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BREAKDOWN CAUSED BY ABRUPT DC-VOLTAGE GROUNDING OF XLPE CABLE INSULATION

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ABSTRACT

This paper shows that although the DC breakdown voltage of XLPE cable insulation with defects is very high, electric breakdown can occur at defects as a result of abrupt grounding after pre-stressing at a DC voltage considerably lower than the breakdown value of cables without the defects. Laboratory experiments were performed using metallic needles inserted 2.6 mm into the 4 mm thick insulation of 1 m long samples of 12 kV XLPE AC distribution cables. The short term DC breakdown strength samples with needle implants was found to be at about 120 kV, a value 3-10 times higher than that obtained from AC 50 Hz endurance testing. During DC pre-stressing the number of abrupt groundings needed to cause initiation of electric breakdown at the needle tips was found to decrease with increasing voltage level. The number of groundings needed was also found to strongly increase with reduced rate of voltage reduction.

At a DC pre-stress level of 95 kV breakdowns occurred after 107 groundings at a rate of voltage reduction of 0.2 kV/ns, while only 4 groundings was needed to cause breakdown if the rate was increased to 2.6 kV/ns.

The short term DC breakdown strength of reference samples, without needle implants, was found to be higher than 400 kV, and no cable failures occurred after 300 rapid groundings at a DC pre-stress level of 150 kV.

KEYWORDS

Test methods, HVDC cables, XLPE insulation, DC breakdown strength, defects, voltage grounding, grounding resistance.

INTRODUCTION

Due to the high and increasing demand for supply of reliable electric power, more high capacity and long distance high voltage DC cable transmissions are required. Until recently most HVDC cables were equipped with insulation of mass impregnated paper, a type of cable that has shown high service reliability. Due to the shift in high-voltage AC cable technology from paper-insulated to extruded polymer cables there is a strong incentive for the cable manufacturer to develop and produce HVDC cables with extruded polymeric insulation offering the same benefits – flexibility and cost-effectiveness – for HVDC transmission. Among these incentives are also: Application of a larger temperature gradient across the insulation and lighter moisture barrier, giving a lighter more compact cable for the same or even higher power rating. In addition joining of extruded cables is considered simpler than in cases of mass impregnated cables.

As for all cables HV there is a also a need for a sound routine test method for HVDC extruded cables. This is partly related to the uncertain effects of defects, which are likely to be present in minute amounts in any high voltage insulation system. In case of a long HVDC subsea transmission cable one critical insulation irregularity may be sufficient to cause a service breakdown. In order to avoid expensive repairs it is essential to be able to reveal such weaknesses before installation. The methods should be applicable for voltage levels up to 600 kV, and for cable test length more than 50 km.

Qualification testing of long HVAC cables is presently done using AC voltage. The most convenient way of producing the required test voltage is to use a series resonance system, either with a variable inductance or with variable frequency. CIGRE has issued a recommendation for test procedures for routine testing of long HVAC cables [1], and are also discussing the use of AC testing of HVDC cables [2]. This is based on the assumption that, with today’s knowledge, applying a high AC voltage is the best method of detecting defects in extruded cables.

The critical flaws in an insulation system for DC applications may, however, be very different from that of AC insulation, and the test methods should reflect this difference. It is for example not likely that partial discharges are as detrimental in DC insulation as it is in AC insulation. Other flaws in the insulation, such as e.g. non-conducting particles with a conductivity different from the main insulation is not very hazardous in an AC insulation, but may cause high E-field enhancement and be very dangerous in a DC insulation [3]. Another particular phenomenon for DC cables is polarity reversal or rapid grounding which may stress the insulation in ways not significant for AC insulation systems. Generally the techniques used to generate the high AC test-voltage limits the length of cable that can be tested. As the length increases, the testing equipment becomes more and more expensive, and finally the testing costs will limit the application of HVDC cable transmissions.

One alternative test method is that where a length of a cable is exposed to a DC voltage for a certain time after which one end of the cable is rapidly grounded. With the other cable termination open-ended, a considerable cable length will be exposed to a rapid polarity reversal, which may initiate electrical treeing and breakdown at the tip of energized irregularities [4]. When repeated on several test lengths, this procedure should give information about allowable working stress of a cable. If such a test procedure turns out to be successful, it may also be used as a part of qualification tests on long lengths of polymer insulated HVDC cables. Possible disadvantages as attenuations and dispersion have to be addressed.

The main purpose of the work presented here has been to test if such a rapid grounding method can be used to detect metallic conducting needle inclusions. This physical breakdown mechanism and the possible application of this test method to detect defects in HVDC extruded polymer cables will also be discussed.

BACKGROUND

In DC cables both metallic and organic irregularities may cause local field enhancement as they are likely to have a different conductivity/permittivity ratio than that of the surrounding insulation. In addition the electric field distribution in the vicinity of such inclusions is a function of the polymer conductivity. In general the time constant for redistribution of charge in a dielectric is given by:

$$\tau_d = \frac{\varepsilon_0 \varepsilon}{\sigma(E,T)} \qquad [1]$$

where $\varepsilon_0\varepsilon$ is the dielectric constant and σ(E,T) the conductivity. The conductivity is known to increase strongly with increasing temperature and electric field, while the permittivity is constant over a broad temperature and electric field region. This means that if the applied voltage varies with a time constant shorter than τ_d, the electric field at the tip of a conductive inclusion will increase in proportion with the applied DC voltage. At a certain voltage level, the time constant τ_d may become sufficiently reduced to allow charge to be injected into the high field region, due to the increased conductivity in this region [3].

Ieda et al [5] used a needle-plane arrangement with metallic needles inserted in LDPE to simulate the effect of conductive contaminants in practical insulation systems. By applying a DC ramp voltage, it was found that tree inception took place at a voltage that increased with decreasing rate of voltage rise. The calculated field strength at the needle tip exceeded by far expected values of the intrinsic breakdown strength of LDPE. This behaviour was explained as a result of homocharge injection into the region surrounding the needle tip that, when given enough time to develop, modifies the maximum field strength sufficiently to prevent treeing. This was further supported by experiments where the voltage polarity was reversed by applying an impulse voltage of opposite polarity to the applied DC field. It was then found that tree growth started at a much lower voltage. The effect of the voltage reversal was more marked the faster the reversal took place. It was even demonstrated that simply short-circuiting the test specimen after DC poling was sufficient to cause treeing at a voltage lower than the DC tree inception voltage [6]. The reason for this was assumed to be that the injected charge needs long time to be removed, and that the field originating from the injected charge alone is sufficient to cause treeing. This assumption was modified by Zeller et al. [7] who, based upon results from measurements of injected charge from needle tips, introduced the concept of a field-limiting space charge injection (FLSC). They proposed that above a critical field E_C, the mobility of the charge carriers sharply increase allowing the insulation to be considered as a resistor with relatively high conductivity. Space charge is then rapidly injected into the high field region until the electric field at the needle tip is reduced to the critical limit E_C and the high conductivity is switched off. Based upon these assumptions Boggs et al have theoretically shown that local heating takes place due to high power dissipation [8]:

$$P = \sigma(E,T) \cdot E^2 \qquad [2]$$

In regions where creations of space charge density results in substantial current density during the rise of voltage. It is shown that the maximum temperature sharply increase with reduced rise time of the applied voltage impulse. Adjacent to the tip extremely sharp temperature gradients, in the range of 500 K/µm, are proposed to occur for the shortest rise times. In addition to the temperature rise, it is suggested that electric breakdown is facilitated by the electromechanical forces acting at the tip due to the remaining injected space charge. Forces likely to be greater than the yield stress of the insulation at elevated temperatures. This mechanism is also proposed to be active during the growth of electrical trees. The discharges in the tree channels result in sudden changes in the field, which may give rise to space charge formation and substantial temperature rise at the tip of the tree branches.

Recently Ildstad and Selsjord [4] performed laboratory DC breakdown testing of 12 kV XLPE cables with needle implants. Measured short term DC breakdown strengths are presented in fig. 1.

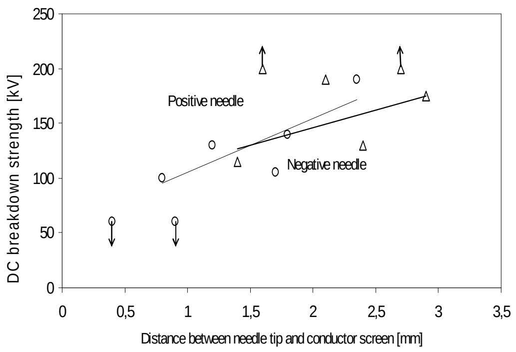

Figure 1: The number of short circuits before breakdown in the insulation as a function of DC pre-stress level for test objects at positive and negative polarity [4].

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The experimental results presented in fig. 2, show clearly that the number of groundings needed to cause a breakdown is strongly decreasing with the DC pre-stress level and was found to be significantly lower in case of negative needle polarity.

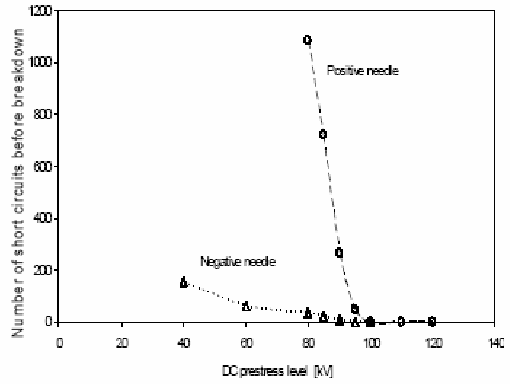

Figure 2: Measured number of short circuits before breakdown of 12 kV XLPE cable samples with needle implants versus positive and negative DC pre-stress level. [4].

Such observations have also previously been qualitatively confirmed by grounding experiments with Rogowski shaped objects of XLPE with semi-conducting needle inclusions [9]. Thus qualitatively it is well documented that conductive inclusions are particularly harmful in case of polarity reversals and rapid voltage transient. It is therefore of great importance that material handling and the manufacturing process is kept extremely clean, and that routine test procedures are available that can detect dangerous inclusion in cable insulation.

EXPERIMENTAL

Cable samples

All experiments were performed using 1 meter long sections of a 12 kV XLPE AC cable. To ensure high voltage testing the samples were equipped with stresscones and with 40 cm long terminations at each cable end. The capacitance of the test objects was found to be C_x= 230 pF.

a)Samples with defects. Into each test object, a nickel plated (sewing) needle, with a tip radius of 50 µm and an overall diameter of 0.8 mm, was inserted through the insulation screen and 2.6 mm into the 4 mm thick XLPE insulation. A specially designed tool was used to reproducibly make the selected distance of 1.4 mm between the needle tip and the conductor screen.

b) Reference samples. Similar cable samples without needle implants. Some of these samples were also equipped with longer terminations for DC short term breakdown testing.

To facilitate rapid (high frequency) grounding of the screen and needle, a metallic mesh was clamped to the insulation screen of each test and securely grounded.

Experimental set up

A sketch of the experimental set up used for DC pre-stressing, and rapid grounding is shown in fig. 3. A sphere gap with a relay driven grounding needle was used as a rapid grounding switch. This relay was digitally controlled by a computer to ensure the same pre-stress time and equal intervals between each grounding surges. A RC filter with a voltage divider was, shown in the right section of fig 3, was used to measure the slope of the voltage reduction.
The rate of voltage reduction, i.e the slope or the front time of the grounding surges, was varied by using selecting grounding resistances R in the range of 90 to 500 Ω.

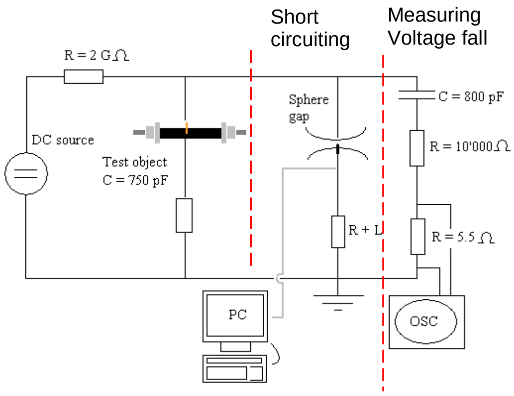

Figure 3: Experimental set up for DC pre-stressing and grounding of the test objects.

The short term DC breakdown strengths of the reference samples were measured using a 800 kV DC source. The AC endurance testing of test objects with needle implants was performed by applying AC 50 Hz voltages in the range of 15- 50 kV and measuring the time to breakdown.

DC Test procedure

The results presented in fig 2 shows that negative needle polarity is more critical than if the needle tip is kept at positive polarity. Therefore during this experiment positive voltage was applied to the cable conductor making the needle a cathode during DC pre-stressing.
The following test procedure was used:

1. First the short-term DC breakdown level was established for each type of test object. This was done by increasing DC voltage in steps of 10 kV every 15 minute until breakdown occurred.
2. Before the first rapid voltage grounding, the samples were subjected to a DC pre-stress for 24 hours. The voltage level used was 50-95 % of the observed short term DC breakdown

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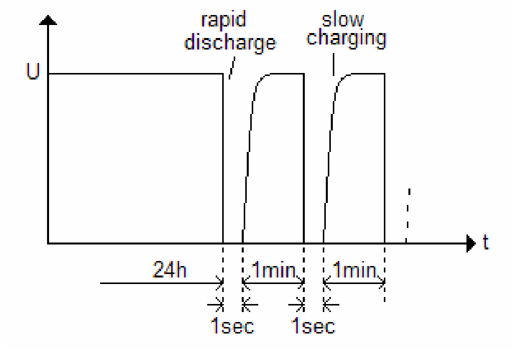
value. - The applied voltage was increased to the selected pre-stress level within 1 minute. During testing 2 cable samples with implants and 1 reference sample were examined in parallel.

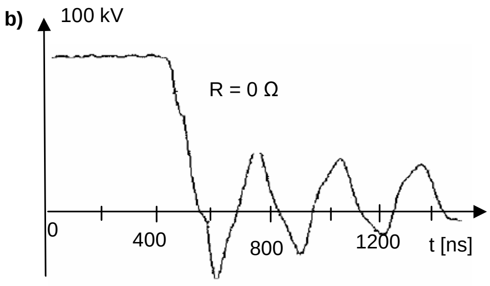
3. When operating the grounding switch the voltage was rapidly reduced to zero at a rate determined by the total capacitance of the test equipment and the impedance of the grounding loop. By varying the grounding resistance R the rate of voltage change during grounding was measured to vary between dV/dt = 2.6 and 0.2 kV/ns.

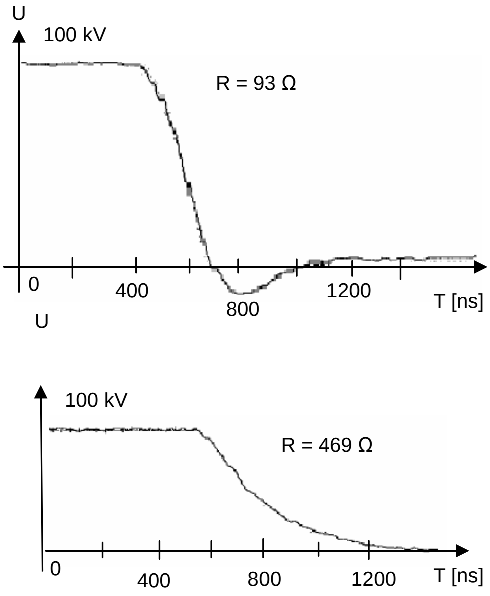
4. After 1 second grounding, the DC voltage slowly builds up across the test object according to $U(t)= U_0 (1-\exp(-t/\tau))$, with a time constant τ = RC of about 0.1 sec. Electrical breakdown occurred if the applied test voltage U_0 became higher than the voltage withstand of the sample. Hence a short circuit DC current was detected and the test procedure terminated. During testing groundings was performed once a minute.

Thus the voltage applied across the test objects during DC pre-stressing and grounding varied as illustrated in fig 4.



a) DC Pre-stressing and grounding procedure





b) Measured voltage reductions using the indicated grounding resistances.

Figure 4: Illustration of the applied voltage during DC pre-stressing and grounding.

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RESULTS

Effect of DC pre-stress level and rapid grounding

Fig. 6 shows results from measurements of the DC breakdown strength as a function of pre-stress level and number of short circuits before breakdown.

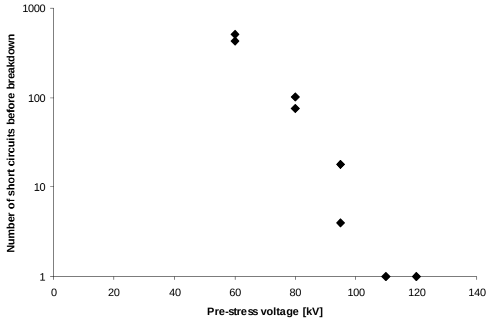

Figure 6: Observed number of short circuits before breakdown as a function of positive DC pre-stress level. Two objects with a needle implant were tested in parallel with a third cable object without needle.

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RESULTS AND DISCUSSION

Short Term DC Breakdown Strength

The average DC breakdown voltages of the cable samples with needle implants were found to be 130 kV, a value in good agreement with the results presented in fig 1. Unfortunately, electric breakdown occurred at the terminations at about 396 kV when testing the reference samples. -Thus the short term DC breakdown strength of samples without needle implants was found to be higher than this value.

Endurance testing at AC voltage

The results presented in Figure 5 show that the effect of AC voltage application is to drastically reduce the breakdown strength of the cable samples. Due to partial discharge activity electrical treeing is likely to rapidly form at the metallic needle tips, drastically reducing the ac voltage endurance to about 10 % of the short term DC breakdown value.

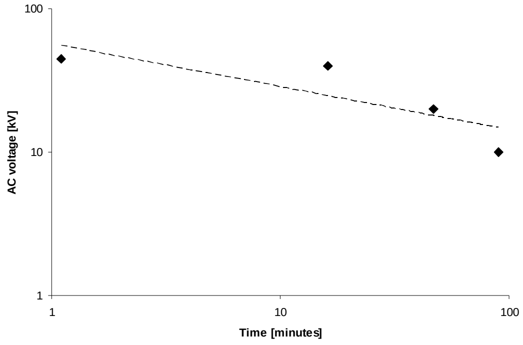

Figure 5: Time to breakdown at AC (50 Hz) voltage testing of cable samples with needle implants.

Effect of DC pre-stress level and rapid grounding

The results presented in fig. 6 show the strong relation between DC pre-stress level and number of rapid groundings needed to cause electric breakdown of the cable samples with needle implants. The effect of subsequent groundings was to weaken the samples in such a way that breakdown occurred at a pre-stress voltage level 40-60 % lower than the short term DC breakdown level of the objects. It was also clearly demonstrated that the number of abrupt groundings needed to cause initiation of electric breakdown at the needle tips strongly decrease with increasing DC pre-stress level.

This is a result in good agreement with the proposed mechanism of voltage dependent homocharge injection during pre-stressing, causing increasing local stress at the needle tips during rapid grounding with increasing voltage level.

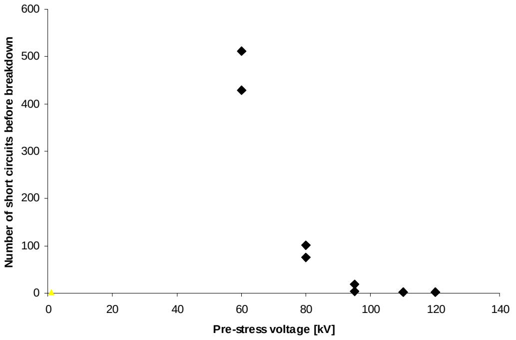

Figure 6: Observed number of short circuits before breakdown as a function of DC pre-stress level.

The results presented in fig. 7 show that the number of groundings needed to cause breakdown, strongly increase with reduced rate of voltage reduction. At a DC pre-stress level of 95 kV breakdowns occurred after 107 groundings at a rate of voltage reduction of 0.2 kV/ns, while only 4 groundings was needed to cause breakdown if the rate was increased to 2.6 kV/ns.

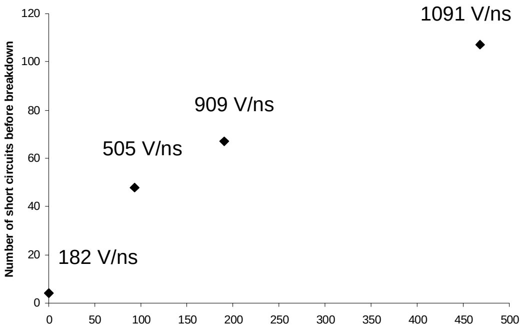

Figure 7: Observed number of groundings needed to cause electric breakdown at a DC pre-stress level of 95 kV. Here presented as a function of the grounding resistance and the indicated rates of voltage change.

When considering grounding of a long energized polymeric DC cable the effect of rapid grounding is that a voltage surge impulse is transmitted along the cable. The magnitude of this voltage wave is opposite to the applied DC voltage with an initial slope determined by the cable dimensions and the impedance of the grounding circuit. Due to losses in the semi-conducting screens and the neutral shield wires the high frequency components of this voltage surge will be stronger attenuated than the low frequency components. Thus the rate of voltage change will be reduced as the voltage wave travels along the cable. The results presented here indicate that by proper selection of grounding impedance the effect of travelling wave attenuation can be reduced, facilitating testing of longer cable samples.

No breakdown occurred in the samples without needle implants, neither during DC pre-stressing nor during the

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rapid grounding procedure. Reference samples were also pre-stressed at 150 kV and no cable failures occurred after 300 subsequent rapid groundings. Thus, XLPE cable insulation without defects does not seem to be damaged by the proposed DC test procedure.

CONCLUSIONS

These preliminary measurements carried out on short XPLE cable samples with metallic needle implants, indicate that DC voltage poling followed by subsequent rapid groundings may become a useful test procedure to reveal insulation weaknesses of polymeric HVDC cables before installation.

Acknowledgments

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