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Performance of Insulators under Impulse, AC and HVDC Voltage

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SUMMARY

Insulators are essential equipment for electric power transmission and they are expected to operate effectively at all times, even in harsh weather and environmental conditions where they are subjected to various stresses. Experiments were undertaken using a 22 kV silicon rubber insulator, to generate an understanding of the breakdown voltage under impulse, AC and HVDC under both wet and dry conditions, and comparative results are presented for the test voltages. The results demonstrated that the impulse breakdown compared to DC and AC occurred at a higher voltage, negative DC breakdown voltage were higher than the positive as a result of charge distribution between the high and low field regions. Finite element models (FEM) were developed to aid the understanding of the differences in the electric field and showed that the field distribution becomes resistive when there is an increase in surface conductivity.

Keywords: breakdown voltage, electric field, Insulators, HVAC, Impulse voltage, HVDC, FEM.

INTRODUCTION

Electrical power transmission from the generating centres to the consumers is achieved through the use of overhead transmission lines operating at either high alternating current voltage (HVAC) or high direct current voltage (HVDC). These high voltage transmission lines must be physically attached to an upright structure, while being electrically detached from the structure. For these two objectives to be achieved in high voltage transmission, an insulator is needed. With the increasingly high demand for electric power, there is a need to improve the present power networks. In such projects, the use of appropriate insulators cannot be overemphasized.

Non-ceramic insulators such as silicon rubber are commonly used in high voltage transmission due to their advantages over ceramic insulators [1]. The advantages include hydrophobic properties, low weight, excellent mechanical and electrical capabilities and less maintenance demands. The dielectric properties of non-ceramic insulators used in outdoor high voltage transmission can be degraded by climate and electrical stresses such as rain, temperature, lightning, humidity, pressure, and ultraviolet radiation [2]. This may lower their performance. This decrease in performance is a consequence of the changes occurring on the insulator surface which can be either physical or chemical [3].

Insulator discharge during the rainy season is also a crucial factor influencing the performance of high voltage transmission insulation [4]. The insulator surface gets wet as a result of light rain and results in an increase in the quantity of leakage current flowing across its surface. Water droplets also alter the electric field intensity in certain locations on the insulator surface, creating an electrical stress on the insulator surface. This initiates partial discharges like corona which is an expected phenomenon for arc formation in high fields; the arc bridges the insulator sheds to cause a complete flashover or breakdown [5-8]. This poses a significant threat to the operation of the electric power transmission system. This flashover scenario also exists in HVDC transmissions where space charges accumulate on the insulator surface and in contaminated areas where increased leakage current heat the insulator surface to form dry band areas that pave way for electrical discharges and finally leads to flashovers.

Previous studies on insulator behaviour under wet conditions have focused on pollution flashover characteristics which include: the effect of contaminants, shed dimensions, water resistivity, insulator material types and leakage distance on the breakdown voltage. In [9] the AC and DC flashover performance of insulator having different shed configuration were investigated and it was concluded that the flashover voltage for a given minimum shed spacing was raised as the leakage distance increases. In [10] the increase in the degree of the contaminants lead to a maximum for the DC positive breakdown voltage and a minimum for the DC negative breakdown voltage, and they are both lower than the AC flashover voltage in [11]. Due to the static field of direct current voltage, more pollutants accumulate on DC than on AC insulators under the same atmospheric conditions [12], The influence of rain intensity and water resistivity on the AC breakdown voltage was investigated by [13], and it was concluded that water resistivity increases the breakdown voltage significantly while the rain intensity slightly affects the breakdown voltage.

Insulators that are able to offer strong resistance to breakdown when subjected to electric stresses under dry condition may not be able to do so under wet or polluted conditions as a result of the distortion in the electric field distribution. In some discharge types such as AC, DC and surge voltages of long duration, ion drift can be of great significant [5]. The movement of these ions can redistribute the field distribution which can influence the breakdown voltage. Finite element models have been develop for polluted composite insulators considering the effect of contaminants [14] and corona ring [15] on the electric field distribution of silicon rubber insulators. In [14], it was concluded that the contaminants distorted the field and reduced the degree of field uniformity. In [15], it was confirmed that corona ring reduced the probability of insulator breakdown in polluted conditions.

This research paper reports an investigation of the flashover performance of a 22 kV insulator. The experimental assessment of the flashover performance was entirely focused on the breakdown voltage value when the insulator was energized by alternating current (AC), standard lightning impulse and direct current (DC) voltages under both dry and wet environmental conditions. Different test systems were constructed for the three types of test voltage at the University of KwaZulu-Natal (UKZN) HVAC and HVDC laboratories. Finite element models were also developed to aid the understanding of the differences in the electric field distribution.

TEST EQUIPMENT AND EXPERIMENTAL PROCEDURES

Test Sample

Figure 1 shows the insulator sample used for this research investigation: a 22 kV silicon rubber insulator. The technical dimensions and profile used are clearly shown in Table 1. A simulated transmission line conductor which is made up of a 1.6cm diameter aluminium tube was attached through a proper hardware (bracket) to the lower part of the insulator. The insulator was suspended through a metal pole scaffolding assembly as shown in figure 2. The scaffolding assembly was grounded and this made the upper part of the insulator grounded.

Table 1: Details of Insulator

Insulator Geometry	Dimension
Number of sheds	8
Arc distance	0.28 m
Leakage distance	0.807 m
Shed diameter	0.066 m
Sheath diameter	0.02 m
Service voltage	22 kV

Figure 2: Photograph of 22 kV SiR insulator setup at the HVDC Lab

Experimental Setup

The AC breakdown tests were carried out by making use of a 240 kV, 150 kVA, 50 Hz cascaded transformer set with a voltage regulator. The AC power was directed to the insulator under test through a water resistor.

For the voltage measurement, a capacitive voltage divider with ratio 1: 4000 was used and recorded by a digital oscilloscope.

The lightning impulse voltage was supplied by a seven-stage Marx impulse generator, which produces 125 kV_{DC} per stage. The voltage waveform produced was a standard 1.2/50 microsecond impulse wave as stipulated in the SANS 60060-1 method of testing in high voltage. The peak voltage was measured and recorded.

The DC voltage was supplied by a two-stage Walton-Cockcroft generator at UKZN HVDC laboratory, the generator has a rated output voltage of ±500 kV, with a current of 7.5 mA. At maximum load current, the ripple factor was lower than 3% and the voltage drop was lower than 10% as specified by SANS 60060-1. The breakdown voltage is measured through a resistive potential divider.

Experimental Procedures

The breakdown tests were carried out in compliance with [16] standard requirements. In the case of the DC and impulse breakdown tests, the insulator was energized with both positive and negative polarities of the applied voltages. To avoid flashovers with external structures, the clearance of the conductor to all external structures was not lower than 1.5 times the length of the insulator dry arcing distance.

The AC and DC voltages were applied and continuously raised until a flashover occurred along the insulator. The last test voltage measured just before the instance of the disruptive discharge was recorded as the breakdown voltage. This same procedure was repeated five times and averaged, where the average breakdown voltages for the AC and DC test is given by:

$$U_{ave} = \frac{1}{N}\sum_{i=1}^{N} U_i \tag{1}$$

Where:

U_i = measured breakdown voltages each time the tests were performed

N = number of repeated test time, which is 5

U_{ave} = average breakdown voltage.

The up-and-down method was used to calculate the 50% breakdown or flashover voltage (U_{50}) during the lightning impulse test, where a total number of 20 impulse shots were used [14].

$$U_{50} = \frac{\delta \times k \times \frac{\sum n \times V_i}{P} \times z \times r}{1000} \tag{2}$$

Where:

z = the scale factor of the impulse measurement circuit.

r = the divider ratio.

U_{50} = the 50% breakdown voltage.

P = number of shots.

For the wet test, the artificial rain was applied to the insulator as shown in Table 2. Under this condition, the insulator was pre-wetted at the outset for at least 15 minutes before the test and maintained all through the duration of the breakdown test.

Table 2: Precipitation conditions for standard procedure

Rate of rainfall (Both the vertical and horizontal component)	1mm/min
Conductivity of Water	100 ±15μS/cm
Angle of rainfall	45^0
Temperature	20^0C

Under the test conditions, the breakdown voltages were taken at a known atmospheric conditions and corrected to the standard atmospheric conditions using the atmospheric correction factors: air density and humidity described in [16]. The humidity correction factor was not applied to the wet test. Also, due to the short distance of the insulator arcing distance, the humidity correction factor was not applied to the dry AC breakdown test.

RESULTS AND DISCUSSIONS

(A). Analysis of the breakdown voltage

The corrected average breakdown voltage results obtained in this research investigation are shown in Table 3.

Table 3: Average breakdown voltage results

TEST VOLTAGE	DRY (kV)		WET (kV)	
	POSITIVE	NEGATIVE	POSITIVE	NEGATIVE
DC	193	223	187	198
IMPULSE	321	309	272	219
AC (RMS)	135		114	

The wet flashover voltage results were expectedly lower than the dry flashover voltage results. This is due to the conduction path provided by the water and the change in the electric field. This result was confirmed by reference [13] where the insulator was subjected to an AC source under artificial rain and it was concluded that the water resistivity has a great influence during the wet test. Reference [17] also carried out wet test on silicon rubber insulators and reported that: a highly resistive layer exist around each conducting water droplets scattered on composite insulator surface, with continuous wetting, the density of the droplets increases and the distance between the droplets reduces. The influence of the electric field on water droplets generates an oscillating force which coalesce droplets with small distance between them to form a random conducting filaments on the insulator surface. These filaments limit the length between the electrodes and this results in a high electric field between adjacent filaments, this high field intensity generates a randomly distributed spot discharge along the insulator surface which consumes the resistive layers around the droplets and destroys the hydrophobicity, this creates room for the filaments to join together to form wet regions, conductive paths, conducive for arc formation which finally leads to flashover.

The average breakdown voltages for negative polarity DC are higher than the positive DC, this is may be due to the distribution of charges. This was confirmed by [18] and explained the mechanism: In the case of positive polarity, ionization by electron collision occur in the high field region close to the high voltage electrode (anode). Electrons with their high mobility move towards the anode, leaving the positive ions behind. The space charge reduces the field strength close to the anode and simultaneously increase the field strength away from it. With the high field region eventually moving further into the gap and increasing the areas of ionization, the electric field intensity at the tip of the charge may be so high to initiate a cathode-directed streamer which may eventually result into a final breakdown. On the other hand, in the case of the negative polarity, the fast moving electrons are repulsed to the low field region while the positive ions are attracted to the cathode and resides in the space between the cathode and the electrons. Close to the cathode, the field is greatly increased, but the ionization region is reduced and once ionization is terminated, the applied electric field clears away the charges from the vicinity of the cathode and the cycle starts again. This slowing action of the ions can only be overcome by a very high voltage, therefore, the negative breakdown voltage is higher than the positive.

It was also observed that the average breakdown voltage for AC was less than DC, this was confirmed by [19] where silicon polymer composites that are employable to a 500 kV HVDC Insulator were subjected to AC and DC voltage and it was attributed to the different mechanism of breakdown: partial discharge for AC and under DC stress, space charge accumulation and distribution. The difference seen in between the AC and the lightning voltage can be attributed to the high rise time of more than 500 ms and an application time of at least one period in the AC [18].

It was also observed from the impulse results that the negative polarity U_{50} was lower than those of the positive polarities under both dry and wet conditions. As suggested by [5, 20, 21], this can be attributed to a reversal polarity phenomenon which is experienced with non-uniform field air gaps. This phenomenon may be caused by the non-uniformity of the electric field, electrode shape and configuration. In [21] different electrode shapes (rod-rod, rod-plane, conductor-rod, conductor-cross arm) and configurations with and without insulators were considered and it was discovered that the electrode shapes has influence on the breakdown.

The lightning impulse voltages were higher than the DC under both polarities, this can be attributed to space charges that have enough time to build up in DC and thus distort the DC field while in high impulse voltage charges do not have enough time to build up [18].

(B). Analysis of the Electric field distribution

This section of the paper presents the modelling of the 22 kV silicon rubber insulator used for the analysis of the electric field. The modelling was carried out with the use of FEMM 4.2 software package [22]. The axisymmetric two-dimensional (2D) problem definition part of the software was used and the four major parts of the insulator that were modelled are fibre reinforced polymer (FRP) core, silicon rubber as a sheath on the rod, silicon rubber as weather sheds, metal end fittings. Table 4 shows the material properties used. The insulator was energized at the metal end fittings below with 22 kV and earthed at the upper-end fittings. The insulator dimensions shown in Table 1 are used in the simulation studies.

Table 4: Material properties

Insulation Part	Relative Permittivity (F/m)	Conductivity (S/m)
SIR	4.3	10^{-12}
FRP Core	7.2	10^{-12}
Air	1	10^{-13}

A number of case studies were considered to understand the difference in the electric field between AC and DC. A small layer (1 mm) was included on the surface to account for the space charge developed under HVDC conditions. The conductivity was altered to ascertain the effect of the space charge on the electric field. Table 5 provides the currents obtained while Figures 6 to 8 illustrate the electric field.

Table 5: Case Studies

Case	Conductivity (S/m)	Current (nA)
AC	10^{-13}	0.45+j*16.60e3
DC1	10^{-13}	0.45
DC2	10^{-12}	0.46
DC3	10^{-10}	1
DC4	10^{-8}	36

The electric field for cases AC and DC1 were similar as illustrated in Figure 8. It is noted in Table 5 that the current was significantly higher for the AC case, however it was the capacitive component. The resistive components were similar. The electric field was most intense at both end fittings. These high field areas give an indication of where the corona discharges are bound to occur [15].

For the DC case space charge existing around the insulator surface may be pulled to the insulator surface [23], to account for the influence of space charge along the surface of the insulator, the conductivity was changed. An increase in conductivity not only results in an increase in current, but also alters the electric field, as shown in Figure 6 and 7, where it can be seen that the equipotential lines follow a different path, and in Figure 8 where the electric field is seen to be lower. As the breakdown of air is dependent on the electric field and it is important that the influence of the space charge on the electric field is considered.

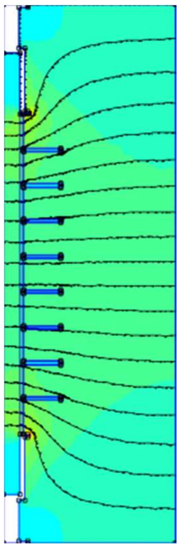

Figure 6: Electric field distribution DC1

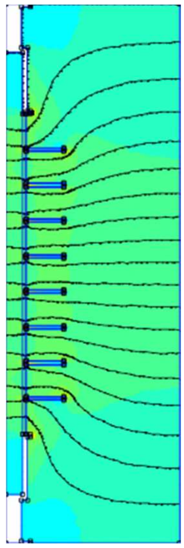

Figure 7: Electric field distribution for DC3

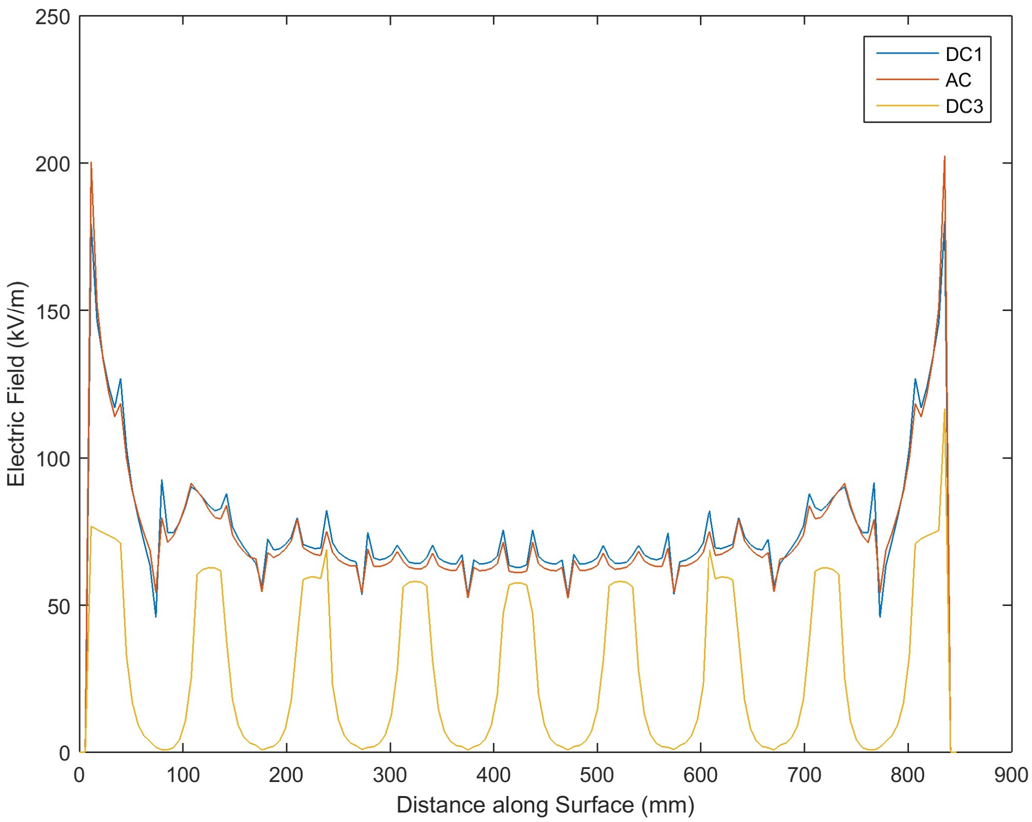

Figure 8: Electric field for cases AC, DC1 and DC3

CONCLUSIONS

The electrical performance of a 22 kV silicon rubber insulator was investigated by analysing the AC, DC and impulse breakdown voltages under both wet and dry conditions and It was discovered that the breakdown voltages were decreased during the wet tests, with the impulse having the highest and the AC having the lowest breakdown voltage. The electric field distribution for DC was proved to be purely resistive and distorted due to the effect of space charge.

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