ON A COMPARATIVE EVALUATION OF THE RETENTION OF THE HYDROPHOBICITY AND THE TRACKING RESISTANCE OF SILICONE ELASTOMERS UNDER AC AND DC STRESSES

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Abstract: This paper deals with comparative studies under AC and DC stress concerning the retention of hydrophobicity with the Dynamic Drop Test (DDT), the evaluation of the so called "morningstar-inception-characteristic" with a needle test in accordance to IEC 61621 as well as the resistance to tracking and erosion with the Inclined Plane Test (IPT) according to IEC 60587 for insulating materials from silicone elastomers. The results show higher retentions to hydrophobicity under DC stress if rms values are compared, but an approach of the failure time to the temporary loss of hydrophobicity, if equal peak values for AC and DC stress are used. Possible causes are investigated by studying electro-hydrodynamic phenomena on inclined planes and discussed in the paper. Investigations concerning the morningstar inception reveal a higher minimum current for the inception of a morningstar under AC stress, whereas lower times to the morningstar-inception above a certain current can be observed under AC stress than under DC stress. This observation may be a result of the dynamic behaviour of the arc in the chosen test setup. The evaluation of the resistance to tracking and erosion shows as expected higher erosion depths for DC stress than for AC stress. A possible reason may be the influence of electrode corrosion and therefore two different materials are used and discussed. The paper concludes with an outlook on further systematic studies to evaluate the influences from the different behaviour of hydrophobicity and tracking resistance of polymeric insulating materials under AC and DC stress.

1 INTRODUCTION

Polymeric (SIR) insulating materials have favourable electrical properties in wet and polluted conditions because of their hydrophobic character which results in significantly higher flashover voltages and lower leakage currents compared to inorganic materials. Regrettably polymers are thermodynamically unstable. Service experiences of silicone composite insulators show that they remain stable for very long periods. Nevertheless it was found that certain stresses may lead to chemical and physical degradation processes, which may result in a reduction of the hydrophobic properties. Hence the evaluation of the retention of hydrophobicity is important, which can be performed by the Dynamic Drop Test (DDT).

The DDT permits an accelerating evaluation of the retention of hydrophobicity, while the loss of hydrophobicity is caused by the used electrolyte in combination with electrical micro-discharges (multi-stress method). The time to loss of hydrophobicity serves as evaluation criterion. Many investigations have been taken by using the DDT under AC stress, concentrating on parameter studies such like the impact of voltage level for a series of polymeric insulating materials [1], [2]. For a ranking of different materials a comparable surface structure is needed, because the retention of hydrophobicity is an interfacial property.

If the hydrophobic character of a polymeric insulating material is lost and not able to recover, an increase of the leakage current and partial discharge activity can be noticed under wet conditions. Therefore the resistance to tracking and erosion has to be guaranteed. The inclined plane test (IPT) according to IEC 60587 has been developed to evaluate the properties of polymeric materials under electrical stress, moisture and contamination. The IPT is a standardized procedure for AC stress (45…65 Hz). The test parameters are chosen to simulate the worst case and have been acknowledged in many studies [3] a. o.

As a result of a globally increasing application of HVDC systems there is a demand on investigations to the transferability of test results and the applicability of test methods for DC stress with the DDT as well as the IPT.

In this paper the DDT is applied under AC and DC stress. For understanding the mechanisms of the electro-hydrodynamic behaviour of droplets in the DDT a high speed camera is used to investigate these phenomena. Furthermore orientating studies of the influence of test parameters with the IPT under AC and DC stress are realized in this paper. Test parameters such as voltage type, voltage level and test duration were modified for two selected materials. Additionally two different materials of electrodes were used to investigate the influence of electrode corrosion on the erosion process of SIR. Finally a needle test in accordance to IEC 61621 under AC and DC stress is applied. This test arrangement facilitates the simulation of a locally stable arcing stress and the evaluation of the so called “morningstar-inception-characteristic” [4].

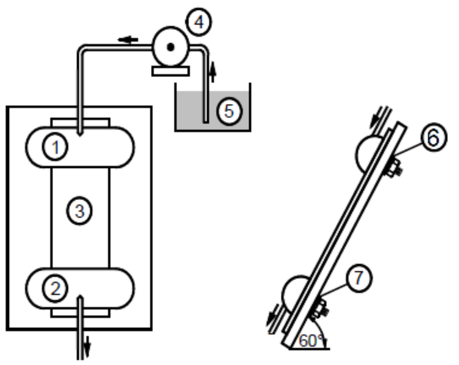
2 EVALUATION OF THE RETENTION OF HYDROPHOBICITY

2.1 Test Material and Test Setup

In the DDT samples from a HCR with an average roughness depth of (3.09 ± 0.716) µm (tactile measurement system) have been tested. In advance of the testing the samples are cleaned with isopropanol and distilled water and rested for min. 24 hours under room climate conditions. The DDT is used to evaluate the retention as well as the recovery of the hydrophobicity after a temporary loss of hydrophobicity caused by an electrical stress in combination with charged water droplets. In **Figure 1** the experimental setup is given. Test parameters are noted in **Table 1**.

Table 1: Test Parameters of DDT

Test Parameter	Value
Distance of electrodes	50 mm
Conductivity of electrolyte	1.5 mS/cm at 20 °C
Flow rate	(1 ± 0.2) ml/min
failure criterion respectively Switch-off criterion (in contrast to [1])	Leakage current > 2 mA for a duration of 2 s
	Test time > 6 h
Drop frequency	(12 ± 1) drops/min^{-1}
Test voltage (AC- and ±DC-stress)	5 kV AC (rms); 7.1 kV AC (peak)
	5 kV DC (rms); 7.1 kV DC (peak)
Number of specimens	8



1 upper high-voltage electrode
2 bottom electrode
3 samples
4 peristaltic pump
5 container for electrolyte
6 high-voltage contact
7 earth contact

Figure 1: Schematic of the DDT

A transformer (35kV/ 4.4 kVA) is used as voltage supply for AC and DC stress. A single-wave rectifier with a ripple factor of max. 18 % is used to generate the DC voltages. These resulting peak and rms values of the rippled DC voltages are compared with the peak and rms values of the AC voltage as shown in **Figure 2**.

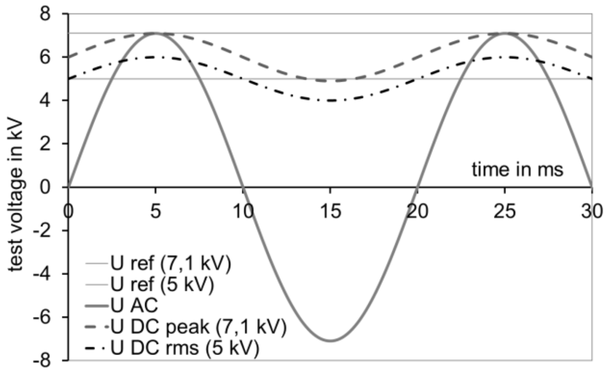


Figure 2: Applied test voltages

The experimental procedure is carried out according to [5].

The study of electro-hydrostatic and electro-hydrodynamic effects was performed by the high speed camera under voltage levels from U = (1…7.1) kV peak for AC and DC stress.

2.2 Results and Discussion

At the beginning of this evaluation electro-hydrostatic and electro-hydrodynamic effects under AC and DC stress are investigated. Droplets with defined volume were created on the upper electrode (**Figure 3**,**Figure 4**).

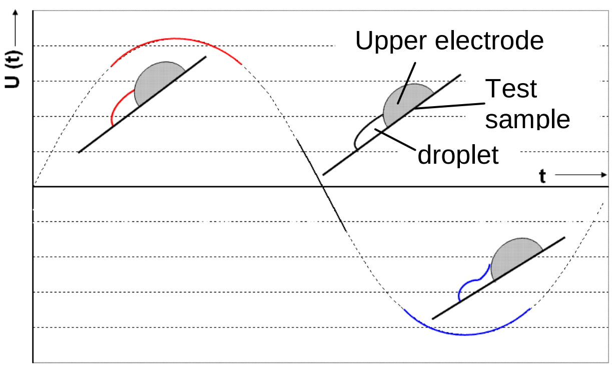


Figure 3: Singular droplet under AC stress

Figure 3 schematically shows the behaviour of an electrolyte droplet under AC stress. The droplet moves in frequency with the applied alternating electric field, in contrast to water droplets on horizontal insulating surfaces without any contact to the electrodes [6], [7]. This observation leads to the assumption that the current value and accordingly the peak of the applied voltage is responsible for the deformation of the droplets in the electric field.

A singular droplet positioned at the upper electrode under DC stress shows no oscillations **(Figure 4)**.

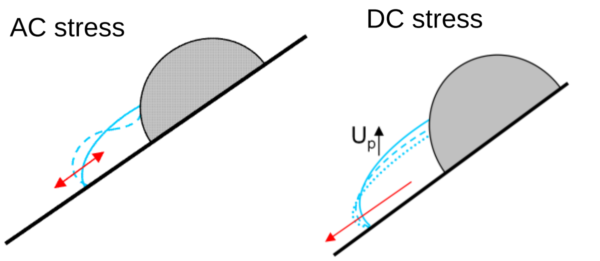


Figure 4: comparison between AC and DC stress of a singular droplet

Increasing field strength leads to deformation in the direction of the applied field. The contact area droplet-specimen remains stable for both used voltage types. Probably the applied electric field strengths are too low to set the droplet in motion.

Further studies of the electro-hydrodynamic phenomena were done by investigating the movement of singular droplets on an inclined surface under AC and DC stress. Again, a clear influence of the applied voltage type is ascertained. At comparable rms values of the test voltage and with an the same volume of the droplets, the shape of rolling droplets under AC stress seems to be compact while droplets under DC stress in the positive and negative polarity are elongated. This observation is confirmed in [8]. Another effect is the secession of electrolyte residues and their adhesion to the surface of the specimen while the droplet is rolling down. It is determined, that the number of electrolyte residues is higher under AC stress. Both the elongation and the formation of electrolyte residues result in an additional increase of the electrical field strength and may possibly lead to a polarity effect for the retention of hydrophobicity under DC stress in the DDT.

The statistical evaluation on the retention of hydrophobicity of a selected silicone elastomer under AC and DC stress is presented in the following.

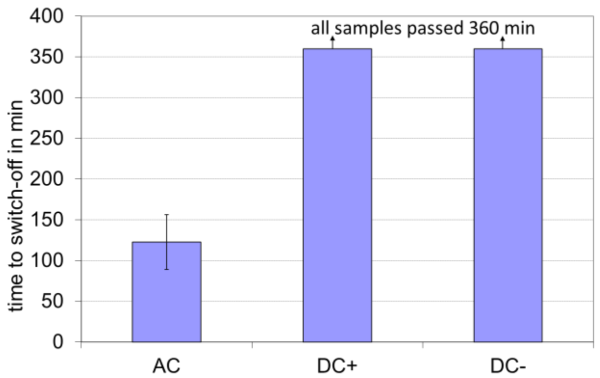


Figure 5: time to switch-off of HCR samples under comparable rms voltage levels

Specimen under AC stress achieved a time to switch-off with a mean of 123 minutes, whereas samples under DC stress with the same rms of 5 kV passed the DDT, and no loss of hydrophobicity within six hours can be noted (**Figure 5**).

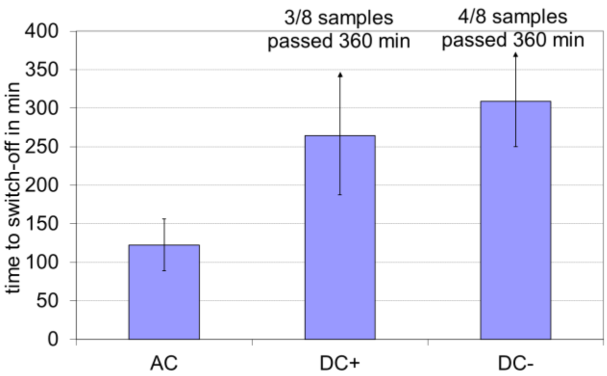


Figure 6: time to switch-off of HCR samples under comparable peak voltage levels

If the DC stress is set to the same peak value like the AC voltage (7.1 kV), the time to switch-off at DC is reduced (**Figure 6**). Four and respectively three test samples pass the DDT within six hours under DC stress and a tend but no significant influence of the polarity is detected.

These results are in correlation with recent findings in the context of WG D1.27 [9]. The investigations were performed with samples of comparable surface properties from HCR and HCEP under AC and DC stress, where the DC source can be considered as an ideal voltage source with a very low ripple factor. Both polymeric insulating materials under comparable AC and DC peak voltage levels show no significant difference in their times to failure. The influence of the ripple of the applied DC voltage should be investigated in further studies.

3 EVALUATION OF THE RESISTANCE TO TRACKING AND EROSION

3.1 Test Material and Experimental Procedure

These investigations are carried out with samples from a HCR and an LSR. Prior to testing the samples are cleaned with isopropanol and distilled water and stored for min. 24 hours under room climate conditions.

For studying the different behaviour of dry band arcing a needle test in accordance to IEC 61621 is used (**Figure 7**). A constant arc current is injected for each testing and can be adjusted by the variable resistor R_{var}. The test parameters are noted in **Table 2.** As evaluation criterion the time to the morningstar inception is used and extends over a period from switch on the voltage to the inception of the morningstar (**Figure 8**). A high speed camera enables the observation of the arc and the recording of the exact moment of the morningstar inception.

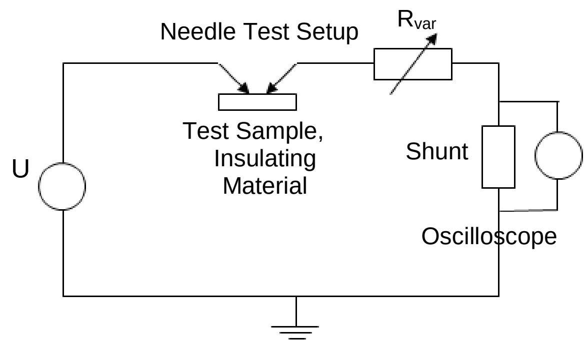


Figure 7: Experimental Test Setup of Needle Test

Table 2: Test Parameters of Needle Test

Test Parameter	Value
Distance of electrodes	6 mm
Inclination angle of electrodes	35 °
arc current	2 mA … 13 mA
Test voltage (AC, ± DC, ripple factor < 0.02 %)	12 kV (rms)
Number of specimens	12

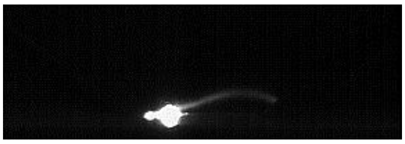


Figure 8: morningstar inception at the left electrode

Parametric investigations in terms of the resistance to tracking and erosion are performed with the inclined plane test according to IEC 60587. The test parameters are given in **Table 3**. The parameters that are standardized for AC stress have been assumed also for DC+ and DC-, the evaluation criterion “erosion depth” is applied.

Table 3: Test Parameters of IPT

Test Parameter	Value
conductivity of electrolyte	2.53 mS/cm at 20 °C
Test time	2 and 6 h
Switch-off criterion, respectively failure criterion	Criterion A: leakage current > 60 mA for a duration of 2 s
Test voltage (AC, ± DC, ripple factor < 0.02 %)	(2.5; 3.5; 4.0; 4.5) kV (rms)
Material of electrodes	Stainless steel, copper
Number of specimens	5 (test time: 6 h) 20 (test time:2 h)

3.2 Results and Discussion

Morningstar Inception

This test arrangement is used to study the dynamic behaviour of AC and DC arcs. Recordings taken from the high speed camera show that the arc that has ignited between the electrodes on the sample`s surface, behaves quite dynamically and changes its arc points continuously. So the time to the inception of a morningstar is dependent on the dynamic behaviour of the arc, where the arc itself is dependent on the applied voltage type. The dynamic behaviour of an AC arc is determined by the extinction of the arc and the inversion of anode and cathode in every half-wave in contrast to a DC arc. This probably leads to a lower temporary and local energy input under AC stress on the sample`s surface than for a DC arc for low currents ($I < 3.5$ mA). If the currents are raised the dynamic behaviour of the DC arc increases, the arc points move up the electrodes (**Figure 9**, **Figure 10**). This behaviour may be caused by the influence of electro-magnetic forces.

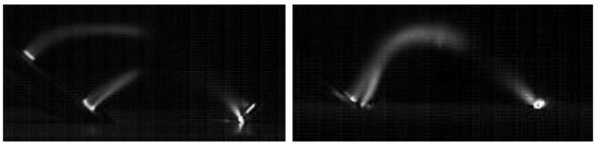


Figure 9: DC arc (left) in comparison to AC arc (right) with the same current of 7.5 mA (rms)

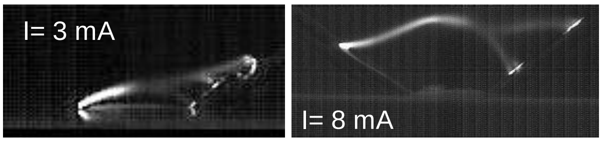


Figure 10: comparison of the arc motion under DC stress for different applied currents

The inception of a morningstar and hence the beginning of deep erosion are caused by the local achievement of the intrinsic decomposition temperature. It can be shown that under AC stress a higher minimum current for the morningstar-inception is necessary than under DC stress for the applied HCR (**Figure 11**).

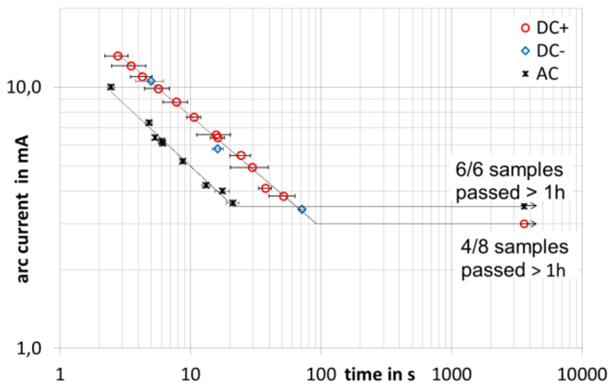


Figure 11: morningstar-inception-characteristic of HCR

The times to the morningstar-inception for currents greater than 3.5 mA are shorter under AC than under DC stress. Both described phenomena are in correlation with observed dynamic behaviour of the arc and by a result of different temporary and local energy inputs for AC and DC stress. These results are in agreement with former investigations with samples from epoxy resins [4].

Resistance to Tracking and Erosion

The inclined plane test is used for both AC and DC voltage to evaluate the resistance to tracking and erosion. Test parameters such as voltage level, material of the electrodes and test duration were modified. To ensure equal stresses, test parameters were chosen which would give no failures of test samples. Therefore the additional evaluation criteria maximal erosion depth and mass loss were applied. Predominantly both criteria are in correlation with each other, so the erosion depth is used as representative evaluation criterion. It is found that predominantly the most intensive erosion (mass loss, erosion depth) for the same test parameters can be observed with DC+, followed by DC- and finally AC stress for both materials (**Figure 12**, **Figure 13**).

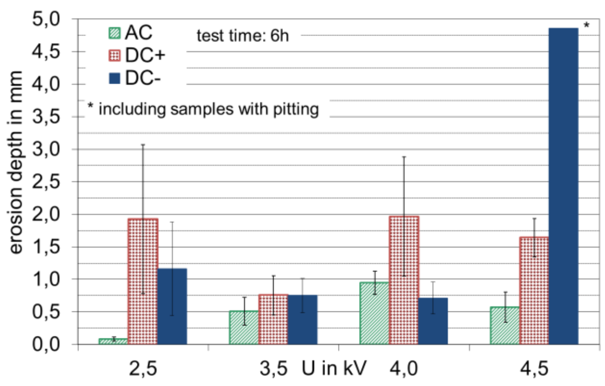


Figure 12: erosion depth of HCR under AC and DC stress (both polarities)

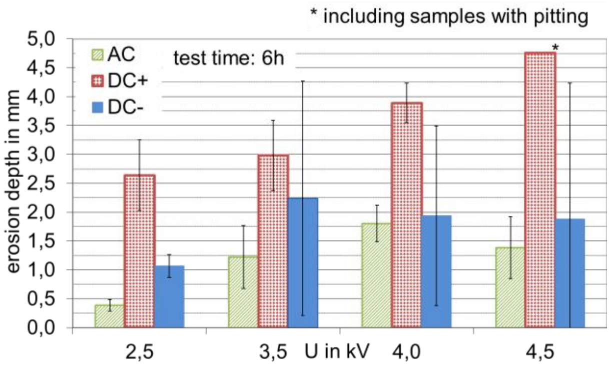


Figure 13: erosion depth of LSR under AC and DC stress (both polarities)

These observations are in correlation with previous studies [5], [10]-[12]. The comparison between the LSR and the HCR shows that, in particular, the used LSR over all voltage types and voltage levels reaches higher erosion depths. So the ranking of the used material does not change with the applied voltage type.

A possible reason for more severe erosion under DC stress can be identified with a higher local burning time of the pre-arcs under DC stress [5]. This results in a higher local energy input under DC stress and may cause more intensive erosion than under AC stress. Furthermore an influence of electrode corrosion especially under DC stress is assumed to affect the erosion process by changing the conductivity of the electrolyte and reacting with the insulating material [13] (**Figure 14**).

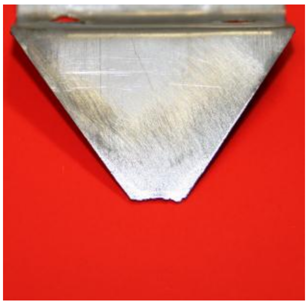


Figure 14: corrosion of upper electrode from stainless steel under 3.5 DC+ for 6 hours

On this account comparative investigations with an increased number of samples and a reduced test time were performed with electrodes from copper and stainless steel for both materials. The results show no significant influence of the electrode material for DC+ stress for both materials, but for samples from LSR under DC- stress (**Figure 15**). Remarkably the used HCR tends to be more susceptible for erosion by using copper electrodes than the used LSR.

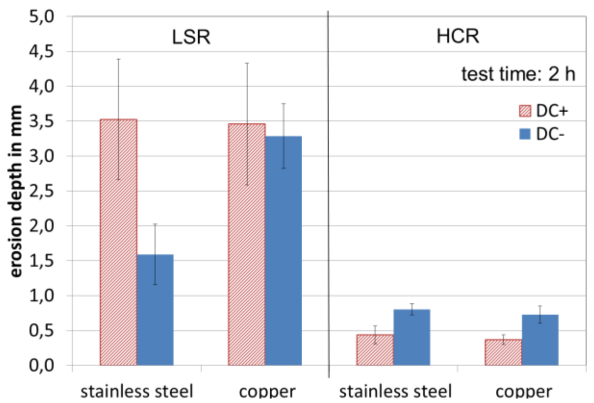


Figure 15: erosion depth for a test voltage of 3.5 kV DC, both polarities

Reactions corrosion product – insulating material are probable. The possible reasons for these observations should to be determined in further studies, for example by variation of the conductivity of the electrolyte or using metal-free electrodes.

The influence of the voltage type on the resistance to tracking and erosion on other insulating materials than SIR cannot clearly be identified. Insulating materials that develop a conductive tracking path may react differently to the applied voltage type. For example HCEP [5] tends to reveal higher erosion under DC stress in contrast to EPDM [11] and CEP [12], which show no significant dependence on the applied voltage type (AC and DC stress) (**Table 4**). A direct comparison of absolute values should be avoided, because of different erosion processes for SIR and other polymeric insulating materials. So the length of the tracking path is an important evaluation criterion for both EPDM and HCEP.

Table 4: comparison of four insulating materials in the IPT for 3,5 kV AC and DC stress for six hours

Evaluation criterion	Voltage Type	LSR	HCR	HCEP [5]	EPDM [11]
Erosion depth in mm	AC	1,224	0,508	<0,01	1,4
	DC+	2,983	0,757	1,16	1,3
	DC-	2,242	0,752	-	1,6

4 CONCLUSION

In this paper investigations on the influence of the voltage type on the retention of hydrophobicity with the DDT were considered. The investigated HCR shows higher retentions to hydrophobicity under DC stress if rms values are compared. In contrast an approach of the failure time to the temporary loss of hydrophobicity is noticed, if the same peak values for AC and DC stress are used. Investigations of electro-hydrodynamic phenomena on inclined planes were done to clarify possible causes. The observations reveal that singular droplets under AC stress move in frequency with the applied alternating electric field and leave electrolyte residues, while they are rolling down. Droplets under DC stress show no oscillations and leave few electrolyte residues, but their droplet shape seems to be quite elongated on the inclined plane.

Further studies should concentrate on the effects of these phenomena on the inception of partial discharges and the initiation of the reduction of the hydrophobicity.

Also investigations to evaluate the morningstar inception by using a needle test under AC and DC stress were done. The results reveal a higher minimum current for the inception of a morningstar under AC stress, whereas lower times to the morningstar-inception above a certain current can be observed under AC stress than under DC stress. Finally evaluations to the resistance to tracking and erosion under AC and DC stress with the IPT were performed. The results show as expected higher erosion depths under DC stress than under AC stress for the used HCR and LSR. A possible reason is a higher local burning time of the pre arcs under DC stress, which results in a higher local energy input and causes more intensive erosion. Additionally electrode corrosion may change the conductivity of the electrolyte and corrosion products are able to react with the insulating material. Therefore first orientating studies with two different electrode materials were carried out. The results reveal no significant differences for DC+ stress for both materials but for samples from LSR under DC- stress.

Further investigations should pay attention to the mechanisms of the erosion of polymeric insulating material and especially the influence of electrode corrosion on the erosion process. Moreover the comparability of insulating materials with different erosion processes (e.g. erosion – SIR, tracking - EP) should be created by using a suitable evaluation criterion.

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