

Aging: What is expected from a Transmission System Operator (TSO)?

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ABSTRACT

Nowadays tendency in France and other European countries is to use HVDC cables (High Voltage Direct Current), for economical and better electrical performance reasons in the case of very long links (i.e. higher current transit capacity ...).

Despite this technology is not yet well known, it is used by many TSO such as RTE in France. However, it can be pointed out that there is a lack of knowledge regarding the behavior of insulation under thermal and electrical stress. Furthermore it can be highlighted that the use of a HVDC cables in the TSO network is totally different compared to the one of a HVAC cables. These differences impact on the aging law of the XLPE insulation present in the cables and also on their lifetime.

Besides the aging of XLPE insulation used in HVDC systems is not well understood and there is a real need to identify the aging laws of these materials exposed to DC voltage.

This paper will present recent RTE HVDC projects and review most important physical phenomena to take into account on the aging of HVDC systems.

KEYWORDS

HVDC cables, Cross linked polyethylene (XLPE), aging, space charge

INTRODUCTION

In order to insure expansion of renewable energy in Europe, the electricity network has to be developed. In this context, the use of Direct Current (DC) links appears to be the most appropriate because of interconnections between countries and because of the length of the links which could be very important.

Furthermore High Voltage Direct Current (HVDC) links offer many advantages compared to high voltage alternative current (HVAC), such as:

- ✓ lack of reactive power

In the case of long distance HVAC connections, reactive power is so important that it becomes necessary to compensate. The cost of compensators in addition to the one of cable system leads to an expensive system in the case of long distances. Meier et al. have mentioned that HVDC system is more profitable when the transmitted power is greater than 200 MW and when the distance exceeds 100 km [1]

- ✓ lower losses in cables

In the case of HVAC system, the losses have

different origin: joule losses in the cable core accentuated by skin effect and proximity effect; joule losses at the metal screen because of the induced current and the dielectric loss of the insulation.

In HVDC systems, joule losses in the cable core are less important but it must be pointed out that converters could also generate losses.

- ✓ lack of the synchronism problem

A major advantage of HVDC system is to enable connections between networks using different frequency.

In this way, it is clear that the use of HVDC cable offers many benefits. Cross linked polyethylene (XLPE) cables are more and more developed for HVDC applications. It can be pointed out that these systems are relatively new and that there is a lack of knowledge regarding the behavior of insulation under thermal and electrical stress. Indeed, the aging law of XLPE exposed to HVDC is not well understood and TSO have a real need to know it, in order to be able to predict the lifetime of their cables network.

Physical phenomena and space charge formation in the XLPE insulation under continuous electrical stress have been studied by many authors. Different mechanisms to explain space charge formation and conduction are proposed in the literature. But all authors are agreed on influence of interfaces on charge generation in the bulk. Nevertheless current knowledge does not allow yet to develop an aging model which considers all the involved parameters.

RTE PROJECTS

Rte is the French Transmission System Operator (TSO) and is in charge of the development and the maintenance of the French electricity network. Nowadays, interconnection links are in development such as France-Spain or France-Italy projects and others like France-England are planned. In this context, Rte makes the choice to innovate in promoting the use of XLPE technology. This new generation of cable offers many benefits such as:

- ✓ Possibility to use the cable at higher temperature ($\geq 70^{\circ}\text{C}$) compared to previous technology such as Mass Impregnated (MI) insulation, where the maximum conductor temperature is limited to 55°C .
- ✓ Lightness which contributes to use less joint and so to reduce system weakness.
- ✓ Environmentally friendly with the absence of oil and lead.

However, it can be pointed out that the aging law of the XLPE exposed to DC stress is not well known and that physical phenomena involved in the aging must be taken

into account in order to predict as well as possible the lifetime of these new cables.

Furthermore operations of HVDC and HVAC links are not similar; this is why Rte pays a huge attention to aging phenomena involved under DC stress.

Indeed, lines solicitations and more precisely load exposure is directly operated by a command. Figure 1 presents load curves of the France-England HVDC interconnection during two different days.

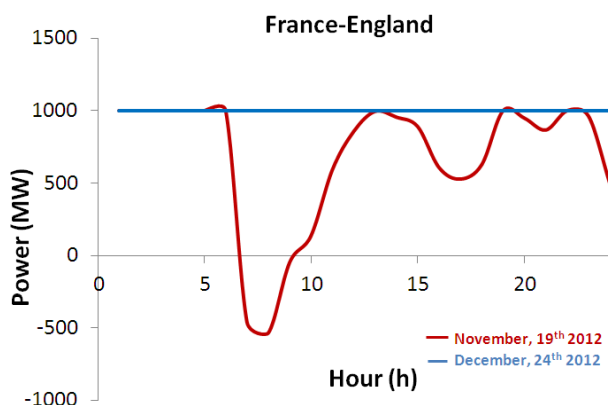


Figure 1: Load curves of the France-England HVDC interconnection on November 19th 2012 (in red) and on December 24th 2012 (in blue).

It can be observed on Figure 1 that the load curve of the France-England HVDC lines on November 19th 2012 is totally different from the one on December 24th 2012. This can be explained by the fact that the use of the only one interconnection between these two countries is function of the electricity market. For example, because of the lack of the amount of electricity in England on December 24th 2012, France-England interconnection was maximum use with a huge importation from France to England.

Figure 2 presents curves load of the France-Spain HVAC interconnection for the same days as those presented on Figure 1.

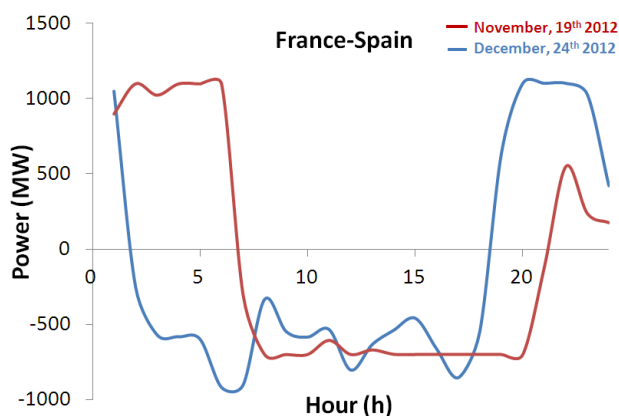


Figure 2: Load curves of the France-Spain HVAC interconnection on November 19th 2012 (in red) and on December 24th 2012 (in blue).

In the case of the HVAC interconnection between France and Spain, it can be observed again that the load curves depend on days. In the case of HVAC links, the load is not controlled as in HVDC system and is generally more variable.

As HVDC lines can be load controlled, they are often full loaded which leads to a maximum conductor temperature exposure during long time. Furthermore, temperature is an important kinetics aging parameters. So, it is clear that the heavy use of HVDC cables has an impact on their lifetime. Therefore further investigations have to be made in order to know if this new technology is time rentable.

PHYSICAL PHENOMENA

HVDC technology definitely offers several advantages in comparison with HVAC system. However, the major obstacle to the implementation of this type of product is mainly because of space charge accumulation in the insulation under continuous electrical stress. These charges are known to cause premature failure because they induce on one hand a distortion of the electric field in the insulation and on the other hand an accelerated aging.

When a dielectric is subjected to electrical, thermal, and mechanical stress, excess of electrical charges can be observed in some parts of the material. These electrical charges, called space charge, are generated when the rate of charge extraction differs from the one of charge accumulation.

Space charge has different origins (as shown in Figure 3):

- Intrinsic: polarization of the dipoles (a), intrinsic or extrinsic ionic carriers (b), electro-dissociation of neutral species (c).
- Extrinsic: injection of holes at the anode (s) and electron at the cathode (e), surface states (f) chemical reactions (g)

When charges are injected into insulation, they are initially trapped in the interfaces and then transfer into the bulk by hopping or tunneling transport. Traps distribution in insulation can be shallow or deep depending on their origin. Deep traps due to chemical origin (crosslinking agents, antioxidants, additives ...) are usually located closed to interfaces. Trapped charges can remain there for few minutes to several hours depending on traps depth.

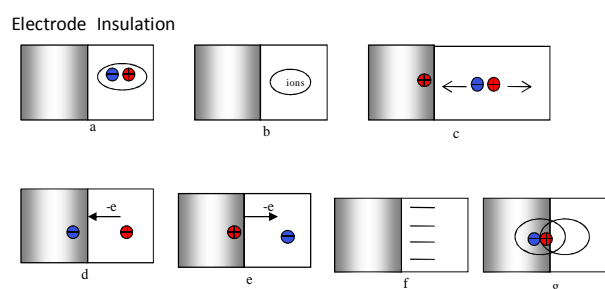


Figure 3: Summary diagram of possible charge generation in insulation [3].

The presence of space charge within the insulation of the

power cables is especially dangerous during polarity reversal because homocharges¹ present in the insulator nearby interfaces can be changed into heterocharges with polarity reversal. These heterocharges can then lead to increase electric stresses within the insulating material. If these one is too high, dielectric breakdown of insulation can occur. This phenomenon can appear with polarity reversal LCC converter².

In the other hand, during operating heterocharges zones in adjacent of opposite electrodes could be formed, which can leads to the increase of the electric stress near SC/Insulating interfaces. This phenomenon can occur with the use of non polarity reversal VSC converter³.

Furthermore, temperature gradient in the insulation at DC nominal voltage can create additional complexity on space charge distribution; this point will be discussed in the following part.

Space charge in Mass Impregnated (MI) insulation

Nowadays most present HVDC installations around the world use oil-impregnated paper insulation with LCC converters with reversal polarity. Although the polarity reversal can be binding in the interfaces only few investigations on space charge measurement on mass-impregnated paper insulation have been carried out. Moshuis et al have shown that homocharges present in MI paper insulation are always observed both at anode and cathode and that specific charge growth/decay pattern occurs in bulk [2]. However homogenous distribution of space charge in bulk and high conductivity of MI paper reduce the electrical stress during polarity reversal. Mass Impregnated non draining papers are usually used on submarine cables and they have proven to be very reliable.

Today MI insulations are less used in new project because of environmental issues concerning the use of lead sheath and oil insulator. XLPE insulation seems to be a good alternative to replace MI cables thanks to its high dielectric strength and electrical resistivity in combination with some excellent physical properties such as resistance to cracking and moisture penetration.

Space charge in extruded (XLPE) insulation

XLPE cables are now used extensively because they offer many advantages (for similar operating voltage) compared to MI paper insulation such as lighter design, easier accessories installation, easier maintenance and repair with no risk for oil leakage.

However some parameters impact largely on space charge generation in XLPE cables.

In the following part, some parameters involved in the charge generation are presented and their influence is discussed.

1 Both homocharges and heterocharges are expressed by the polarity of the electrodes and the polarity of the charges within the material adjacent to the electrodes.

2 LCC (Line Commutated Converters)

3 VSC (Voltage Source Converters)

Materials

During cable fabrication process, some additives (e.g. antioxidant, cross linking agent) are added into the insulation in order to improve its themomechanical properties. These additives impact significantly on the morphology of the polyethylene.

Antioxidants are added in the insulator in order to prevent its oxidation during the production process or during its life-service. Antioxidants capture the radicals and prevent in this way degradation of the insulation. However it can be mentioned that antioxidant decomposition residues can be found after cooling in amorphous areas and they can contribute to the accumulation of positive or negative charge according to the nature of the antioxidant used (aromatic amine or phenolic based antioxidant).

Cross linking agent added during manufacturing process can build up bridges between different polymer chains, which make the material more stable at high temperature from the mechanical point of view. However after cooling process (during polymer production) several residues coming from these cross linking agent can be generated (e.g. acetophenone, cumyl alcohol, alpha-methyl styrene, water ...). These residues are also known to be one cause of space charge accumulation in the insulator under continuous (DC) stress.

So the choice of insulation materials for HVDC application is not an easy task. There is a real need to control complex process parameters at the same time.

Interfaces (SC/Insulating, lubricant agent, Insulation/insulation)

The nature of SC/Insulating interfaces are closely related to the formation of space charge and conduction under high field. Figure 4 shows space charge formation for SC/Insulating and AU/Insulating interfaces during polarization and depolarization. With SC interfaces, positive charges are observed little after application of the voltage. For a higher field ($60 \text{ kV} \cdot \text{mm}^{-1}$) negative charges injected from the cathode are also observed. This is not the case for polymer with metallic gold electrodes, for which no charge is observed whatever the voltage.

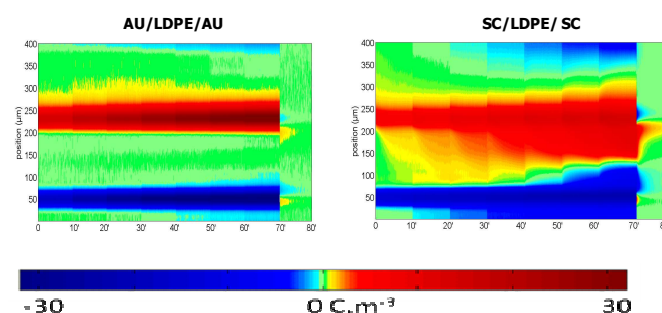


Figure 4: Profiles of space charge obtained on charges of LDPE /AU (190µm, top left), LDPE/SC (190 µm, top right) for a 30 up to 90 $\text{kV} \cdot \text{mm}^{-1}$ at room temperature [3].

So, a particular attention is needed to select conductor and insulation screens materials to reduce space charge injection and to promote their extraction. However, interfacial phenomena appear to be more complicated because many factors such as surface states, nature of the additives, chemical and physical structures of

polymers affect space charge formation in complex ways.

Nowadays the length of the produced cable doesn't allow the use of only one cable for one project. It means that connections between cables are necessary. These one are made thanks to the joint. Joint structure is almost identical to that of the cable (tri-layer structure), however materials used can be different. So with joints and terminations two critical interfaces can be identified:

- SC/ lubricant/ Insulator:

Lubricant oil may be used between cable and sleeve to ease fitting process. However recent researches have shown that the presence of oil could change SC/Insulating interface behavior and charge generation mechanism in the insulation. In the presence of lubricant (zinc stearate), homocharges generation have been observed for electric field greater than 17 kV / mm [5].

- Insulator/ insulator:

Cable insulator (XLPE) could be in contact with stress cone insulator (EPDM, Silicon,...) with different permittivity. In this case, interfacial charge can be formed: amount and sign of charge depend on the materials permittivity difference. So conduction is influenced by a neighboring insulator. Two kinds of charge formation could be observed at the interface. The first one appears quickly after voltage application which is relating to the difference permittivity between materials according Maxwell Wagner theory.

$$\Delta\rho = \rho_1 - \rho_2 = \frac{\varepsilon_0(\varepsilon_1 - \varepsilon_2)V_0}{d_1\varepsilon_2 + d_2\varepsilon_1} \quad (1)$$

Where ρ is charge density, ε is permittivity, d is thickness of each layers and V_0 is applied voltage.

The second one is slower and it is seemed to be related to charge injection from electrodes. When space charge is formed at the interfaces, electric field may be distorted which can lead to unexpected accident. Charge accumulation for combinations of XLPE with different polymers such as silicone-rubber, EP-rubber and epoxy resin, have been investigated by Miyake [8]. It was shown that the quantity of interfacial charge in the insulating/insulating contact is not negligible and depends on the nature of the interfaces (see Figure 5).

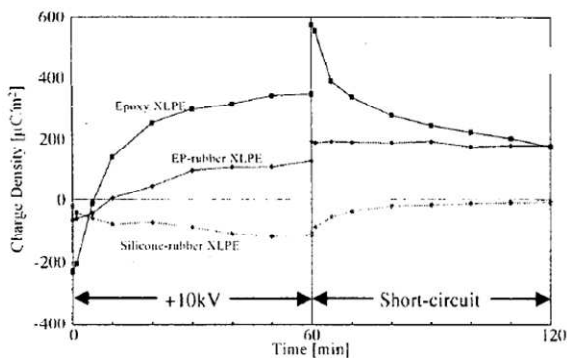


Figure 5: Space charge dependence at XLPE/Epoxy, EP-rubber / XLPE and epoxy resin/ XLPE interfaces [8].

A particular attention is also needed during the preparation of cable core for SC screen transition zone to insulation one to ensure a smooth region. During fitting of stress cone working area must be kept particularly clean and free of dust.

Electrical and thermal stress

The charge injection into the polyethylene is favored by the increase of the electric field and the temperature (see Figure 6), because electrical conductivity is dependent on the electrical field and the temperature. Increase of electric field accelerates the conduction current in the bulk and decreases the thresholds corresponding to the transition from Ohmic to SCLC (Space Charge Limited Current) conduction.

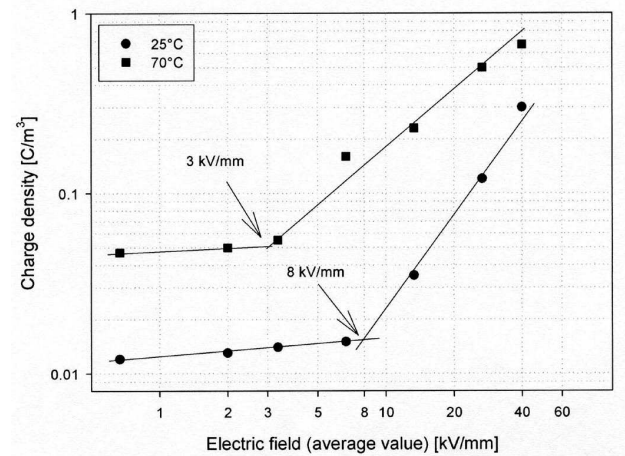


Figure 6: Space charge accumulation characteristics for XLPE cable at 20°C and 70°C (isothermal tests) [4].

For fields below to threshold field, local conductivity in the isotherm insulation is identical to macroscopic conductivity. In this case, no space charge remains trapped in the insulation bulks. For higher fields, however, the conductivity varies depending on the position as shown by Figure 6. In this case, as the total injected charge cannot be extracted by SC screens, space charges amount increase and accumulate which causes locally modification on the internal field.

HVDC cables have also a particular behavior regarding temperature gradient. It is important to remember that under service condition cable temperature is not uniform across the insulation and decreases from the conductor to the metallic sheath during operation. This difference could be significant, especially for submarine cables ($\Delta T \geq 15^\circ\text{C}$ with a conductor temperature $\geq 70^\circ\text{C}$). This phenomenon modifies insulation conductivity within bulk and at the SC/Insulating interfaces. With no temperature gradient, electrical field is capacitive and it is maximum at the inner SC electrode but in the presence of thermal gradient, electrical stress is reversed and becomes maximum at the outer SC electrode. An example is illustrated on Figure 7 for an average electric field of $3\text{ kV}\cdot\text{mm}^{-1}$ and $\Delta T = 10^\circ\text{C}$.

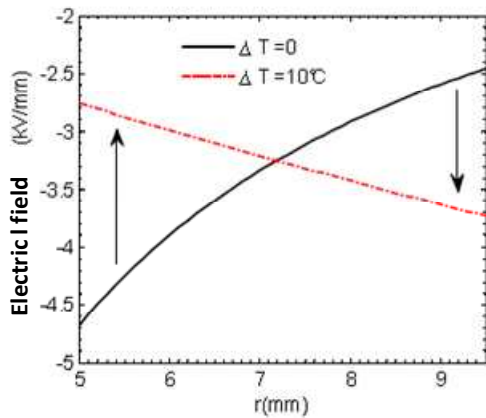


Figure 7: Electric field profiles with no thermal gradient (black curve) and in the presence of thermal gradient (10° C between the inner and outer electrodes - red curve) [4].

Several authors are based on Maxwell equation, to quantify the electric field modification under temperature gradient. Expression of charge density associated to thermal gradient under an ohmic SC/insulating interface assumption, can be described [4] by the following equation (2):

$$\rho(r) = -\epsilon E(r) \frac{\Delta W}{k_B T^2} \frac{dT}{dr} \quad (2)$$

Where r is the radial coordinate and ΔW is activation energy.

This equation is not exactly representative about what happen when the electric field exceeds the threshold for space charge accumulation, because in this case conductivity depends also on temperature gradient and space charge accumulation.

There is only few results on the effect of thermal gradient on space charge, because the separation between bulk charges due to temperature gradient and injected charges is difficult. However, this phenomenon has been investigated by Fabiani and al [4] on mini cables. Their results show that injection of charge at the electrodes may prevail over bulk charge accumulation produced by a temperature gradient in the case of a considerably larger electric field compared to the threshold. Nevertheless, choice of materials with low temperature dependence present a challenge for cable manufactures.

MODEL DEVELOPMENT

A cable is complex system regarding its geometry and the nature of the materials. Numerical charge transport models, which have been developed in cross linked polyethylene under thermal and DC stress are not numerous. In most models, Shottcky injection with unipolar or bipolar hopping transport in the bulk by discrete or exponential distribution of traps levels for plan geometry is considered [6-7]. Recent models have introduced an interface region at each electrode in order to consider the influence of SC/insulating imperfections on space charge behaviour [3].

Despite these models could explain some experimental observations, as the enhanced injection of one kind of carrier once the carriers of opposite sign reach the electrode, or the accumulation of heterocharges at the electrodes... more improvement is needed in this area, because developed models until now, are based on simplified physical assumptions. These assumptions don't allow to consider all physical phenomena at the same time.

Furthermore, if these models can be representative about what happen for a limited time (around some hours); it is not really the case for longer time. Models have to predict almost 40 years exposure because it's precisely the lifetime which is expected for HVDC networks by TSO.

It is now clear, that a deep investigation of the effect of trapped space charges on the aging of polymeric insulating materials subjected to thermo-electrical stress is needed.

CONCLUSION

Results of space charge measurements on the Crosslinked polyethylene (XLPE) have shown that the interfaces are particularly critical regarding space charge generation. Surface states conditions, nature of additives, chemical and physical structures of polymers affect space charge formation at the interfaces. These aspects should be taken into account in the choice of materials for HVDC application.

Even if insulator materials are always XLPE, it is necessary to keep in mind that history of insulation from melting to extrusion and amount of peroxide and anti-oxidant could modify microstructure and so properties of the polymer. Due to the complexity of the phenomena involved (injection / trapping / extraction etc.), it is not easy to predict the distribution of space charge in the cable but development of representative model for cable aging have to be made. These aspects are great challenges for TSO and cable manufacturers at the same time.

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