Method (TSM)	
	Insulation conductivity σ as low as possible	Electric resistivity parameters α and β	Calculation of temperature coefficients a and electric field β $\rho = \rho_o \exp[-(\alpha T + \beta E)]$			
Thermo-mechanical (II)	Resistance to laying and bending, during manufacture and on site	Deformability		Bend test	heat cycles; Lightning impulses when hot + resistance to DC voltage after laying test	
	Limit overheating in transient operation	Thermal diffusivity (high)				
	Dissipate losses by joule effect	Thermal resistivity (low)				
	Durability of mechanical properties in operation	tensile strength, mechanical properties before and after ageing	Mechanical tests			
	Dimensional stability	Deformability and Longitudinal shrinkage compared to a qualified cable			Lightning impulses when hot + resistance to DC voltage	Long-term

Table 2: Functional analysis of the insulation

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Area	Functionalities	Assessment criteria	A. Tests on core or Material tests	B. Non-electric functional tests	C. Short-term electric functional tests	D. Long-term electric functional tests
Chemical (III)	Resist development of electro-chemical treeing process phenomenon *	Watertight construction				
	Compatibility with SCI and SCE	Chemical inertia		Compatibility test		Long-term
	Resistance to thermo-oxidation	Mechanical properties before and after thermo-oxidative ageing	Mechanical tests			Long-term
	Minimise cross-link decomposition by-products	Weight loss after thermal ageing	Thermogravimetric analysis (ATG)			
	Minimise insulation water absorption capacity	Mass variation	Water absorption gravimetric test for insulation (insulation solubility at a given temperature)			
Other (IV)	Processability/extrudability	Surface condition with SCI and SCE No voids and contaminants in the insulation	Semi-conductor screen protrusion measurements Inspect for voids in the insulation Inspect for contaminants in the insulation		Lightning impulses when hot + resistance to DC voltage	
	High thermal resistivity		HD 633 S1 (1997)			

* not taken into account because cable with radial sealing

Table 3: Functional analysis of the insulation (continued)

THE QUALIFICATION TESTS THAT CONTRIBUTE TO STANDARDISATION AND INNOVATION

Progress towards standardisation

The experience gained by cable-manufacturers for a long time over dielectric tests performed in the laboratories with AC cable systems has allowed them to discover the maximum permissible electric field at power frequency and the lightning impulses of their cables and accessories. Each manufacturer has constructed their own quality index for their cable system and which complies with TSO requirements in terms of service life. This rating is used to construct the international standards which are used by the majority of cable-manufacturers at the request of the TSOs. These are IEC 60 840 and IEC 62 067. So, using the test results we can construct future standards.

For HVDC, there is no standard, only the CIGRE recommendations. A quality index for HVDC cables will be constructed thanks to results providing to development and qualification tests carried out by cable-manufacturers. These data will be used to define technical requirement levels in the next HVDC international standard.

In addition, the more tests we complete, the more information we have to work on extensions to the HVDC qualification for inclusion in future specifications or standards, resulting in fewer tests in the future.

Promote innovation

HVDC links installed today are designed to carry high power. These are 2500 mm² cable sizes or above with a DC voltage of 320 kV. If we compare the electric fields for conductor and insulation between a DC 320 kV cable and AC 400 kV cable, the stresses are greater on the DC cable. Due to non-linear distribution of the field in the insulation of the DC cable there is a very strong field on the insulation which highly stresses the joint and the termination. The electric field stress on the insulation has never been increased for around 15 years, even for 400 kV AC.

Cable technology	Int G in kV/mm	Ext G in kV/mm
DC 320 kV	17	16.5
AC 400 kV	16	9

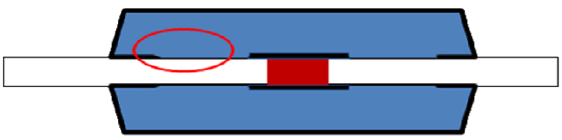

Figure 5: Comparison between potential gradient of HVDC and HVAC cable

Consequently, the cable-manufacturers were required to innovate in order to control both the correct preparation of interfaces using the right materials where the electric fields are highest and within deadlines compatible with projects, or fairly short deadlines. Simulations of field calculations, re-calculated based on the results of development dielectric testing have largely contributed to this innovation.

Innovation has also benefited from the results of unsatisfactory qualification tests.

Qualification testing is used to validate cable systems and also to sanction cable systems that do not meet the required functionalities. For HVDC, we observe many qualification test failures proving the complexity in the design and development of these systems and proving that qualification testing is needed for developments in this technology according to current knowledge.

Cable system tests are expensive and time-consuming, but this is the price of learning the reliability and performance of these systems and to meet TSO requirements.

CONCLUSIONS

The development needs of electricity networks in France and Europe are significant and will remain so for the coming years. Qualification testing is essential because it is a good way to learn and understand the behaviour of cables in terms of electric field, thermal and thermo-mechanical stresses. Laboratories must continue to develop in order to test cable systems and to construct HVDC reference tables similar to AC cables.. The feedback for qualification and development testing will be used to construct future HVDC standards. This can only be done with full cooperation between the cable-manufacturers and TSOs in international bodies for setting standards.