Development of Joints & Terminations for HVDC Extruded Cables

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DEVELOPMENTS OF JOINTS AND TERMINATIONS FOR HVDC EXTRUDED CABLES

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HVDC CABLE SYSTEMS: INTRODUCTION

1. PAPER INSULATED HVDC CABLES:
A long a positive experience is available up to 500 kVDC both on land and submarine systems:
• Self-containing oil filled cables (SCOF)
• Mass impregnated cables (MI)

2. EXTRUDED HVDC CABLES:
Very popular in the last decades because:
• Length of extruded cables can be substantially longer than SCOF cables because no oil feeding is necessary.
• Current-capacity can be higher for extruded cables compared with MI ones, because the service temperature can be increased from 60-70°C up to 90°C.

Two types of HVDC extruded cables are available:
a) XLPE cables (world-wide used)
b) P-laser cables (Prysmian only):
• Thermoplastic compounds (peroxide-free process) extruded with innovative technology line. No gases generated in the cable insulation during the vulcanization.
• No degasing required vs. several weeks necessary for XLPE.
• Stable characteristics up to 130°C.
In the 90\textsuperscript{th} existing HVAC accessories were used for first tests on 200-250 kVDC XLPE cables. The behaviour of XLPE HVAC cable accessories under DC voltage was satisfactory, but it was necessary to solve some problems, because unexpected failures occurred during the electrical tests:

- Many tests and investigations were launched to study the failures mechanism under DC voltage and to improve the accessories performances.
- **Aging of materials, charges accumulation** at the interface XLPE cables / accessories and **interpretation of failure mechanisms** in the HVDC accessories have been studied.
- **Design criteria for HVDC cable accessories are totally different from those used for HVAC applications.** Even if many components of joints and terminations are similar in AC and DC accessories, the electrical stress distribution inside the accessory and the behaviour of the materials under DC voltage are very different.

Accessories already qualified on 320 kV DC **XLPE** and **P-laser extruded cables** will be presented and the development of 525/600 kV DC extruded cable system will be mentioned.
HVAC ACCESSORIES SUBMITTED TO DC TESTS ON HVDC EXTRUDED CABLES

170 kV AC XLPE cable accessories used for the first tests on 200-250 kV DC XLPE cables:
• Outdoor terminations, both with porcelain and composite insulator.
• Straight joints with EPR pre-molded body.

Initially some faults were experienced on the XLPE cables under the joint sleeves, due to the cable preparation:

- Peeling tools and polishing techniques normally used for AC cables were affecting the cable performances under DC Voltage.
- Specific tools and smoothing techniques were developed for DC applications, solving the problem.

After the improvements on the XLPE cable preparation, the accessories were qualified at 250 kV DC according to the ELECTRA 291 requirements.
For the qualification of 320 kV DC extruded cable systems, two different families of accessories were tested: joints with EPR pre-molded sleeve and joints with SILICONE pre-molded sleeve.

**EPR pre-molded joint**

Straight joint connecting two cable with similar dimensions

**EPR** sleeve during the expansion onto the carrier tube, to be carried out just before fitting it on the cables.

**SILICONE** pre-molded joint

Asymmetrical joint connecting cables with different dimensions

**SILICONE** sleeve during cables plug-in operation.

EPR joints passed all the tests, while several SILICONE joints failed the thermal cycles test, just after the polarity reversal.
WHY SOME TYPES OF ACCESSORIES THAT NORMALLY PASS THE AC QUALIFICATIONS CAN FAIL THE DC TESTS, WHILE SOME OTHER ACCESSORIES PASS BOTH AC AND DC QUALIFICATIONS WITHOUT PROBLEMS?

BEHAVIOUR OF THE MATERIALS AND DESIGN CRITERIA ARE DIFFERENT IN AC AND DC.

AC electrical field inside XLPE cable:

- A – stress at full load (max working temperature)
- B – stress without current (ambient temperature)
- C – initial stress just after the voltage application

DC electrical field inside XLPE cable:

- The electrical field distribution on AC cables depends on relative permittivity \( \varepsilon \) of insulating materials and it is quite stable in the range of temperatures between ambient and working temperature. The max electrical stress on the cable \( E_i \) is at the conductor screen.

- On DC cables the electrical field distribution depends on the materials conductivity \( \sigma \) that is strictly related to the temperature and the local electrical stress. While at ambient temperature the electrical field distribution is similar to the AC one, in hot conditions the maximum stress is located at the cable outer screen. This outer stress \( E_o \) is the more critical for the accessories, since it is directly applied to the cable/accessory interface.
1. Electrical DC stress distribution inside the cable insulation is strictly depending on the temperature. At hot temperature the DC stress applied at the interface between cable and accessory is higher.

2. Temperature distribution in the accessory to be calculated for adjusting the value of materials conductivity according to the actual temperature.

3. Electrical DC field plotting to be calculated according to Laplace Law, introducing the conductivity values of materials at their temperature.

4. Calculated stresses can be compared with the design strengths values established by dielectric laboratory tests carried out on accessory materials. This is the design criteria used for AC accessories, but IT IS NOT PROPERLY WORKING IN DC.
Electrical behaviour of pre-molded joint under AC voltage:

Electrical field distribution inside HVAC accessories is determined by the permittivity $\varepsilon$ of insulating materials that is quite stable in the range of temperature between ambient and the maximum service temperature:

Excluding the faults due to poor cable preparation, the typical AC breakdown starting point is in correspondence of the higher stress area, when the stress applied to the joint is exceeding the admissible AC dielectric strength of the insulating material:
Electrical behaviour of pre-molded joint under DC voltage:

When the same joint body is submitted to DC tests, the breakdown typically occurs under the joint semi-conducting stress relief cone, puncturing the XLPE cable insulation.

In DC the breakdown starting point is not the area where the higher electrical stress is applied, but it is the interface between cable and accessory.

There is another phenomenon that strongly affects the accessories performances in DC: the “space charges” accumulation.
SPACE CHARGES PHENOMENON IN DC XLPE CABLES

In the XLPE cables, gases developed during the extrusion process (by-products of the vulcanization) are normally present. The “space charges”, due to the presence of the gases created by residues of peroxide dissociation under the action of the electrical field, are very important in DC, since the electrical stress inside the cable insulation is affected by them.

• XLPE cables are normally submitted to a very long degassing process, heating the cable in the factory for several weeks, before shipping. Nevertheless some space charges remain inside the XLPE cables.

• Accessories have to be designed taking into consideration the presence of space charges, because the DC electrical field can orientate and accumulate them where layers of material with different conductivity are present (i.e. the cable/accessory interface).
Space charges accumulation can affect the design of HVDC accessories:

Space charges accumulation can increase the local electrical stress, creating the conditions for an electrical breakdown. The accumulation of space charges along the cable/accessory interface is strictly depending on the conductivity of the materials.

Surface charge \( K(t) \) at the interface between two dielectrics (A and B) according to Maxwell-Wagner theory:

\[
K = \frac{\varepsilon_A \sigma_B - \varepsilon_B \sigma_A}{\sigma_A dB + \sigma_B dA} \cdot U_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right),
\]

where \( dA, dB \) are the thickness of the two dielectrics, \( \sigma_A, \sigma_B \) their conductivities, \( \varepsilon_A, \varepsilon_B \) the permittivities and \( \tau \) the time constant.

- Higher is the difference in terms of conductivity and/or permittivity for the two materials, greater is the surface charge along their interface.

- For this reason cable insulation and joint insulation should have, as much as possible, similar conductivity values.

![Electrical conductivity at 50°C of some materials tested on HVDC systems](image)

Silicone worst than EPR because its conductivity is 1 order of magnitude greater than EPR one and farer from XLPE conductivity.

P-laser better than XLPE because its conductivity is closer to that of EPR.
HVDC ACCESSORIES: LESSONS LEARNED

• The development of joints and terminations for HVDC extruded cables has required the introduction of specific tests on materials and new design approaches for the prediction of the accessories performances under DC electrical field:
  
  a) Their behaviour is strictly depending on temperature-related insulation characteristics.
  
  b) Accessory performances can be influenced by the phenomenon of the “space charges accumulation” along the interface between cable and accessory, closer are the conductivity values of cable and accessory insulation, lower is the space charges accumulation.

• Accessories with EPR pre-moulded components have shown very good performances on 320 kV DC extruded cables.

• Precautions are recommended during accessories handling to avoid the presence of moisture, very critical for DC applications.

• Preparation of the extruded cable insulation surface very important: skilled jointers and special tools are required for this operation.

• Terminations filled with oil: special treatment (draying + degassing) required for the oil.
AVAILABLE 320 kV DC EXTRUDED CABLE ACCESSORIES

Following 320 kV DC accessories have been qualified and installed on XLPE cable systems with very positive service record:

Outdoor termination
- Composite insulator
- EPR stress cone
- Explosion-proof

G.I.S. termination
- Dry-type
- EPR stress cone

Straight joint
- EPR pre-molded sleeve
- Sectionalized and un-sectionalized

Asymmetrical joint
- EPR stress cones
- Plug-in installation
NEXT STEP: 525/600 kV DC EXTRUDED CABLE SYSTEM

TESTS ON MV EXTRUDED MODEL CABLES (XLPE and P-LASER)

The DC voltage applied on models was calculated in such a way to apply to the joint interface the same average electrical stress present on 320-525 kV DC full-size cables.

Elaspeed joints were submitted to thermal cycles up to 90° C, changing polarity every 10 cycles and increasing the voltage up to breakdown, occurred at 225-230 kV DC.

Interesting results for the development of 525/600 kV DC accessories, because the breakdown stresses reached on models were exceeding the stress that would be applied on 525 kV full-size cables during Type Testing according to CIGRE requirements.

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Elaspeed description:
- Embedded electrode.
- EPR high permittivity layer.
- EPR insulation.
- EPR semiconducting sheath.
- EPR outer sealing sheath.

MV models have been used for testing new joint design and compounds formulation, before going into the full-size accessories development process.
CONCLUSIONS

DC Voltage is very important for long distance power transmission. Future connections up to 525-600 kV DC are expected: extruded cables are ready for this challenge, especially considering the new P-laser cable technology, based on thermoplastic compounds with optimized characteristics for DC applications.

HVDC P-laser cable advantages:

- Thermoplastic compounds (peroxide-free process) extruded with innovative technology line. No gases generated in the cable insulation during the vulcanization.
- No degasing required vs. several weeks necessary for XLPE.
- Conductivity value closer to the EPR one: better condition from the “space charges accumulation” point of view.
- Stable characteristics up to 130° C.

Joints and terminations, today available up to 320 kV DC, are under development up to 525/600 kV DC applications introducing new solutions, innovative design and materials specifically studied for EHVDC applications.
Thank you!

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