Modeling of the breakdown voltage of solid insulating materials using fuzzy logic techniques

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Abstract- **In this paper , two different Fuzzy Logic (FL) models have been proposed those are able to predict the AC breakdown voltage of five solid insulating materials due to Partial Discharge (PD) in cavities. 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 ϵ_r. The requisite data on 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 PD with different depths and diameters. The proposed FL models seem to be capable of predicting the breakdown voltages quiet efficiently and within a small value of mean absolute error.**

Keywords : Insulation breakdown, Microdefects, Soft Computing Models, Fuzzy logic.

I. INTRODUCTION

The PD studies under AC can mainly be categorized but not limited to the following types; the physics of PD inception, the factors governing the breakdown voltage by PD in cavities, observation of the degradation process due to PD etc. It continues to evoke a lot of interest amongst the insulation researchers. In order to start a PD, two conditions must be fulfilled. First, the magnitude and the distribution of the electric field in the cavity are such that a self-sustaining discharge can develop. This condition is generally translated into minimum breakdown voltage across the cavity. Second, a free electron must be present at a suitable position in the cavity to start the ionization process[1]. This starting electron may be supplied by external sources, field emission or by de trapping of electrons deposited at the cavity walls by previous PD activity. The recurrence of PD at AC voltage of 50 Hz is explained by the voltage polarity change every 10 ms[2].

Apart from the AC voltage waveform as mentioned in the previous paragraph, the magnitude of the breakdown voltage due to PD in cavities for solid insulating materials is governed by many factors, such as, the thickness of the solid insulating material [3-4], void size and void diameter [5-7], void shape [8-9], gas and gas pressure within the void [1]. The degradation process of an insulating material can be very easily observed with the help of electron microscopy.

The breakdown voltage due to PD in cavities is a nonlinear phenomenon. The magnitude of this voltage is critical for design of any insulation or insulation systems. So, it is extremely necessary to predict this voltage. Hence, different models are proposed by the insulation researchers for prediction purpose, most of them are based on experimental observations aiming at to develop a quasi-empirical relationship. These models have predicted the voltage as a function of the thickness of the insulating material [3-4], void diameter and depth [5-7] or void shape [8-9]. All these models described there are essentially conventional models, which are extremely rigid. But S. Ghosh et. al [10-13] have proposed Artificial Neural Network (ANN) models for predicting the Partial Discharge Inception Voltage (PDIV), the Partial Discharge Extinction Voltage (PDEV) and the breakdown voltage due to PD in cavities for insulation samples. Similarly Kolev et. al. [14] have proposed an Adaptive Neuro Fuzzy Inference System (ANFIS) for modeling of the PDIV and PDEV. Hence, the rigidity in the conventional models has been appropriately taken care of by utilizing an ANN structure and an ANFIS structure. The models based on these structures are known as the Soft Computing (SC) models. These models are not only flexible but also can be improved simply by providing additional training data [15-16]. In addition, this kind of model can be developed more accurately in a shorter time.

In this paper, two FL models are proposed to predict the breakdown voltage due to PD for this material under AC condition with a Cylinder-Plane electrode system. As a diagnostic tool, SC techniques have been exploited for breakdown voltage estimation under artificially created air cavities of different sizes at the center of the sample. Multiple cavities are not considered as the other points in the samples of the insulating materials are lightly stressed by the developed field pattern. Section II of the paper describes the experimental set up and the procedure adopted for obtaining the experimental data on the breakdown voltages and relative permittivity. Section III has described the two proposed FL models applied for predicting the breakdown voltage of five insulating materials under AC conditions. Section IV has provided the concluding remarks.

II. EXPERIMENTAL SET UP

A. Sample Preparation

The samples are prepared from five commercially available insulation sheets, namely White Minilex Paper, Leatherite Paper, Lather Minilex, Glass Cloth and Manila Paper of different thicknesses. The variations of thicknesses are as follows:

White Minilex Paper: 0.26 mm, 0.18 mm and 0.125 mm.

Leatherite Paper:0.235 mm, 0.175 mm and 0.13 mm.

Lather Minilex: 0.245 mm, 0.185 mm and 0.12 mm.

Glass Cloth:0.195 mm and 0.155 mm.

Manila Paper: 0.035 mm and 0.06 mm.

Thus, the thickness range is varying from 0.035 mm to 0.26 mm. Before testing, the conditioning procedure was adopted to the test specimen in accordance with that laid in ASTM Handbook [17]. 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.

B. *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.

C. *Electrode Geometry*

The cylinder-plane electrode system as shown in the Figure 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.

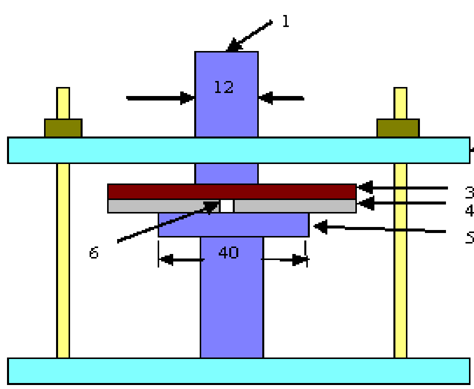

Figure 1. Cylinder-Plane Electrode System used for Breakdown Voltage Measurement

D. *Measurement of AC Breakdown Voltage*

The AC voltage of 50 Hz applied to the insulating samples was obtained from a 40 kV AC/DC Series Hipot Tester (MODEL: HD 100) manufactured by Hipotronics, USA. The voltage is raised in steps of 200 V and held constant for a period of 30 s in each level until the breakdown occurs. The total time from the application of voltage to the instant of breakdown were noted down. Nine data points were obtained for a particular type of sample and void condition and the scale factor for the Weibull Distribution is taken for prediction. The procedure for calculating the Maximum Likelihood (ML) estimate of the scale factor is provided in[18]. All the tests were carried out in air at room temperature and atmospheric pressure. The breakdown data obtained are then corrected for atmospheric condition before being used for modeling.

E. *Measurement of relative permittivity of solid insulating materials*

To measure the relative permittivity, 12mm diameter of the insulating samples was silver coated at the identical zone on both the sides. The silver coated samples were then pressed between the two brass sample holder electrodes of the Dielectric Interface of an Impedance Gain / Phase Analyzer (Solartron, U.K.). An ac voltage of 0.1 V (r.m.s) at 50 Hz was applied to the samples from the Impedance Gain / Phase Analyzer and relative permittivity values of the insulating materials are recorded. Table I shows the measured values of the relative permittivity of materials at 50 Hz frequency.

III. MODELING OF THE BREAKDOWN VOLTAGE

The breakdown voltage due to PD in cavities for the five insulating materials in Section II has been modeled as a function of the thickness of the materials t, void depth t_1 , the void diameter d and relative permittivity ϵ_r that is, $V = f(t, t_1, d, \epsilon_r)$. The ά values calculated as per the procedure described in [18] is taken for this purpose.

In order to model the breakdown voltage, two Fuzzy Logic (FL) techniques using Mamdani Fuzzy Logic (MFL) and Adaptive Sugeno Fuzzy Logic (ASFL) are proposed. MATLAB 7.1 has been used for carrying out the computations associated with the two FL models. Out of the 130 sets of input output patterns, 115 sets of input-output patterns have been used for the purpose of training in ASFL model. The rest 15 sets of input-output patterns have been used for testing purpose. The ASFL model has been trained for 400 iterations before tested with 15 sets of data. The number of iterations was fixed at this value, as it was felt that it would be just appropriate to train a large Sugeno rule base.

The sequential mode of training has been adopted for the ASFL model.

A. *MFL model*

The equations involved in framing the rule base are explained in details in an earlier work [19] for this model. The procedure for finding the relationship between the linguistic values and the actual values of t, t_1, d and ϵ_r is also provided there. The Triangular Membership function has been used for t, t_1, d, ϵ_r. The number of rules in the rule base involving all the five materials is 72 for this model. In addition, the relationship between the linguistic values and the actual values of the breakdown voltage V is also determined. The triangular membership function has also been used for V.

In this model it was found in some cases that two rules associated with two different insulating materials had identical linguistic values for t, t_1, d and ϵ_r (antecedent part of the rule). As a result, it was extremely difficult to identify an insulating material based on rules. This problem was solved by assigning a different identification number to a particular material. Hence, in addition to the fuzzification of the four input parameters, the identification number was also fuzzified and incorporated in the antecedent part of the rules.

Since, there is no formal training in the MFL model, 115 training patterns is used to form the 72 rules in the rule base heuristically. All the equations involved in the MFL model are explained quiet exhaustively in [19]. The consequent part of all the 72 rules are altered on a trial and error basis, till the Mean Absolute Error of the test data E_{ts} reaches a reasonably low value. It is a good performance measure for judging the accuracy of a Fuzzy Logic model and is expressed as

$$E_{ts} = (1/15)^* \mid (\sum_{z=1}^{15} (V_{3z} - V_{2zm}) / (V_{3z}) \mid {}^*100 \qquad (1)$$

The lowest value of E_{ts} is seemed to be obtained as 2.8444% with this model.

B. ASFL model

The block diagram and the equations involved in framing and training the rule base is explained in details in an earlier work [5] for this model. The procedure for finding the relationship between the linguistic values and the actual values of t, t_1, d and ϵ_r is the same as the MFL model. Similarly the identification number was also fuzzified and incorporated in the rule base as in the MFL model. Also the number of rules in the rule base is 72. The error for the z^{th} pattern at the m^{th} iteration is given by

$$e_{zm} = V_{3z} - V_{2zm} \qquad (2)$$

Where V_{3z} is the value of ά for the z^{th} pattern and V_{2zm} is the modeled value of the breakdown voltage.

The Mean Square Error (MSE) for the training patterns at the m^{th} iteration is expressed as

$$E_{tr} = (1/115)^* \sum_{z=1}^{115} (e_{zm})^2 \qquad (3)$$

The value of m is 400 as has been mentioned before and the E_{tr} at this value of m is 0.0021 with learning rate of LMS algorithm at 1.85.

On completion of the training with 115 sets of input output patterns, 15 sets of input output patterns are used for testing purpose. The Mean Absolute Error (MAE) for the test data E_{ts} is calculated in equation (1) based on the least value of E_{tr} in equation (3). The E_{ts} is found out to be 1.5653 % with this model.

Comparison of the proposed models

Table I shows a comparison of the experimental and modeled value obtained in the MFL and ASFL models with the 15 testing patterns for all the five materials.

TABLE I.
COMPARISON OF THE EXPERIMENTAL AND MODELED VALUE OF THE BREAKDOWN VOLTAGE UNDER AC CONDITION

t (mm)	t_1 (mm)	d (mm)	(kV) (Experimental)	(kV) (MFL)	(kV) (ASFL)
0.26	0.025	3	2.2807	2.2500	2.1853
0.125	0.125	2	2.2697	2.2692	2.2412
0.18	0.025	1.5	2.2885	2.2516	2.2653
0.13	0.125	5	1.3306	1.4558	1.3301
0.175	0.125	4	1.8313	1.8558	1.8273
0.235	0.025	2	2.2909	2.4429	2.2899
0.195	0.025	5	2.2294	2.2312	2.2312
0.155	0.025	3	2.2447	2.2366	2.2448
0.155	0.125	1.5	2.3088	2.3052	2.3052
0.035	0.125	3	0.8154	0.8429	0.8148
0.06	0.025	2	0.8388	0.8419	0.8419
0.06	0.125	4	0.8758	0.8357	0.8762
0.245	0.025	5	2.2697	2.4500	2.2708
0.185	0.125	1.5	2.3088	2.2500	2.3052
0.125	0.025	2	2.3170	2.4500	2.3120

From Table I, it may be seen that all the two FL models, namely MFL and ASFL have been very effective in predicting the breakdown voltage due to PD in cavities for the five insulating materials and the MAE of the test data, E_{ts} obtained are 2.8444% and 1.5653 % respectively.

IV. CONCLUSION

The breakdown voltage due to PD with the samples of the five insulating materials was modeled using two FL models. The error values clearly indicate that the MFL and the ASFL model are capable of predicting the breakdown voltage quite effectively. The models are developed for artificial voids in the solid insulating materials. In reality, the voids have different geometry and are randomly distributed in the insulating material. But, since the center of the insulating materials is stressed by the electrode system considered here, the artificial voids are situated just below the center of the sample with different dimensions.

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