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INTERFACES IN ACCESSORIES FOR EXTRUDED HV AND EHV CABLES

Joint Task Force
21/15

August 2002

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Prepared by

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Keywords: interfaces, accessories, cable systems, extruded cables

1 INTRODUCTION

Although interfaces in joints and terminations of extruded HV cables have been identified as crucial parts, some of the mechanisms related to ageing are not well understood. For this reason, a task force has been established to study the behaviour of interfaces in accessories for HV and EHV extruded cables. The scope is limited to non-bonded interfaces between solid insulating materials, but includes the applied lubricants.

The Joint task force 21/15 (JTF21/15) is installed by Study Committee SC21 (Insulated Cables) and SC15 (Materials) and is called ‘Interfaces in accessories for extruded HV and EHV cables’. The members of the task force are cable systems and/or materials experts.

Within CIGRE, interfaces are also subject of study for WG15.10. This working group is concentrating on the material aspects of interfaces and has developed and selected interface models for laboratory testing.

1.1 Terms of reference of JTF 21/15

The joint task force is reviewing the state of the art regarding the interface behaviour in accessories for extruded HV and EHV cables.

The objectives for JTF 21/15 were:

a. to evaluate short term behaviour of interfaces (parameters influencing withstand strength)
b. to evaluate ageing behaviour and relevant parameters
c. to make practical recommendations for evaluating, testing and installing interfaces in extruded HV and EHV cable systems

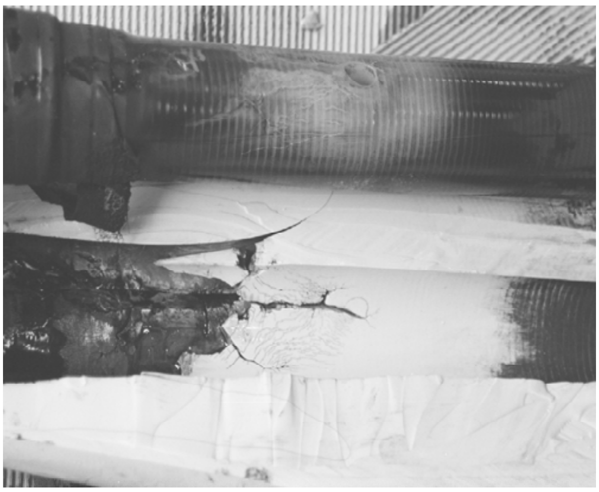

Figure 1: Electrical treeing in an interface, leading to failure of the termination [31]

The task force will not deal with partial discharges and electrical treeing in interfaces, since these processes are strongly influenced by the type of accessories (materials, design, etc.). The focus will be on the parameter settings to prevent partial discharges in interfaces and those phenomena that could lead to partial discharges in service. Partial discharge detection on installed cable systems was studied by Cigré WG 21-16 [26].

1.2 Interfaces to be studied

The interfaces to be studied are those in accessories for extruded HV and EHV cables between solid insulating materials. Although the cable is an essential part of the accessory, it will not always be explicitly mentioned.

Interfaces in accessories are between (figure 2):

- rubber insulating body and cable insulation, in a liquid or gas filled termination (a), in a dry-type termination (b), in a composite joint (c) or in a premoulded joint (d)
- stress-cone and epoxy body, in a dry-type termination (b) or composite joint (c)
- adaptor sleeve and joint body (e)

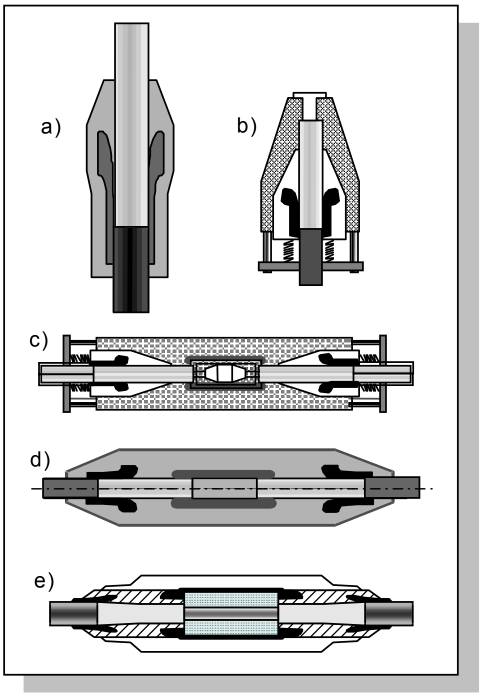

Figure 2: Typical accessory arrangements for HV extruded cables [1]

1.3 Materials involved

Interfaces exist between two solid polymer parts. The materials involved in these interfaces and various related abbreviations are summarized in Table 1. The international standards dealing with symbols and abbreviations of polymers respectively rubber and latices appear not to be harmonized yet.

Polyethylene mainly divides into two big families: LDPE (Low Density Poly Ethylene, density in the range 0.910-0.925 g/cm^3) and HDPE (High Density Poly Ethylene, density in the range 0.941-0.965). In addition to these two main families it is worth mentioning LLDPE (Linear Low Density Poly Ethylene). In cable manufacturing PE is used both for insulation and for jacketing. The cross-linking (peroxide or silane) of PE leads to XLPE (Cross Linked Poly Ethylene) and is widely used both for MV and HV cables, particularly for allowing high operating temperatures up to 90°C.

The general term EPR is used as an abbreviation for Ethylene Propylene Rubber (see Table 1). EPR divides into two kinds of polyolefin polymers: EPM and EPDM. EPM represents an Ethylene Propylene copolymer while EPDM denotes a terpolymer based on three monomers: Ethylene, Propylene and a non-conjugated Diene. Both grades EPM and EPDM are suitable for peroxide cross-linking while only EPDM allows sulphur cross-linking. Mixing of EPR with other components leads to the final EPR compounds for power cables and accessories applications.

SiR consists of a so-called silicone-oxygen (polysiloxane) polymeric main chain, which exhibits high thermal and high UV stability. This main polymeric chain carries methyl-groups as well as other functional groups like vinyl- or hydrogen-functions. RTV, XLR, LR or HTV (definitions see Table 1) rubbers are the most widely used grades in electrical applications. Whereas RTV-2, XLR and LR are vulcanised by a so-called addition curing reaction of A- and B-component, HTV rubber normally is peroxide cross-linked. The main differences in RTV-2 versus LR or HTV are viscosity and processing. SiR can be formulated to obtain very low Shore hardness and modulus of elasticity [9].

Various types of Epoxy and fillers are used for electrical applications. Among them a typical resin system is solid Bisphenol A type [2,2-Bis-(-4-hydroxyphenyl)-propane)] epoxy resin. Technical production of oligomeric epoxy resins involves reaction of Bisphenol A with Epichlorhydrin to give a reactive intermediate. These reactive epoxy resin intermediates are the basis, which is polymerized (polyaddition) with so called hardeners. Hardeners could be either solid powdery acid anhydrides or aliphatic polyamines resp. polyamidoamines. Cycloaliphatic epoxy resins are cured normally with acid anhydrides. Aminic systems can be hardened at room temperature or below 80°C, while acidic systems need temperatures over 80°C for hardening. Results are the various Epoxies, which are classified as duroplastics.

Lubricants are widely used as slip-on materials to ease the installation of cable accessories. Silicone greases as well as silicone fluids can be used with either SiR or EPR accessories. Other materials are greases based on fluorinated polymers or polyethylene glycol modified greases. Generally speaking, grease is formulated from a liquid basis polymer and a thickener, mostly silica flour and some additives. In contrast to grease e.g. silicone fluid is a pure silicone polymer. Regarding installation and the interface, the degree and speed of migration of the paste into the insulating material are of interest. In the case of a pure fluid, the interface may get dry after a certain period of time, while, for greases, the thickener may remain in the interface after the fluid migrates [5].

Table 1: Summary of symbols and abbreviations of plastics

Abbreviation in literature	**Material (as used in this paper)**	**Abbreviation (as used in this paper)**	**DIN ISO 1629 Mar 1992**	**DIN EN ISO 1043 Part 1 Jan 2000**
SiR, SIR, MVQ, VMQ*)	Silicone rubber	**SiR**	MVQ, VMQ	SI
RTV RTV-2	Room Temperature Vulcanising, 2-component silicone rubber	**RTV**		
LR, LSR XLR	Liquid Rubber, Liquid Silicone Rubber, Extra Liquid Rubber	**LR**		
HTV, HCR	High Temperature Vulcanising, High Consistency Rubber	**HTV**		
EPR	Ethylene Propylene Rubber	**EPR**	EPM **)	E/P
EPM EPM, P	Ethylene Propylene Copolymer ('EPM, P' stands for peroxide vulcanised EPM)	**EPM**	EPM	E/P
EPDM EPDM, S EPDM, P	Ethylene Propylene Diene Terpolymer ('EPDM, S' stands for sulphur vulcanised; 'EPDM, P' see above)	**EPDM**	EPDM	-
EP	Epoxy resin	**Epoxy**	-	EP
HDPE, LDPE	High Density Polyethylene, Low Density Polyethylene	**PE**	-	PE PE-LD PE-HD
XLPE	Cross-linked polyethylene	**XLPE**	-	PE-X
	Grease, silicone oil, paste, lubricant	**Lubricant**	-	-

*) Q indicates rubbers with poly-siloxane-groups in the main chain, e.g. MVQ = Methyl-Vinyl-Poly-Siloxane
**) M indicates rubbers with saturated poly-methylene main chain; R indicates rubbers with unsaturated poly-carbon main chain. Note: this deviates from the wide spread use to indicate rubbers in general by R.

2 INTERFACE PARAMETERS

Interfaces are characterized by the initial or short-term breakdown strength and long-term ageing properties. In section 3 the ageing phenomena will be discussed while in this section the focus will be on the initial breakdown strength.

The electrical withstand strength of interfaces is influenced by a combination of several parameters. In the design of interfaces the following parameters should be taken into account:

1. smoothness of the surfaces
2. contact pressure on the interface
3. type of lubricant in the interface
4. electrical field distribution in the interface
5. temperature and temperature changes
6. quality of accessory installation

Most of the parameters mentioned interact with each other. In the following paragraphs, the parameters will be discussed separately.

2.1. Smoothness of the surfaces

A partial discharge in a cavity in insulating materials occurs at roughly the same or higher inception voltage as between equally spaced metal electrodes [2]. The inception voltage between metal electrodes for a certain gas is given by the Paschen curve. According to this curve, the breakdown stress of a gap depends on the gap distance, type of gas and pressure in the gap. At fixed pressure, the Paschen curve indicates higher breakdown stresses for smaller gaps. In line with the diagram in fig. 3 the smaller the cavities, the higher the stresses at which partial discharges incept.

Interfaces without microscopic cavities do not exist, and surface scratches in the order of a few microns are inevitable. In order to avoid partial discharges arising form these scratches, the size of cavities should be limited to a few microns (depending on the electrical stress). Therefore an accurate adaptation of the insulating surfaces in the interface is needed. This can be achieved by smoothing of the insulation surfaces.

Typical example for calculating the surface smoothness from the Paschen curves [2].

Assume a typical radial stress in the cable insulation, adjacent to the interface, of 3.6 kV/mm at Uo (radial stress at the insulation screen of the cable) and assume that the accessory is required to be free of partial discharges at 2Uo, then the inception stress in a possible gap has to be higher than:

$$E_{gap} = \varepsilon_{r,PE}/\varepsilon_{r,cav} \times E_{min} \times 2$$
$$= 2.3/1 \times 3.6 \times 2 = 16.6 \text{ kV/mm}$$

Reading from figure 3, the cavity size in such case has to be smaller than about 20µm.
Sanding with grade 400 leads to a roughness R_z= 10 µm (R_z=R_{max}-R_{min}).
Assuming that the mould irregularities are significantly smaller (order of 1µm), the achieved cable insulation smoothness with paper grade 400 is sufficient.

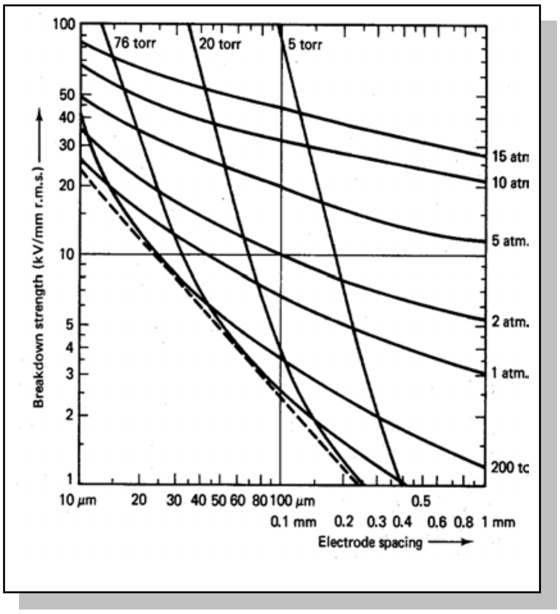

Figure 3: Breakdown strength of air gaps, derived from the Paschen Curve [2]

The surface smoothness of moulded rubber or epoxy insulators can be achieved by equivalent surface smoothness of the moulds. Smoothness in the order of a few micrometers can be achieved without difficulties. The surface smoothness of the cable insulation, however, depends on the applied peeling and smoothing techniques, performed on site in a less well-controlled environment. This part of the interface depends on the jointer skills. Therefore it is desirable, particularly for high stress accessory designs, to prescribe the required smoothing technique for the preparation of the cable insulation. Although interface pressure is discussed in a separate paragraph, it is mentioned here that the pressure in the interface and the adaptability of the insulating materials determine the sensitivity to surface irregularities.

2.2. Contact pressure

As described in paragraph 2.1, the sensitivity of the interface to irregularities depends on the interface pressure (figure 4). High interface pressures minimize the size of micro cavities in the interface. In practice, two different methods to achieve the required interface pressure have proven to be suitable:

1. application of external mechanical forces, using springs. This method is used in the so-called inner cone model of composite joints or dry-type terminations, pushing a rubber part against an epoxy body
2. use of elasticity of the rubber body expanded on the cable insulation. This method is used in slip-on joints and stress-cones. Expansion percentages of 5 to 50% are common practice. The interface pressure obtained by this method depends on:
   - E-modules of the applied rubbers
   - strain of the rubbers
   - wall thickness of the rubber

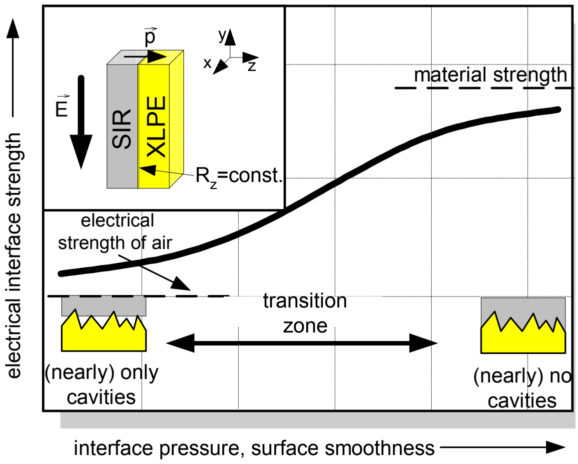

Figure 4: electrical interface strength vs. interface pressure and surface smoothness [3]

2.3. Lubricant

Lubricants are basically used to relieve the friction between rubber parts and the other insulating materials during installation. Silicone fluids and greases are commonly used for this application.

Lubricants also tend to increase the initial breakdown strength (figure 5). However it is not recommended to use lubricants for this reason. On the long-term, lubricants probably migrate (at least partly), resulting in a more or less dry interface, possibly leaving air gaps behind.

The migration rate of the lubricant depends on:

- type of lubricant
- type of insulating materials
- contact pressure
- temperature

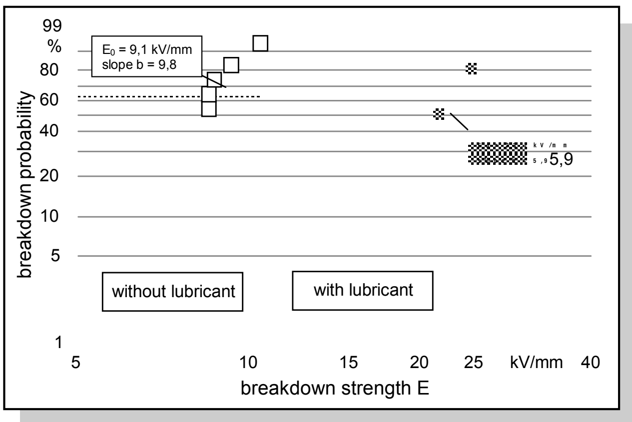

Figure 5: effect of lubricant oil on the breakdown strength of a typical XLPE-SIR interface [3]

Another issue regarding lubricants is the presence of air bubbles trapped in the interface during installation. In particular greases with a high viscosity are more likely to enclose air bubbles. The design of the accessory or the applied installation method should prevent the formation of air bubbles.

2.4. Electrical field distribution

During operation of the cable system, the interfaces are subjected to electrical stresses (figure 6). The following stress characteristics can be distinguished:

- direction
- amplitude
- distribution

The component along the surface of the insulators is called the parallel, longitudinal or tangential electrical stress and is generally regarded as the most important one. Also the amplitude (e.g. for inception of partial discharges) and the distribution (e.g. for electrical treeing) will affect the interface behaviour.

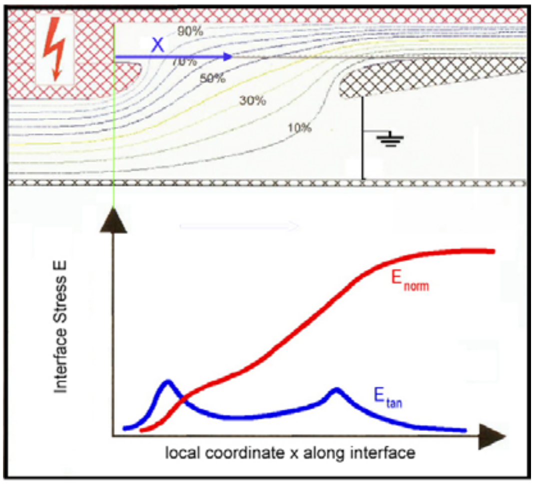

Figure 6: typical electrical field distribution in the interface of a pre-moulded joint

It is preferred that areas with highest electrical stress coincide with highest interface pressure. In most of the accessory designs the shape of the stress-cones and embedded electrodes control the electrical field distribution.

2.5. Temperature and temperature changes

It is known that operating temperatures influence the withstand stresses of insulating materials. Although this might contribute to the weakening of the interface, thermo-mechanical effects usually have a much larger influence at the interface, as they could lead to movements along the interface. Reasons are e.g. differences in thermal expansion coefficients or external mechanical forces. In this respect temperature changes, i.e., temperature cycling and/or temperature gradient, are of more importance than temperature itself.

High temperatures in cable and accessories can lead to deformations of the cable insulation. During the cooling down period of cable and accessories thermal shrinkage of materials will occur. This may result in pressure changes at the interface and should be properly taken into account during accessory design.

2.6 Quality of accessory installation

The installation of accessories is considered as the most critical step in realizing a cable system. In particular, the interfaces are influenced by the installation, since in most cases the cable insulation is prepared on site. The insulation surface must be prepared most carefully. Installation instructions must clearly indicate the cable preparation, including the smoothing technique and/or the required smoothness. During installation, also the positioning of components is of utmost importance. The installation procedure and instructions, including the drawings, must be clear and unambiguous.

During the installation the following aspects should be taken into account:

- final cable diameter and roundness
- straightness of the cable
- smooth and regular insulation surface
- smooth and regular transition from insulation screen to cable insulation

- correct positioning of accessory parts
- dryness and cleanliness

It is essential that the jointers shall be well trained, to provide the necessary skills.

3 LONG TERM PERFORMANCE OF INTERFACES IN CABLE ACCESSORIES

The ageing of interfaces can be considered as a change in one or more of the parameters mentioned above, leading to a decrease of the dielectric strength of the interface. Electrical ageing of interfaces, as a result of intrinsic electrical ageing of the applied materials, is not likely to occur. The electrical stresses in interfaces are low compared to the withstand stresses used for cables and accessories [3]. More likely, mechanical and thermo-mechanical effects change the interface parameters. Thermo-mechanical effects can cause formation of cavities and in extreme situations even gaps between the insulating materials. It is obvious that gaps or large voids cause partial discharging, followed by electrical treeing or tracking in the interface.

The formation of cavities and gaps in interfaces can be the result of a combination of effects, such as:

- migration of the lubricant
- movements in the interface
- reduction of the interface pressure due to relaxation of materials
- electrical ageing of interfaces
- contamination of the interface

3.1 Migration of the lubricant

It is general practice to use lubricants in accessories to relieve the friction between cable and accessory parts during installation. Already during the installation most of the lubricant is pushed out of the interface. The remaining film of lubricant will disappear in time, due to migration into the insulation materials. Depending on the type of lubricant and the materials applied, the migration time can vary between hours and years. Greases composed of fluid and solid filler can dry out (migration into the insulating materials), leaving filler behind. Sufficient interface pressure in combination with the smoothness of the surfaces will prevent the formation of cavities.

3.2 Movements in the interface

Interfaces have been shaped carefully in order to obtain a secure fit between the insulating surfaces. If the insulating surfaces can move in respect to one another, due to thermal expansion or external forces, the interface pressure can decline locally causing a weak spot and in some extreme cases even gaps in the interface. The insulating surfaces shall be shaped in such a way that if movements can occur, this will not lead to the formation of gaps.

3.3 Reduction of the interface pressure due to relaxation of materials

Interface pressure can decrease due to deformation of the cable insulation or due to relaxation of the rubber.

Deformation of the cable insulation can occur at high temperatures. The accessory design has to prevent unacceptable deformation of the cable insulation.

Relaxation of the rubber can occur in those designs where the interface pressure is achieved by expanding a rubber sleeve onto the cable insulation. To prevent critical low interface pressures, the setting of the rubber should stabilize at a safe value. Important parameters describing the setting of rubber are the so-called compression set and tension set.

In the case of interface pressure applied by external means (i.e. springs), their mechanical design has to secure a sufficient pressure level during the lifetime.

3.4 Electrical ageing of interfaces

Due to the fact that partial discharge is a symptom of an insulation defect, the inception and occurrence of partial discharges may accompany the electrical ageing of interfaces as well. Because of the different accessory designs on the market, it is impossible to deduce a single relationship between the magnitude of partial discharges and the remaining lifetime. However partial discharge characteristics and its development may give indications for the incipient failure [29, 30].

4 TESTING

There are several ways interfaces in HV accessories can be tested. Roughly speaking we can distinguish between laboratory testing and on site testing. Laboratory tests can be performed at different levels:

- Material test
- Model tests on material samples
- System tests on cable and accessories

As none of these tests can solely represent the characteristics of the interface in field operation completely, the optimum has to be found in a combination of these tests.

Regarding an interface, the breakdown strength of the insulation materials itself is of minor importance, due to the lower electrical stresses in the interface section. More important for the interface breakdown strength are the mechanical properties of the materials, i.e.:

- Modulus of elasticity
- Hardness
- Compression set or tension set
- Surface roughness

The right combination of these mechanical properties has to ensure a tight fit between the insulation surfaces, thus leading to the required electrical interface performance.

Tests on interface models offer the possibility of a statistical result evaluation of different interfaces at relatively low cost. Cigré WG15.10 deals with the subject of models intensively [17]. An important conclusion that can be drawn from their work is that different model types should be used to investigate different aspects of electrically and/or mechanically stressed interfaces. A model for real accessory design purposes should be a realistic simulation of the practical interface situation [20, 27], or e.g. by using a lower voltage class accessory of the same design [29].

A good interface design has to prevent inception of partial discharges. Therefore the models studying electrical treeing in interfaces can be of importance for basic material investigation. For the evaluation of interface design parameters, partial discharge free arrangements are more suitable. The results of model tests can directly be used for comparison of different parameter settings. The absolute values can be transferred to real accessory designs, using special algorithms, but should be done with great care.

Once a design is completed, prototypes subjected to system tests are indispensable for the qualification of interfaces.

Development tests on systems should represent electrical, thermal and thermo-mechanical service conditions. For this reason it is recommended to include the following conditions in the development test program:

- Elevated electrical stresses to accelerate ageing

- Mechanical stress to simulate installation and service conditions
- Thermo mechanical stress during load cycles
- Transient voltages as impulse voltage
- Partial discharge monitoring (continuously or periodically)

In particular the thermo-mechanical conditions are most complicated to predict. The thermo-mechanical forces highly depend on the design and the way of installation e.g.: flexible and rigid installations, load and environmental conditions. During the development and qualification of HV cable systems, the accessories should be installed in practical worst-case condition (maximum mechanical forces). Tests should incorporate heating cycles and voltage simultaneously. During the cycle period, partial discharge measurements should be made at different conductor temperatures. After thermo-mechanical ageing it is recommended to perform the impulse voltage test, in order to detect possible weakening of the interface.
To verify the performance of the interface and the complete accessory, the prequalification test as recommended by Cigre [6] and standardized by IEC [7] is a necessary and reliable method for testing.

Outdoor terminations sometimes have to operate at low temperatures. This circumstance can represent a more critical condition for interfaces than elevated temperatures. Testing of these terminations in cold conditions and varying temperatures should be taken into account during the development.

The final step in commissioning a cable system is the after laying test. The AC voltage test is an important one to verify the correct preparation and installation of the accessories on site [12, 13]. Testing with DC voltage is not recommended. The electrical field distribution in the interface for DC voltage can differ completely from that for AC voltage.

If there is a need for monitoring accessories in service (e.g. higher failure rate than normal), the most appropriate test method is on-line partial discharge monitoring. The partial discharge tests are preferably executed under different environmental and/or load conditions, in order to determine the thermo-mechanical impact on the interface. The recommended frequency of testing will highly depend on the nature of the discharge pattern and accessory type. In high stress accessories (e.g. slip-on joints for EHV) partial discharges in interfaces of the order of a few pico-coulombs can lead to breakdown within hours, while for some low stress accessories (e.g. outdoor termination) partial discharges in interfaces can be withstood sometimes for several years.

5 RECOMMENDATIONS AND CONCLUSIONS

Interfaces in HV and EHV cable accessories should be designed in such a way that, under operating conditions, a tight fit between cable and accessory or between other insulating bodies is always secured. Once the insulating surfaces do not adapt carefully, cavities will be formed leading to inception of partial discharges.

A proper interface design does not allow partial discharges. Once discharges have been initiated and continue to occur, probably electrical ageing in the form of electrical treeing or tracking in the interface is progressing and finally leads to failure of the accessory.

The reliability of interfaces in HV and EHV extruded cable accessories is strongly dependent on the mechanical and thermo-mechanical design of the accessories and the interaction with its environment, i.e. method of installation and service conditions. During the development of cable systems, these circumstances have to be taken into account. For this reason the long term or prequalification tests of the entire system (cable and accessories) is of eminent importance.

The quality of the interface depends on the cable surface preparation. This has to be ensured by clear procedures, adequate quality management systems (e.g. ISO 9001 [24]) and skilled jointers.

Although there is no general relation between the partial discharges and the remaining lifetime, trend analyses by means of online partial discharge monitoring can give indication if risk of failure is involved for the type of PD patterns observed.

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