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DC extruded Cable Development Testing

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ABSTRACT

Development of insulation systems that can handle a high DC stress is a challenge. Under this condition salts become ions (Onsager effect), ions migrates towards the electrodes. Meanwhile they can be trapped in the polymer material depending on its structure. Surface charges appear at interface where there is a variation of dielectric properties, charges are injected by electrodes.

This is the reason why CIGRE has defined in brochure 496 "Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV" a series of subjects to be addressed during the development of HVDC insulation system.

This paper describes investigation techniques that can address these development tests.

KEYWORDS

Space charge, XLPE, VSC.

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DEFINITION OF DEVELOPMENT TESTS

Development testing of a cable system is defined in CIGRE brochure 496. Development test are "Tests made during the development of the cable system". They differ from Prequalification tests "Test made before supplying on a general commercial basis a type of cable system, in order to demonstrate satisfactory long term performance of the complete cable system.", Type tests " Tests made before supplying on a general commercial basis a type of cable system covered by this recommendation, in order to demonstrate satisfactory performance characteristics to meet the intended application", Routine tests, Sample tests and After installation tests.

The development tests have a free format but must include

- An evaluation of the materials and processes employed. Such evaluations would normally include electrical resistivity assessments, breakdown tests and space charge measurements.
- An analysis of the electric stress distribution within the cable system insulation for a range of typical installation and loading conditions.
- An assessment of the long-term stability, possibly involving factory experiments to assess the ageing effects of various parameters, e.g., electrical stress, temperature, environmental conditions etc.
- An assessment of the sensitivity of the electric stress distribution to the expected variations in cable dimensions, material composition and process conditions (extrusion, post extrusion treatments and finishing.

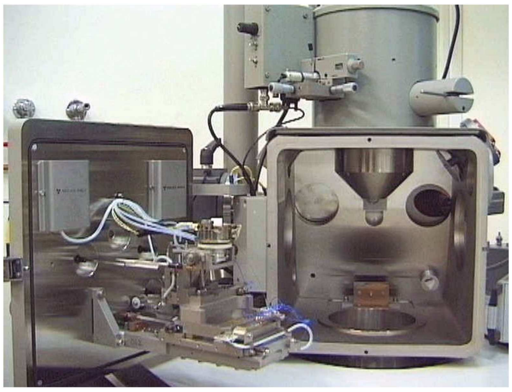
Any additional development test is of course welcome.

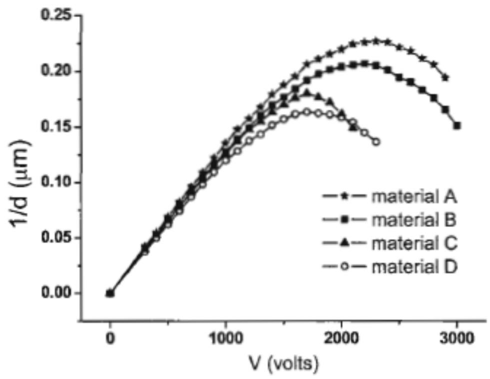
EVALUATION OF MATERIALS

Before being part and interact together as part of an insulation system, dielectrics and electrode material are checked on their own, a series of electric tests are available.

Insulation materials

The mirror method allows characterising the deepest traps energy and density in the insulation material. It is a very clean method as there is no need of electrode close to the observed area.[1]





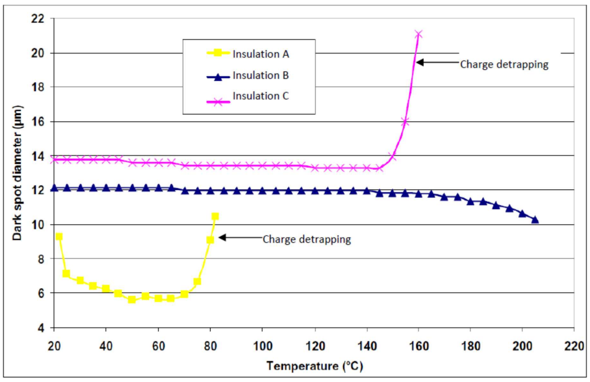


Fig 1: SEM dielectrometer mirror chamber

Mirror curve (trap density) of different materials [1]

Mirror curve (trap depth) of different materials [2]

More traditionally films can be tested between two metal electrodes to measure breakdown strength in DC and impulse condition.

Measurements on film must be carefully handled when extrapolating results to a full size insulation system as the basis for extrapolation of dielectric properties is no known [3]

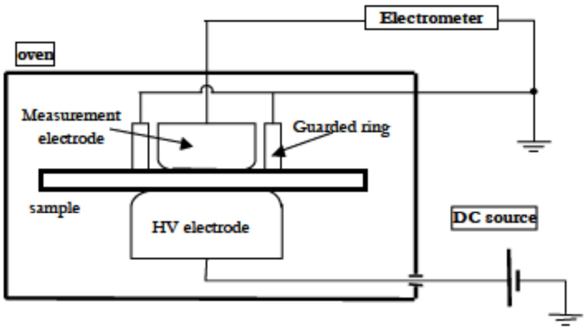


Fig.2: example of arrangement for conductivity measurement on films

Measurement of the insulation conductivity as a function of electric stress and temperature is a key parameter for the dimensioning of HVDC insulation system. Measuring the actual property of the material, taking into account the time constant, the trap density and finally the actual electric field that is applied to the material is a challenge. Details can be found in [4].

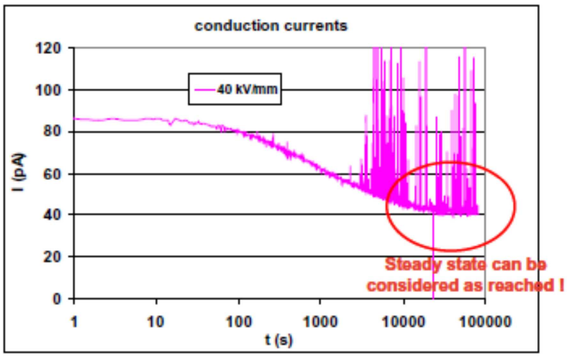


Fig. 3 : example of current recording during a conductivity measurement.

Conductivity measurements can also be addressed using miniature cables. See paragraph "Insulation Systems".

Semi-conductive materials

The main dielectric properties of semi-conductive materials are:

- Conductivity, to screen the insulation during impulse tests, classical techniques are used for this measurement.
- Charge injection and recombination. This is measured as insulation system arrangement because the result is strongly depending on the insulation material.

Insulation systems

Here the combination of insulation and semi-conductive materials is extensively evaluated.

The development proceeds with the study of models that are progressively closer to the final system

The samples are films, miniature cables, model cables, prototype cables.

Films

They are mainly used in order to do a first selection between a huge number (more than 10) of different materials and/or of different combinations of semi-conductive materials and insulations.

Typical tests performed on films are:

- SPACE CHARGES measurements (usually, during polarization with both polarities and in "volt off" conditions to evaluate the dynamic of the decay of the trapped charges. Such tests can be performed at ambient temperature and as a function of different temperatures).
- HVDC TEST UP TO BREAKDOWN (vs. different thermal conditions) see above paragraph on insulation.

Miniature cables

They are used to:
- confirm results obtained by means of film model (but on a number of combination less than 10)
- establish the main parameters used in the mathecmatical models (thermal conductivity / electric

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conductivity «ALFA» / «BETA»).

Typical tests performed on miniature cables are:

- SPACE CHARGES measurements (usually, during polarization with both polarities and in "volt off" conditions to evaluate the dynamic of the decay of the trapped charges. Such tests can be performed at ambient temperature and as a function of different temperatures).
- HVDC TEST UP TO BREAKDOWN (vs. different thermal conditions)
- ELECTRICAL CONDUCTIVITY vs. ELECTRICAL FIELD AND THERMAL CONDITION
- ELECTRO THERMAL AGEING
- REVERSAL POLARITY TEST

the decay of the trapped charges. Such tests can be performed at ambient temperature and as a function of different temperatures).)

- HVDC TEST UP TO BREAKDOWN (vs. different thermal conditions)
- LOADING CYCLES VOLTAGE TEST UP TO BREAKDOWN (voltage is increased once a week or once a month. If a thermal instability condition is reached the voltage is reduced and Model cable will be aged at that voltage level for 1 year)
- IMPULSE TEST
- IMPULSE TEST SUPERIMPOSED ONTO HVDC
- REVERSAL POLARITY TEST

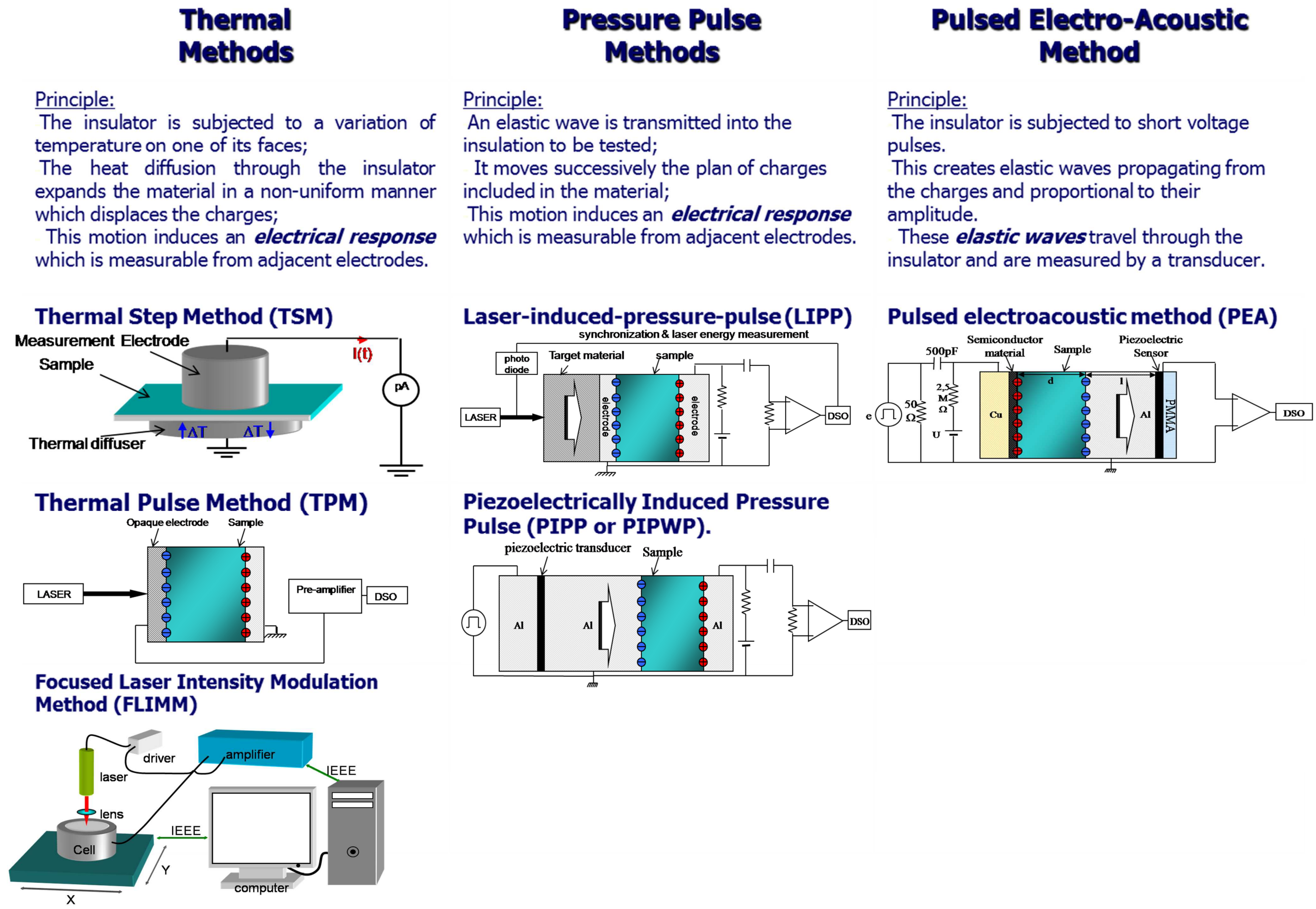

Fig. 4: Principle of space charge measurement techniques

Model cables

They are used to:
- confirm results obtained by means of miniature cable (but on a number of combination less than 5)
- verify the production technology
- better verify electro-thermal ageing performance

Typical tests performed on MODEL CABLES are:

- SPACE SCHARGES measurements (usually, during polarization with both polarities and in "volt off" conditions to evaluate the dynamic of

Prototype cables

They are used to:
- verify realaibility of the production technology
- better verify electro-thermal ageing performance

Typical tests performed on PROTOTYPE CABLE

- LOADING CYCLES VOLTAGE TEST UP TO BREAKDOWN (voltage is increased once a week or once a month. If a thermal instability condition is reached the voltage is reduced and

Model cable will be aged at that voltage level for 1 year)

- IMPULSE TEST
- IMPULSE TEST SUPERIMPOSED ONTO HVDC
- TYPE TEST IN ACCORDANCE TO CIGRE TB 496
- PREQUALIFICATION TEST IN ACCORDANCE TO CIGRE TB 496

Space charges

The measurement of space charges is a common factor for all sample types.

As an example, fig. 5 shows the evolution as a function of stress of space charge on a film of XLPE insulation system [5].

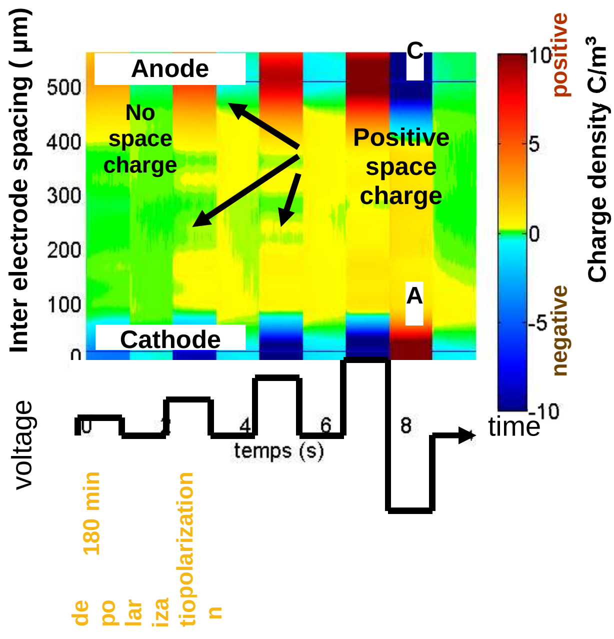

Fig. 5: example of space charge evaluation on a film of XLPE

Space charge is also measured on model cables [6]

Evaluation of processes

Processes must be evaluated from a cleanliness point of view. As seen on Fig. 5, the space charge density inside the material is in the range of some C/m^3. If we assume that the molecular mass of the charge carriers is 100g, and there is one charge per carrier, this gives a quantity of 100/F g/m^3 where F is the Faraday number i.e. 10^5 C/mole.

So the concentration of the charge carrier is 10^{-3}g/m^3 i.e. 1ppb.

This very small quantity cannot be measured through chemical analysis. To assess the process quality, the manufacturer has performed statistical controls addressing the space charge properties for different material batches and production campaigns.

Breakdown tests

Breakdown tests are performed in different voltage and load conditions: HVDC, lightning impulse, superimposed lightning impulse, switching impulse and superimposed switching impulse. This enable to address the thermal stability of insulation and the polarisation effects on the impulse level.

As an example, fig. 6 shows the results of electro-thermal ageing of miniature cables (conductor diameter 10 mm; insulations thickness 5.5 mm). Three samples, 100 m long each one, were submitted to ageing test at constant voltage, followed by weekly voltage step increase; during the test thermal cycles (70℃ to ambient, 8 hours h eating and 16 hours cooling) and 5 polarity reversals per day were performed. The test was interrupted after the cables had withstood 68 kV/mm due to the limit of laboratory terminations [7].

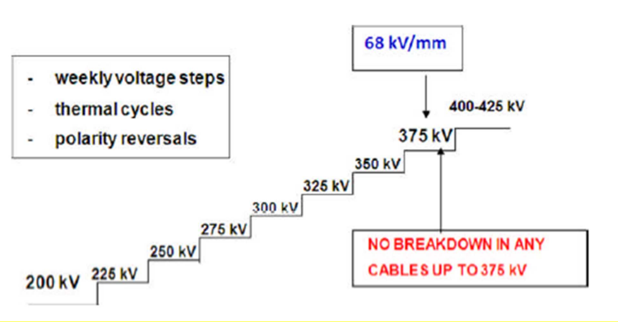

Fig. 6: example of electro-thermal ageing of miniature cables

Space charge measurements

ANALYSIS OF THE ELECTRIC STRESS

Electric stress is usually analysed in terms :

The LAPLACE field:

The LAPLACE field is the electric field that is calculated when there are no charges in the insulation material.

The RESISTIVE field:

The resistive field is the electric field that is calculated taking into account the applied voltage, the temperature profile in the insulation and the dependence of resistivity as a function stress and temperature. When the LAPLACE field is distorted by the variation of resistivity, space charges are created according to the equation:

$$div(E) = \rho/_{\epsilon}$$

A difference in resistivity (or permittivity) at an interface creates a layer of space charge that derives from the local change of electric field.

The FIELD ENHANCEMENT by space charges:

The field enhancement by space charges is the difference between the measured electric field in the insulation and the resistive field. These charges originate from ionisation of salts of the insulation material (Onsager effect), or from injected charges.

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The FIELD ENHANCEMENT FACTOR:

The FIELD ENHANCEMENT FACTOR (FEF) is the ratio of the Total field measured / LAPLACE field at the same location.

The higher the FEF, the more critical is the material.

As an example Fig. 7 shows the electric field that has been measured under voltage and current in a model cable insulation while it was submitted to a high load sequence. The calculated LAPLACE field and RESISTIVE field are shown for reference [6]. The measured total field as a function of time enables the calculation of the FEF, the measurement technique is TSM.

In this case, the FEF is minimum at the electrodes and maximum in the middle of the insulation.

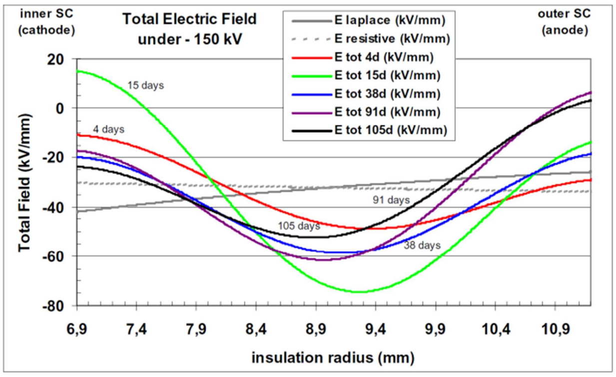

Fig. 7: Total electric field distributions of model cable under applied voltage and thermal gradient. Capacitive and resistive (steady state) distributions have been included for comparison

Other patterns can be measured where the FEF is higher at the electrodes than in the middle of insulation [8].

Fig.8 shows the total electric field measure on a different insulation system under a high load period, the measurement technique is PEA.

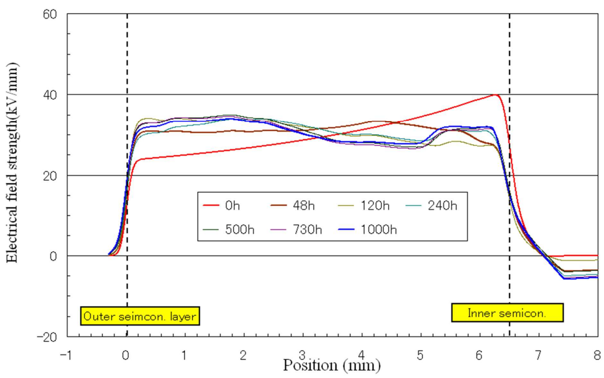

Fig. 8: LAPACLE field and resistive field during a high load period on model cables.

FEF is not the only parameter to select an insulation system. It must be considered as associated to other properties as the dynamic of the charges, trap depth, etc.

LONG TERM STABILITY ASSESSMENT

An evaluation of the attitude of insulating materials to undergo thermal instability under DC polarization can be done by means of temperature measurements during voltage step tests. The example in fig. 8 shows the surface temperature of a miniature cable during a breakdown test under DC field. The cable was insulated with a commercial AC-XLPE and tested at 70℃ with 60 minutes voltage steps. The trend of thermal instability is quite evident. In this case the test was aimed at reaching the breakdown. Similar tests can also be performed with full size cables, usually with voltage steps of longer duration (at least one week) and aimed to evaluate the inception of thermal instability.

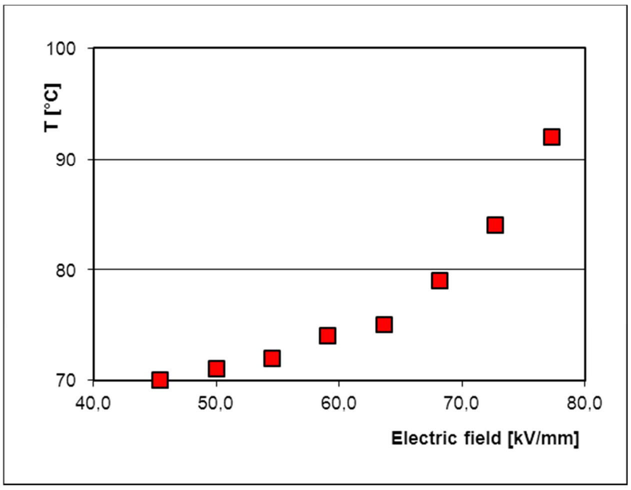

Fig. 9: example of thermal instability during a DC breakdown test of a miniature cables

The final step of the development of extruded cables for DC application is a Prequalification Test on a complete cable system according to CIGRE TB 496.

Fig. 10 shows a cable system submitted to a PQT: the circuit was composed by about 100 meters of XLPE cable, two composite terminations, two straight and two sectionalised joints.

Fig. 10: HVDC cable system during a Prequalification Test according to CIGRE TB 496

SENSITIVITY TO MATERIAL AND PROCESSES VARIATIONS

HVDC insulation systems are very sensitive to small variation in the chemical composition of the materials. It is the know-how of the manufacturer to master it through a fine tuned material and process control [2].

CONCLUSION

The HVDC extruded cable systems have a bright future, first for underground transmission projects where there is a preference for HVDC extruded due to the efficiency of jointing and the reduced weight as compared with the MI cable. Engineers have developed cables systems that comply with the CIGRE TB 496 qualification recommendation. Through further development tests, operation feedback, academic and applied research, the questions about the long term behaviour will get an answer and the design rules will be improved consequently.

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