



Electrical assessment of commercial 6.0-kV HTV silicone rubber for power insulation



Rodolfo Cardoso Buontempo^a, Adriano A. Dellallibera^b, Eduardo C. Marques Costa^{c,*}, José Pissolato^d, Darcy Ramalho de Mello^e, Lucia Helena Innocentini Mei^a

^a Universidade Estadual de Campinas – UNICAMP, Faculdade de Engenharia Química – FEQ, Campinas, SP, Brazil

^b Indústria Eletromecânica Balestro Ltda., Mogi Mirim, SP, Brazil

^c Universidade de São Paulo – USP, Escola Politécnica, Depto. de Engenharia de Energia e Automação Elétricas – PEA, São Paulo, SP, Brazil

^d Universidade Estadual de Campinas – UNICAMP, Faculdade de Engenharia Elétrica e de Computação – FEEC, Campinas, SP, Brazil

^e Centro de Pesquisas de Energia Elétrica – CEPEL, Rio de Janeiro, RJ, Brazil

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ABSTRACT

Silicone rubber has been widely used for electrical insulation in several power devices, e.g.: power insulators and metal-oxide surge arresters. In accordance with international standards, High-Temperature-Vulcanization Silicone Rubber for electrical power insulation should support 3.0 kV in electrical tracking and erosion tests, which are well established by the IEC. However, most of silicone rubbers used for manufacturing of electrical power components supports a maximum voltage of 2.75 kV. This research proposes a careful evaluation of the electrical performance of a new 6.0 kV silicone rubber developed by a worldwide-known manufacturer in the electrical power segment. The new silicone rubber is submitted to electrical tracking and erosion tests using two different approaches described in the IEC 60587: the step and steady methods. These two testing procedures are carried out in AC, following the normative recommendations, and also adapted for DC analyses. This research presents three principal contributions: a testing methodology considering both AC and DC, important conclusions on an emergent technology for electrical insulation in power systems and a quantitative analysis of erosion in polymeric composites based on the mass loss.

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1. Introduction

In the last decades, porcelain and glass have been substituted by High-Temperature-Vulcanization (HTV) silicone rubber in the electrical insulation of power systems. This process has been even more evident in power distribution grids, with a new class of polymeric insulators and silicone-housed surge arresters. The first transmission line with polymeric insulation was designed in Germany in the end of the 1960s [1]. Currently, the polymeric insulators represent almost 50% of the insulation market in the North America [2,3].

In the South America and Europe, the replacement of ceramic/glass by silicone rubber in insulators production began after 1980. In Brazil, this new technology was established only in 1987 because of the unknown electrical performance of these

polymeric devices concerning the aging and physicochemical degradation caused by various environmental agents [3,4]. Currently, there are more than 50.000 km of transmission and distribution lines only in Brazil, which requires more than 400.000 new insulators [3,5].

A significant effort has been observed in the development of high-performance polymers for electrical power insulation and new test methodologies for evaluation of new polymeric composites for physical–chemical and electric stresses [3,4,6–8]. Currently, the evaluation criteria for electrical testing of new silicone composites are based on recommendations established by the *International Electrotechnical Commission* (IEC). In accordance with the testing criteria provided by the IEC, silicone rubbers are submitted to electrical tracking and erosion tests using samples with dimension 50 mm × 120 mm × 6 mm [9]. These silicone strips are tested as being dipoles, i.e., are submitted to a variable AC voltage signal at industrial frequency of 50/60 Hz. This electrical testing methodology is divided into two tracking tests in the IEC 60587: *step* and *steady methods* [9].

* Corresponding author.

E-mail address: educosta@pea.usp.br (Eduardo C. Marques Costa).

The polymeric insulators, polymer-housed surge arresters and other power components are designed with silicone rubbers that support tracking voltages up to 3.0 kV. Nevertheless, a worldwide-known manufacturer has recently developed a new silicone composite that, according to the manufacturer's catalog, supports a tracking voltage of 6.0 kV. Therefore, this research proposes an evaluation of this new 6.0 kV silicone rubber based on the electrical tracking and erosion tests described in the IEC 60587. In addition, the conventional electrical tracking and erosion tests are also adapted for DC test conditions, which lead to some important conclusions on this new silicone rubber for insulation of HVDC power systems [10–12].

Furthermore, the testing methodology proposed in this research quantifies the erosion of the silicone samples based on the lost weight after the electrical tests. The quantitative analysis of erosion was not prior established by the IEC that evaluates the silicone samples based only on visual characteristics in the eroded surfaces. This quantitative analysis represents an additional novelty of the current research and an improvement in the available testing methodologies for electrical insulation using polymeric composites.

2. Electrical tracking and erosion tests

The IEC 60587 defines tracking as a progressive degradation in the surface of a solid insulating material due to local discharges, resulting total or partially conducting paths and erosion that can be measured in this research by the mass loss because of the leakage current through the sample. The testing methodology proposed in this research is based on the normative recommendation in the IEC 60587 [9]. Two standard procedures are proposed by the IEC: the step and steady methods.

The *step method* is performed considering silicone samples with size 50 mm × 120 mm × 6 mm. An initial voltage of 1.0 kV is applied between the two extremities of the samples that are connected to the two electrodes spaced 50 mm from each other. After one hour, 0.25 kV is incremented to the prior voltage value and successively hour by hour up to 6.0 kV. Usually, five identical samples are considered in the test and the end criteria are determined when a 25 mm eroded path is observed on a sample or when the leakage current through a sample exceeds 60 mA at least 2 s [9].

Another criterion to determine the end of the experiment is the tracking current. The maximum current through a specimen is up to 60 mA. If the current exceeds 60 mA, the protection device acts with no more than 2 s or when a specimen presents expressive erosion. Tracking current through the silicon rubber surface is not commonly observed because it produces SiO₂ that is not a solid electrical conductor. Thus, there is a very low probability of tracking currents through the surface of the silicone specimens.

In the *steady method*, the samples (with size 50 mm × 120 mm × 6 mm) are submitted to a constant voltage for six hours. The end criterion is determined if any sample fails after six hours of test. Thus, the voltage classification of the silicone rubber is determined based on the voltage level during the six hours of test.

The step and steady methods are complementary, because the step method is usually applied to set the initial voltage level of an unknown material that in sequence is submitted to the steady method based on the voltage value previously determined in the step method. However, these two methods are valid for voltage levels no greater than 6.0 kV [9].

The testing procedures in the IEC 60587 are carried out from an AC power voltage source with fundamental frequency of 50–60 Hz. However, the electrical tracking and erosion tests are also carried out in this research using a DC power source. The electrical circuits

for AC and DC tests are almost similar, varying only in the voltage supply and measurement devices. The AC and DC circuits used during the electrical tracking and erosion tests are described in Figs. 1 and 2, respectively.

The AC and DC circuits have a similar variable autotransformer (Variac) connected to the primary winding of the power transformer (Trafo) in order to deliver up to 6.0 kV at the secondary winding, as described in Figs. 1 and 2. The principal difference in the power supply circuits in Figs. 1 and 2 is that a half-wave DC rectifier (represented by a single diode) is placed at the secondary of the power transformer in Fig. 2. Another variation is in the output voltage monitoring of the power transformer. The AC output voltage of the power transformer is monitored by a single potential transformer whereas in the DC circuit the output voltage is monitored using a voltage divider and a capacitor to filter excessive oscillations in the rectified power signal. Both circuits are composed of five selectable resistors, from 1 kΩ up to 37 kΩ, that permit to control the voltage and current at the samples S1 to S5, as indicated in Figs. 1 and 2. The voltage and current can be monitored at each sample from measurements obtained at the electrical circuit connected to the secondary of the power transformer and from meter/relays Tc1 to Tc5, as described in Figs. 1 and 2.

The electrical tracking and erosion tests are carried out in AC and DC, based on the step and steady methods. Thus, the results and conclusions can be valid for power systems in AC and DC.

3. Manufacturing the specimens and procedures during the electrical tracking and erosion tests

The five specimens are manufactured according to the design in the IEC 60587 (Fig. 3). First, the silicone rubber compound is pressed in a steel mold using a heated press at temperature of 180 °C for 10 min.

The samples are cooled at laboratory temperature of 23 ± 2 °C during 24 h in order to stabilize the material. The further step is to drill the orifices for fixing the electrodes at the extremities of the specimens, as described in Fig. 3.

In sequence, the surfaces of the five specimens were polished with sandpaper with granulation of 1200 for removal possible contamination resulted from the molding process, which can interfere in the hydrophobicity and electrical conducting on the silicone rubber surfaces of the specimens. The molding and cleaning/polishing processes are shown step by step in Fig. 4.

The specimens are immersed in deionized water, after polishing process, and after rinsed with isopropyl alcohol. Finally, specimens are dried at laboratory temperature (23 ± 2 °C) during 24 h. After the molding and cleaning processes, as demonstrated in Fig. 4, the weight of each specimen is measured and recorded using an accurate weighting device.

After the electrical tracking and erosion tests, all the specimens are cleaned using a toothbrush with soft bristles. The purpose of this process is to remove the residual material (silicon dioxide) due to degradation of polydimethylsiloxane (silicone polymer). This procedure must be performed carefully in order to remove only the residual dust and particulate matter on the surface of the specimens.

After testing and cleaning processes, the specimens remain 24 h at laboratory temperature of 23 ± 2 °C and after weighted again using the same weight device. The difference between measurements, before and after the electrical test, is used to determine the percentage erosion for each specimen. The ambient humidity during the electrical test was monitored, showing percentage values no greater than 30%.

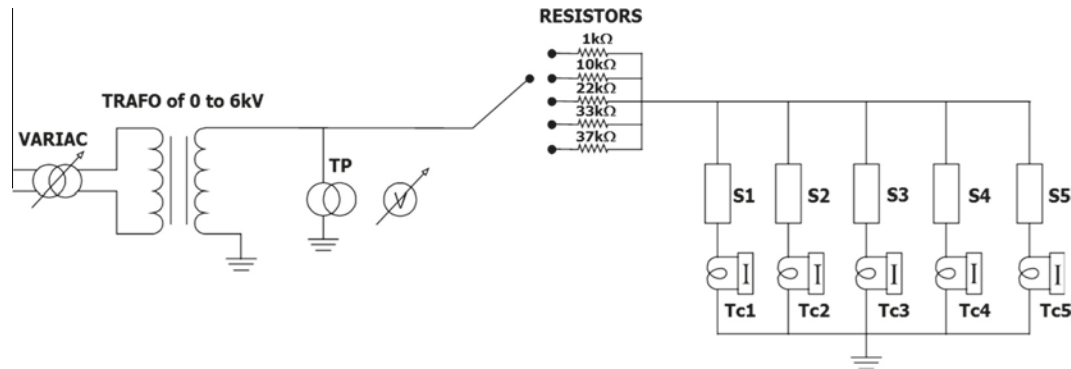


Fig. 1. Electrical circuits for tracking and erosion tests for AC power signal.

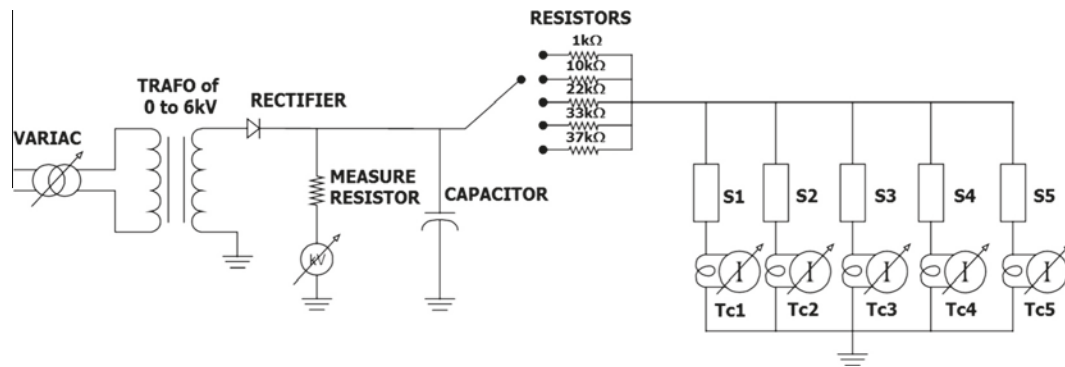


Fig. 2. Electrical circuits for tracking and erosion tests for DC power signals.

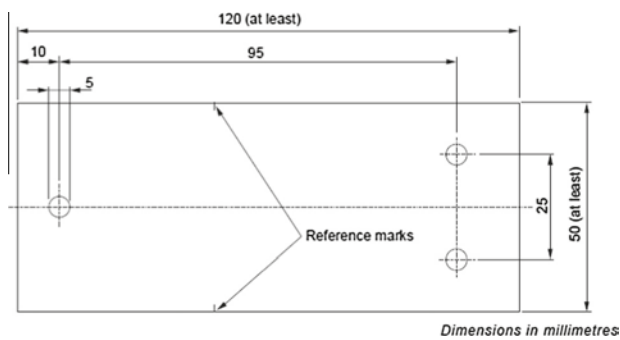


Fig. 3. Geometrical characteristics of the specimens according to IEC 60857 [9].

4. AC and DC analyses based on the step method

The voltage classification of the new silicone rubber was 6.0 kV, considering both AC and DC electrical tracking and erosion tests with the step method. A total of ten silicone samples were tested, five samples were considered in the AC procedure and other five in DC. The voltage polarity in the DC test was negative, because based on previous experimental observations, the negative polarity showed to be a more conservative test, i.e. presents a major probability of erosion. The ambient temperature was controlled and monitored during the tracking and erosion tests, following the IEC standards ($23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$) [9].

All samples were submitted to a progressive voltage level from 1 kV up to 6.0 kV, incrementing 0.25 kV per hour, which leads a total time of 20 h. No sample showed a 25-mm eroded path through the silicone surface or exceeded 60 mA. Although samples presented a great performance in the electrical tracking, the real

performance of the silicone rubber was determined in the erosion test. The lost weight of each sample is calculated after the AC and DC electrical tests, based on the initial weight of the samples (before the electrical tests) and after the tracking and erosion tests. The position and connecting configuration of the electrodes for each specimen is described in Fig. 5.

The electrodes are located at the extremities of the specimens and there is a reference mark that indicates 25 mm from the bottom electrode to the middle section of the test specimen, for a better visualization eventual 25-mm eroded path on the silicone rubber surface.

Initially, the erosion is measured based on the percentage lost weight for AC and DC step methods for each sample, as described in Fig. 6.

The average erosion in AC was 3.5% whereas the average in DC was 0.75%. Though the AC and DC tests using the step method resulted in a low erosion, the samples submitted to erosion test in DC described a better performance than the samples submitted to AC tracking and erosion tests. Figs. 7 and 8 show the samples after the electrical tests in AC and DC, respectively.

Significant erosion was observed in the sample 5 after the electrical tests in AC, as described in Fig. 7. A percentage erosion of 9.1% was calculated for the sample 5 based on the weight loss after the electrical tracking and erosion tests in AC. Percentage erosion values around 3.5% were calculated for the samples 2 and 4 after electrical tests in AC. On the other hand, all samples submitted to the electrical tests in DC presented erosion values of no more than 1%.

5. AC and DC analyses based on the steady method

The five samples were classified as 6.0 kV after the electrical tracking and erosion tests based on the steady method in AC and

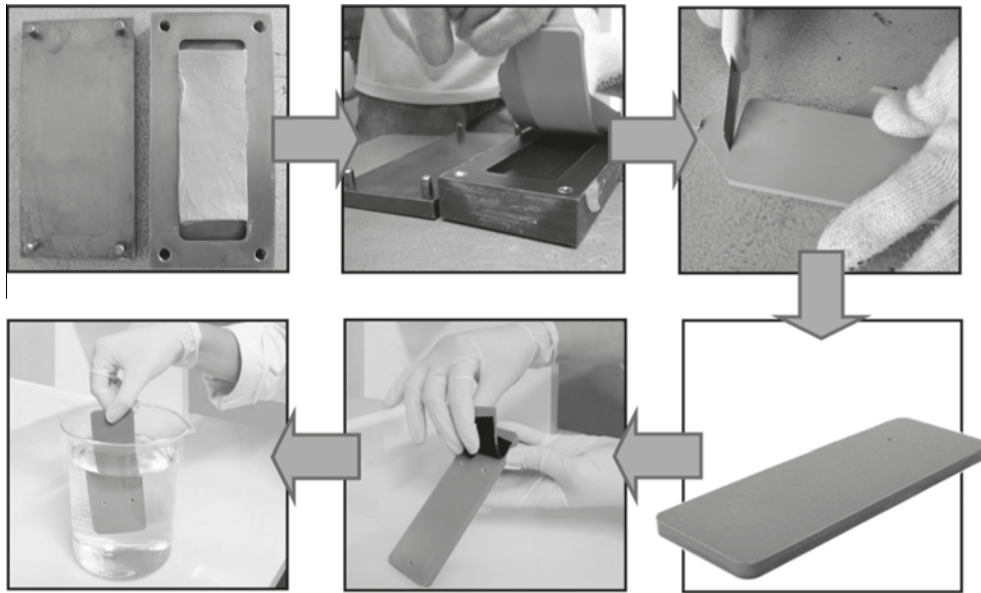


Fig. 4. Molding, polishing and cleaning processes for specimen manufacturing.

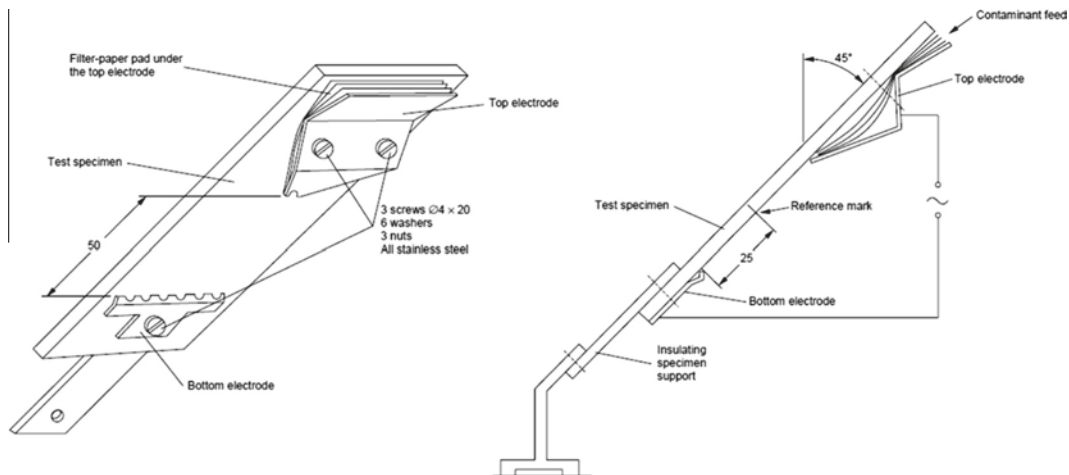


Fig. 5. Installation of test bodies and the electrodes according to IEC 60857 [9].

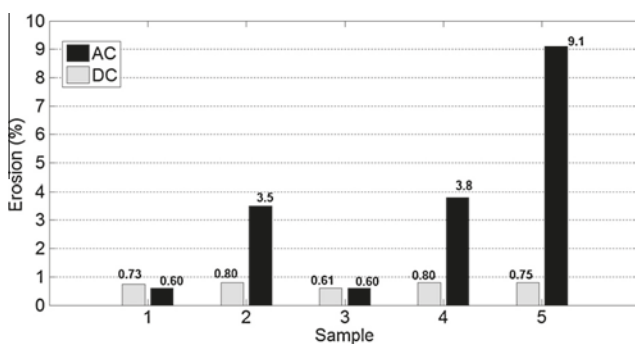


Fig. 6. Erosion measurements based on the step method during twenty hours.

DC. Samples were energized for more than six hours with a constant voltage of 6.0 kV, as determined by the IEC [9].

The five samples presented a low weight loss after the AC and DC tests, as indicated for each sample in Fig. 9:

Results obtained from the erosion test demonstrated a similar behavior in AC and DC tests. All samples described percentage erosions up to 0.2%, which means a great electrical performance of the new 6.0 kV silicone composite. The average erosion of the samples submitted to electrical tracking and erosion tests in AC was 0.1% whereas the average erosion of the samples tested in DC was approximately 0.08%. Both averages are significantly low, proving that the new silicone rubber is indeed classified as 6.0 kV.

The visual aspects of the specimens after the electrical tracking and erosion tests in AC and DC are shown in Figs. 10 and 11, respectively.

The visual aspects of the specimens demonstrate low surface erosion that is confirmed in the quantitative analysis presented in Fig. 9. The samples submitted to electrical tracking and erosion tests in AC show more pronounced visual erosion than the samples submitted to the same tests in DC. However, the quantitative analyses (Fig. 9) show that the percentage erosions after the electrical tests in AC and DC are practically similar.



Fig. 7. Samples after electrical tracking and erosion tests in AC (step method).



Fig. 8. Samples after electrical tracking and erosion tests in DC (step method).

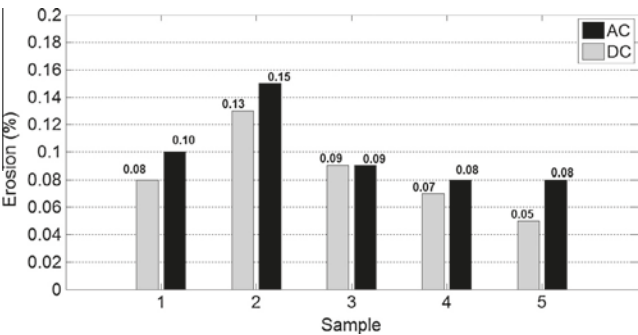


Fig. 9. Erosion measurements based on the steady method for six hours.

6. Conclusions

An experimental research was proposed for evaluation of a new class of polymeric composite for electrical insulation of various power components and systems. The testing methodology approached in the electrical trials was adapted for AC and DC from normative recommendations in the IEC 60587. Thus, the original content of the paper is composed of three principal contributions: the technical reports on the new 6.0 kV silicone compound, the proposed testing criteria applied for electrical tracking and erosion tests in DC and a quantitative analysis of erosion based on the weight loss that is not established by the IEC.

Two standard methods for evaluation of polymeric composites for electrical insulation were approached: the step and steady



Fig. 10. Samples after electrical tracking and erosion tests in AC (steady method).

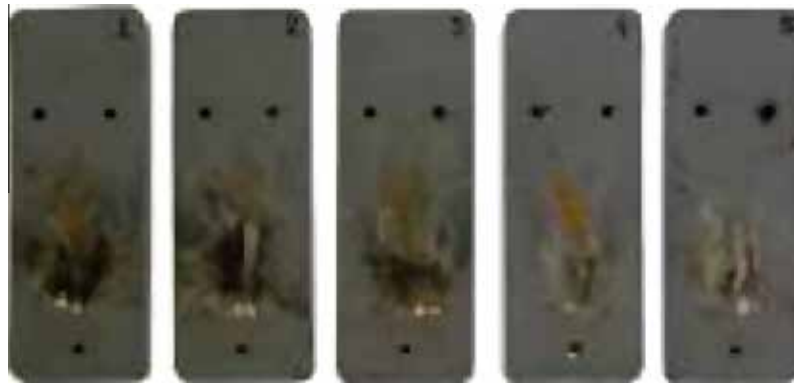


Fig. 11. Samples after electrical tracking and erosion tests in DC (steady method).

methods in AC and DC. Twenty specimens were evaluated using the standard electrical tracking in AC and an adapted version for the same test in DC. The erosion evaluation was also carried out in AC and DC in order to quantify the erosion by means of the mass loss of each specimen.

Although all specimens presented a tracking voltage of 6.0 kV, as indicated by the manufacturer, percentage erosion was quantified as a function of the lost weight of each sample. A more expressive performance was observed in specimens submitted to DC tests, which presented in average percentage erosion no greater than 0.1% for the step and steady methods. These results prove that the new 6.0 kV silicone compound could represent a possible application also for HVDC systems. However, this statement depends on further physical–chemical analyses for evaluation of hydrophobicity, tear strength, elongation, hardness, chemical composition and pollution contamination (which polymeric insulators are exposed in sea cost and industrial/urban areas).

The results obtained from the AC analysis showed a good performance for the 6.0 kV silicone rubber. Only one sample demonstrated significant deviation from the average erosion. This behavior could be attributed to failures in the sample manufacturing or even problems in the testing electric circuit. However, even with a possible failure, all samples were classified as 6.0 kV and relatively low average erosion was calculated from the analyses in AC.

The technical literature has previously established that the inclined plane testing has some “uncontrollable” variables that are responsible for scattering the results [8]. For example, one of these variables is the condensation on the specimen surface, leading to the contamination flow to deviate constantly from the center of the sample. If this flow is concentrated in the center of the specimen, then degradation is more likely to concentrate in one spot as well. Probably, some of these factors imply in the scattered results observed in Figs. 6 and 9. However, in order to avoid erroneous conclusions, the IEC recommends the use of several samples in tracking and erosion tests [9].

Additional information concerns the AC and DC tracking and erosion tests. The objective of the proposed research was not to determine the most conservative testing procedure, in AC or DC. However, as a further research, a statistical analysis could be conducted in AC and DC involving a great number of samples. Furthermore, an alternative procedure using infrared laser can be applied in order to reduce possible inaccuracies due to undesirable variables, as described in previous technical literatures [7].

The new silicone rubber supports a tracking voltage of 6.0 kV with low erosion levels, as shown the quantitative analyses. Addi-

tional physical–chemical and mechanical analyses are required for more conclusions on the real performance of the new silicone composite for electrical insulation of power systems in AC as well as in DC, such as: basic impulse insulation tests, design failure analysis, hydrophobicity and aging tests. However, these additional analyses are proposed for further researches as a complementary content.

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