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Breakdown voltage of solid insulations: Its modeling using soft computing techniques and its microscopic study

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ABSTRACT

In this paper four different Soft Computing (SC) models have been proposed which are able to predict AC breakdown voltage of the two solid insulating materials, namely Leatherite Paper and Manila Paper. The predicted voltage is a function of four input parameters, such as, the thickness of the insulating sample t, void depth t_1, void diameter d and relative permittivity of the materials ε_r. The requisite data on the breakdown voltages are obtained after statistical analysis of the experimental observations performed with a cylinder-plane electrode system by step-stress method. The voids are artificially created for initiation of Partial Discharge (PD) with different depths and diameters. The proposed SC models seem to be capable of predicting the breakdown voltages quiet efficiently and within a small value of mean absolute error. In order to get a better insight of the breakdown phenomenon, the two solid insulating materials have been observed using a Scanning Electron Microscope (SEM). The SEM images clearly show the degradation taking place in these materials leading ultimately to the breakdown.

Introduction

The Partial Discharge study has been an important topic in the field of solid insulations over the past few decades, which is very much evident from the large number of papers associated with it [1–16]. It is well known that voids within the solid insulating materials are the main sources of Partial Discharge (PD). These voids or cavities are essentially gas-filled and can result from many causes. In case of epoxy castings, gas-filled cavities can be caused by air leaking into the mould during curing. If the voltage between the electrodes is raised to the point that the field within the cavity goes above the breakdown strength for the gas within the cavity, a PD can take place. The time taken for breakdown to occur depends on the applied voltage and the size of the cavity [16]. If an electron is present within the critical volume of the cavity, the electron is accelerated in the electric field and produces electron gain during collisions with other molecules. The electron grows exponentially resulting in the development of a streamer. A resistive channel is developed across the cavity in few ns. The conductivity of the streamer reduces the field across the cavity. The streamer dies, once the field across the cavity drops below that necessary to support the streamer, leaving large quantities of positive and negative charges. At the end of the PD process, the field in the cavity can be reduced to zero. If the field in the cavity is reduced to zero, the electric field in the solid insulating sample is the same as if the cavity is filled with a conductor. Filling the cavity with a conductor would cause an increase in the capacitance between electrodes, which would cause a flow of charge into electrodes for a constant voltage across them. The charge, which flows into the electrodes, is the apparent PD magnitude.

It is found that the magnitude of the PD in insulating materials due to voids and thus breakdown due to PD in cavities, Partial Discharge Inception Voltage (PDIV) and Partial Discharge Extinction Voltage (PDEV) is affected by several factors such as, the thickness of the solid insulating material [17], void thickness [18], void diameter [19,20], immersion medium [21–24], gamma irradiation [25] the nature of the voltage waveform [26], relative permittivity ([21,27]), gas and gas pressure within the void [15].

The breakdown voltage due to PD in cavities is a nonlinear phenomenon. The magnitude of this voltage is critical for judging the quality of the insulation for industrial purpose. However, it is extremely difficult to predict this voltage. Hence, it is necessary to resort to the process of modeling in order to predict the magnitude of this breakdown as a function of different variables. Some literatures can be found in which this voltage is predicted as a function of the thickness of the material [27] or as a function of position, size and shape of the void [28]. All these models are essentially conventional models. The conventional models, which

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solve any application oriented problem, either involve the use of classical approximation theory or the development of quasi-empirical relationship. The conventional method of solving any particular issue has it's limitations, as it is only valid for the range of input variable considered [29–31]. Hence, these methods are inherently rigid in nature and there is hardly any scope of making it flexible. The Soft Computing (SC) model on the other hand is highly flexible and a model can be improved simply by providing additional training data [32–34]. In addition, this kind of model can be developed more accurately in a shorter time. Kolev and Chalashkanov [35] have proposed an ANFIS structure for the prediction of the PDIV and PDEV using the experimental data from CIGRE Method II Electrode System provided in [36]. Similarly Ghosh and Kishore [37,38] have proposed ANN models for predicting the PDIV and PDEV of insulation samples. Hence, the rigidity in the conventional models have been appropriately taken care of by utilizing an ANFIS and ANN structure respectively.

From the previous paragraphs, it is quite evident that SC model is an important and a flexible model in predicting the breakdown voltage due to PD in voids. The use of this model in order to tackle this PD issue needs further exploration as the prediction of this breakdown voltage is so important industrially. Moreover, it is also an interesting exercise to know the state of the solid insulating materials at different stages of the applied voltage ultimately leading to breakdown. This curiosity can be satisfied by observing the samples of the solid insulating materials under a Scanning Electron Microscope (SEM) [39–41].

This paper primarily attempts at modeling of PD initiated breakdown voltage of solid insulating materials by four different SC techniques. The requisite experimental breakdown voltage data under AC conditions are generated in the laboratory with artificially created void and insulation dimensions using Cylinder-Plane Electrode System. Section 'Introduction' of the paper has reviewed the existing literatures on the breakdown voltage of the solid insulating materials in general while giving more emphasis on the breakdown due to PD in cavities. The advantage of using SC models over the conventional models in solving the prediction of breakdown due to PD in cavities has been discussed in this section. Section 'Experimental set up' discusses the experimental set up for the Cylinder-Plane Electrode System used for obtaining the breakdown voltage data under AC conditions. The statistical analysis of the breakdown voltage is carried out in Section 'Statistical analysis of the experimental data'. Section 'Modeling of the breakdown voltage' has described the four proposed SC models for predicting the breakdown voltage of the two solid insulating materials. The SEM results for the solid insulating materials have been presented in Section 'Monitoring of the state of solid insulating materials through SEM observations'. Section 'Conclusion' has provided the concluding remarks.

Experimental set up

Sample preparation

The samples are prepared from commercially available insulation sheets of Leatherite Paper and Manila Paper of different thicknesses. The variations of thicknesses are as follows:

Leatherite Paper:	0.235 mm, 0.175 mm and 0.13 mm.
Manila Paper:	0.035 mm and 0.06 mm.

Before testing, the conditioning procedure was adopted to the test specimen in accordance with that laid in [42]. This ensured that the surfaces of the insulating sample were cleaned and dry, since the contamination on the insulating specimen or absorption of moisture may affect the breakdown voltage.

Creation of void

The voids of different sizes are artificially created by means of a spacer made up of Kapton film, with a circular punched hole at the centre. The diameter of the voids is 1.5 mm, 2 mm, 3 mm, 4 mm and 5 mm. The thickness of the Kapton spacer used is of 0.025 mm and 0.125 mm. Thus, the sizes of the void, that is, the volume of air space, depends on a typical diameter of the punched hole and thickness of the spacer.

Electrode geometry

The Cylinder-Plane electrode system as shown in the Fig. 1 is used for breakdown voltage measurements. The electrodes, both high voltage and ground, were made of brass. They were polished, buffed and cleaned with ethanol before the start of the experiment. Further, the electrodes contact surfaces are cleaned by ethanol between two consecutive applications of voltage to avoid contaminations that may arise due to application of voltage. Sufficient care had been taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The insulation sample is sandwiched between the electrodes with the help of insulating supports.

Measurement of AC breakdown voltage

The AC voltage of 50 Hz power frequency applied to the set-up was obtained from a 40 kV AC/DC Series Hipot Tester (MODEL: HD 100, Accuracy = ±2%, Resolution: 200 V rms) manufactured by Hipotronics, USA. The voltage is raised in steps of 200 V and held constant for a period of 30 s at each level until the breakdown occurs for materials, such as Leatherite Paper and Manila Paper. For high reproducibility, nine breakdown voltage values are obtained for a particular thickness of the material and a particular void condition. All the tests are carried out in air at room temperature and atmospheric pressure. The experimental data generated under AC conditions are presented in Table 1 for Leatherite Paper and the values in the last column indicate the arithmetic mean of nine breakdown voltage values.

Measurement of relative permittivity of solid insulating materials

To measure the relative permittivity, 12 mm diameter of the insulating samples was silver coated at the identical zone on both the sides. The silver-coated samples were then pressed between

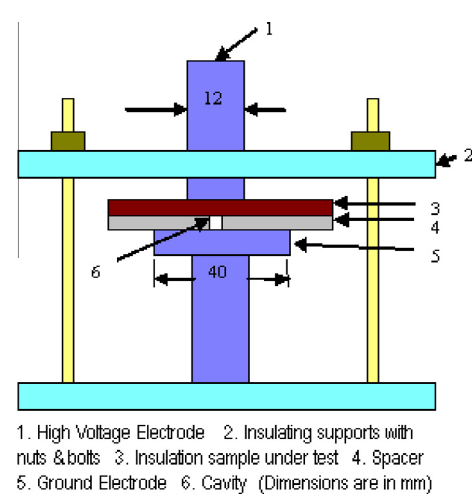

Fig. 1. Cylinder-plane electrode system used for breakdown voltage measurement.