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Correlation of Breakdown Strength Parameters of Solid Insulation using Artificial Neural Network (ANN)

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ABSTRACT

The objective of this work is to determine if a relationship could be found between dielectric strength and other basic properties of electrical insulating materials such as volume resistivity, dielectric constant or relative permittivity and dissipation factor or loss tangent, on empirical basis, by using variables predicted by basic theory. A simple equation to predict the dielectric strength of a solid insulating material in the ambient medium has been proposed using ASTM electrode system. Also, Artificial neural network theory is used to predict the value of dielectric strength of solid insulating materials provided thickness of insulation, volume resistivity, dissipation factor and dielectric constant are known and the results thus obtained have been compared with those obtained by the proposed equation.

Key words: Breakdown Strength, Loss Tangent, Relative Permittivity, Solid Dielectrics, ANN

INTRODUCTION

The theory behind dielectric breakdown has always been to a great extent equal part of speculation, art and science. The interaction of fields, particles and atoms on a microscopic level is so complex that exact quantum mechanical solution to all but the simplest atomic structure has been impossible [1-2]. A myriad of factors, which might influence dielectric strength, could be listed and evaluated [3-5]. These include intrinsic material properties, a host of external environmental factors and assorted test conditions that may exist. However, if the environmental factors and test conditions are kept constant the list can be shortened considerably. If this were the case, then a list of intrinsic material properties which might affect the dielectric strength such as relative permittivity (ξ_r), loss tangent ($\tan\delta$), ionization energy (E_i), sample thickness (t), mobility of charge carriers (μ), number of charge carriers (n), free path among molecules (λ) and free volume of the material (V_f) would result [6-7]. Out of the above parameters ξ_r, $\tan\delta$, and t can be measured in a relatively straight forward manner. However, the others cannot be measured readily. Mobility of charge carriers is very difficult to define [8]. However, the volume resistivity (ρ_v) measurement can be used to determine μ through the equation $\rho_v=1/ne\mu$, if the number of charge carriers are known.

The mean free path of a free electron in a material is dependent upon the free volume of a material and the molecular agitation within the material. Both of these are temperature dependent. The increase in free volume with temperature leads to an increase in the mean free path. However, the increased molecular agitation at high temperatures tends to decrease this path. Thus, the measurement and calculation of this parameter is most difficult. Furthermore, from the energy considerations, the kinetic energy which an electron acquires when subjected to an electric field is dependent upon the mean free path between collisions. Also, the mean free path λ should be equal to the cube root of the free volume V_f.

With these constraints in measuring the above listed intrinsic properties, Swanson et al [6] suggested a relationship given by equation (1) to correlate the dielectric strength E with volume resistivity, relative permittivity and loss tangent.

Dielectric Strength $$E=A+ B\log (\rho_v /\xi_r \tan\delta) \quad (1)$$

This is based on the assumption of performing experiments on the test samples of same thickness in a group, which is again an approximation to eliminate t from the above equation.

Though Eq. (1) holds good for the evaluation of dielectric strength of a number of solid insulating materials, it suffers from the disadvantage that it is valid for a particular large thickness of 1.397 mm and cannot be used for dielectrics of smaller thickness. However it is well established that the thickness affects the dielectric strength of solid insulating material.

Using the above approach the breakdown strength (BDS), relative permittivity (ξ_r), loss tangent ($\tan\delta$) and thickness (t) of different solid insulating materials in the ambient medium have been measured and correlated incorporating the thickness of the samples to estimate the BDS of solid insulants.

EXPERIMENTAL TECHNIQUES

For obtaining correlation between breakdown strength parameters based on eq. (1) certain measurements need to be taken. These include measurement of dielectric properties such as relative permittivity, dissipation factor and volume resistivity and measurement of breakdown strength of solid dielectrics.

Measurement of Relative Permittivity and Loss Tangent of Solid Dielectrics

Fig. 1 shows the three-electrode system as described in [9] to measure the relative permittivity and loss tangent of various dielectrics. Measurements were made using 6451 LCR data bridge (Forbes-Tinsley) shown in Fig. 2. Measurement of ξ_r and $\tan\delta$ were carried on Polyethylene, Fiber Glass, Leatheroid, Polythene coated Leatheroid, Empire cloth, Mica and Kraft paper.

Breakdown Strength of Solid Dielectrics

The electrode assembly for obtaining the electric strength is as per IS: 2584-1963[10]. Five samples of equal thickness were tested with this arrangement. Taking the ratio of average breakdown voltage to average thickness of the sample, electric strength was determined.

For measurement of breakdown voltage of solid dielectrics high voltage is obtained using H.V. testing transformer (30kVA; 150kV) shown in Fig.3.

(a) Schematic of three electrode system **(b) Three electrode system Experimental Setup**

Fig.1 Three-electrode system used to investigate the relative permittivity and loss tangent

Fig. 2 LCR Data-Bridge

Fig. 3 High voltage Testing transformer

Sample Preparation

No special efforts were made to clean or modify the test samples i.e. Polyethylene, Fiber Glass, Leatheroid, Empire cloth, Mica, Kraft paper and Polythene coated Leatheroid in any way since it was assumed that any contaminants such as ionic impurities which would influence the dielectric strength would also influence other properties being measured. Thus the materials were tested as received in the laboratory.

The sample thickness was measured at some randomly distributed 20 points, spread all over the sheet area with a micrometer having a least count of 0.01mm. The average of the 20 measurements was taken as the average thickness of the sample.

RESULTS & ANALYSIS

Analysis based on Fundamental Theory

Volume resitivities of the materials were not measured practically but noted from the literature available [11-13]. Based on the experimental procedure discussed some data was measured experimentally and some data has been taken from literature [14-16].

Collecting all relevant data for different insulating material samples, log $(\rho_v/\xi_r \tan\delta)$ was calculated for each of them. Samples were grouped together according to thickness and for each group measured electric strength was plotted against the quantity log $(\rho_v/\xi_r \tan\delta)$.

The plot is as shown in Fig. 4. For thick samples the slope of straight line is lesser than the slope for thin samples and these decreases in a regular fashion.

Equations (2) to (5) plotted in Fig. 4 are for four thickness groups of samples [0.1-0.27mm, 0.29-0.41mm, 0.45-0.59mm and 0.63-0.88mm].

$$E1=-24.03+4.795\log_{10}(\rho_v/\xi_r \tan\delta) \quad (2)$$

$$E2=-19.2+4.268\log_{10}(\rho_v/\xi_r \tan\delta) \quad (3)$$

$$E3=-15.36+3.683\log_{10}(\rho_v/\xi_r \tan\delta) \quad (4)$$

$$E4=-8.887+2.956\log_{10}(\rho_v/\xi_r \tan\delta) \quad (5)$$

Thus all the measured data can be put in the form of an equation

$$E= -A+B \log(\rho_v/\xi_r \tan\delta) \quad (6)$$

Considering the mean value of a particular range of thickness of samples, it was observed that that constant 'B' is inversely related to thickness 't' of the sample. Fig. 5 shows a plot between 'B' values versus thickness 't' of sample which is again a straight line and mathematically expressed as B= 5.3-3.2t .

Thus finally equation relating all these data can be expressed as

$$E=-16.8693+B\log_{10}(\rho_v/\xi_r \tan\delta)$$

Where 16.8693 is the average of 'A' values of equation (2) to (5), so

$$E=-16.8693+(5.3-3.2t)\log_{10}(\rho_v/\xi_r \tan\delta) \quad (7)$$

The calculated values using Eq. (7) and measured values of electric strength of various solid insulating materials mentioned earlier are listed in Table -1. Errors in most of the cases are within ± 10 %.

Table -1 Measured Values of Electric Strength of Various Solid

Material .	t (in mm)	ξ_r	tan δ	ρ_v	V(Measured) (In kV/mm)	V(Swanson's Correlation) (In kV/mm)	Error (in %)
Polyethylene	0.19	2.2123	0.0025	$2.1*10^{16}$	64.368	70.3054	9.2242
	0.41	2.0381	0.0042	$2.1*10^{16}$	57.317	56.4690	1.4795
Fiber glass	0.34	7.5112	0.0045	$4.6*10^{12}$	42.058	42.6624	1.4371
	0.52	6.5728	0.0051	$4.6*10^{12}$	36.538	34.5344	5.4835
Leatheroid	0.47	5.2834	0.05	$1.6*10^{10}$	23.404	24.0601	2.8032
	0.47	4.2171	0.044	$1.6*10^{10}$	24.489	24.6424	0.6266
Polythene coated Leatheroid	0.27	3.8411	0.0062	$3.4*10^{11}$	38.148	41.4846	8.7466
	0.52	3.0521	0.0096	$3.4*10^{11}$	31.730	30.6336	3.4553
Empire cloth	0.33	2.4624	0.0251	$5.4*10^{13}$	46.06	46.5418	1.0461
	0.52	2.3216	0.0551	$5.4*10^{13}$	38.461	36.3089	5.5957
Mica	0.2	7.9341	0.006	$4.2*10^{14}$	54	57.4372	6.3652
	0.45	7.3689	0.009	$4.2*10^{14}$	45.777	44.1249	3.6090
Kraft paper	0.41	2.6311	0.2511	$0.5*10^{9}$	19.146	18.5401	3.1647
						M.A.E.	**4.0797**

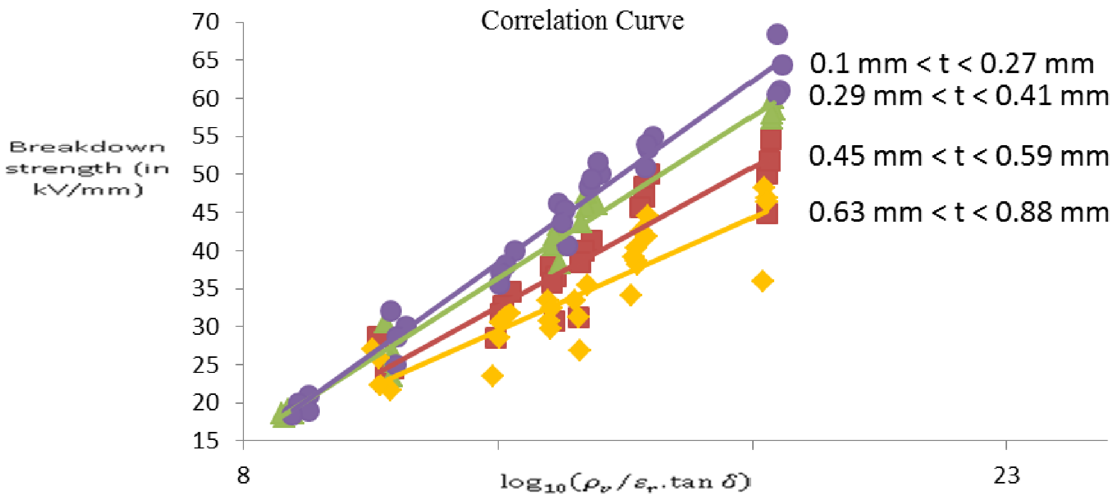

Figure 4. Correlation Curve for Breakdown Strength

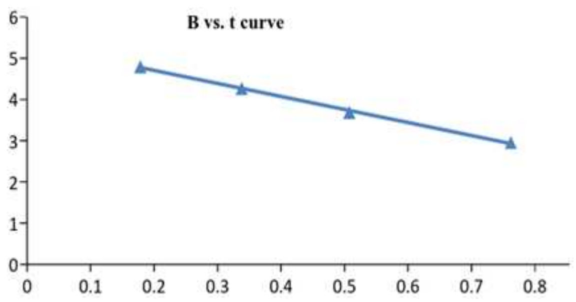

Fig. 5 'B' versus 't' curve

Table -2 ANN Model Configuration

ANN Parameters	Specification
No. of training patterns	91
No. of testing patterns	13
No. of neurons in input layer	4
No. of neurons in output layer	1
Transfer function	Log-sigmoid (for hidden layers) Linear (for output layer)
Performance function	Mean squared error (for training) Mean absolute error (for testing)
Training algorithm	Levenberg-Marquardt algorithm
No. of epochs	1000
Stopping criteria	Early stopping

Analysis based on ANN Implementation

Data for training and testing of ANN model is taken from experimental readings as well as literature [14-16].The available data set contains 104 input-output pairs. These 104 input-output data pairs are divided into two groups; one containing 91 data pairs and other containing 13 data pairs. ANN model is trained and validated using 91 data pairs and then trained model is tested using 13 data pairs.

In this study each input or output data x_i is normalized as p_i before being fed to the ANN model according to the formula

$$p_i=x_i/x_{max}, \quad i=1,2,\ldots\ldots,n \qquad (8)$$

Where x_i and x_{max} are the actual data and the maximum value of the input (or output) data respectively, and n is the number of input-output pairs [17].

For preparing ANN model MATLAB (R2010a) is used. Thickness of insulation, relative permittivity, dissipation factor and volume resistivity are used as inputs and breakdown strength is used as target. As every parameter (except input and target data) of ANN model is chosen by hit and trial, ANN model is configured as shown in Table -2. For prediction of breakdown strength of solid insulating materials various topologies of multi-layer perception were studied. The selection of the apt network size is very vital because this not only reduces the training time but also greatly enhance the ability of the neural network to represent the problem in hand. Unfortunately there is no thumb rule that can dictate the number of hidden layers and the number of neurons per hidden layer in a given problem.

Various ANN architectures with one, two and three hidden layers with varying number of neurons in them were studied for prediction of breakdown strength. Out of the various ANN architectures obtained with satisfactory performance the best ANN architecture consists of 4 – 2 – 9 – 1 ANN architecture (4 neurons in input layer, two hidden layers with 2 and 9 neurons respectively and 1 neuron in output layer).

Fig. 7 shows the performance plot of 4 – 2 – 9 – 1 ANN architecture (4 neurons in input layer, two hidden layers with 2 and 9 neurons respectively and 1 neuron in output layer). It can be seen that the best validation performance in terms of Mean Square Error by the end of the training process is 0.0020577. The best validation performance is achieved at 67th epoch and the Mean absolute error (MAE) is found to be 1.5129 percent.

Table -3 gives the predicted values of breakdown strength by the chosen architecture along with corresponding thickness of insulation, relative permittivity, dissipation factor, volume resistivity and measured values of breakdown strength. Percentage error for individual sample and mean absolute error are also shown in Table-3.

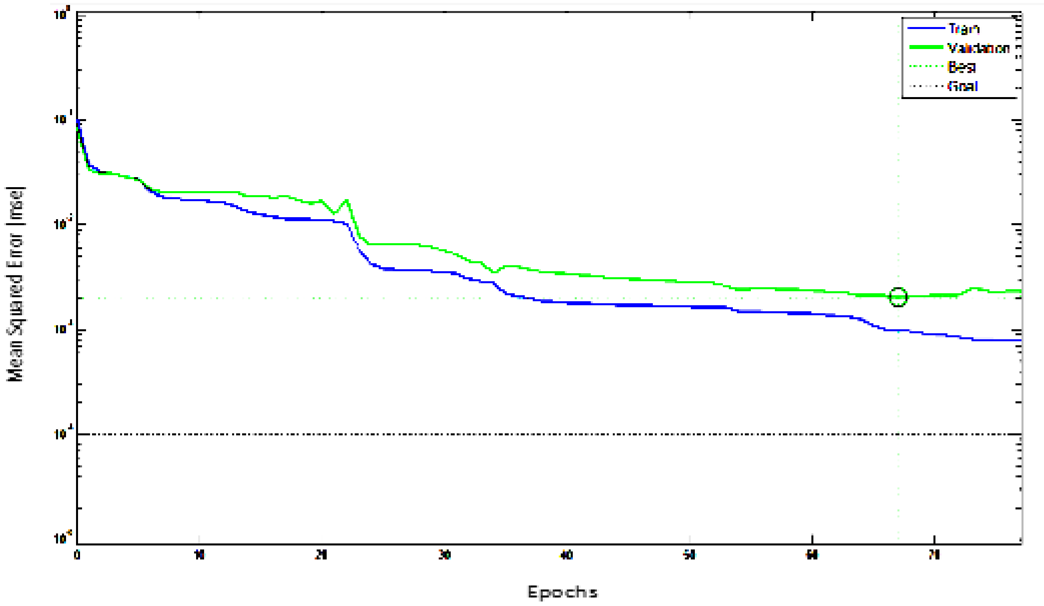

Fig. 7 Performance Plot for Network Architecture 4 – 2 – 9 – 1

Table -3 Predicted Values of Breakdown Strength

Material	**t (mm)**	ξ_r	tan δ	ρ_v	**V (Measured) (kV/mm)**	**V (ANN) (kV/mm)**	**Error (%)**
Polyethylene	0.19	2.2123	0.0025	$2.1*10^{16}$	64.368	64.6036	0.3660
	0.41	2.0381	0.0042	$2.1*10^{16}$	57.317	57.0971	0.3836
Fibre glass	0.34	7.5112	0.0045	$4.6*10^{12}$	42.058	40.4464	3.8318
	0.52	6.5728	0.0051	$4.6*10^{12}$	36.538	36.4318	0.2907
Leatheroid	0.47	5.2834	0.05	$1.6*10^{10}$	23.404	23.5358	0.5632
	0.47	4.2171	0.044	$1.6*10^{10}$	24.489	23.9477	2.2105
Polythene coated Leatheroid	0.27	3.8411	0.0062	$3.4*10^{11}$	38.148	38.1468	0.0031
	0.52	3.0521	0.0096	$3.4*10^{11}$	31.730	31.6974	0.1028
Empire cloth	0.33	2.4624	0.0251	$5.4*10^{13}$	46.06	47.7325	3.6311
	0.52	2.3216	0.0551	$5.4*10^{13}$	38.461	38.9327	1.2264
Mica	0.2	7.9341	0.006	$4.2*10^{14}$	54	52.7536	2.3081
	0.45	7.3689	0.009	$4.2*10^{14}$	45.777	45.0618	1.5624
Kraft paper	0.41	2.6311	0.2511	$0.5*10^{9}$	19.146	19.7563	3.1878
						MAE	**1.5129**

For the purpose of comparison, measured values of breakdown strength and predicted values of breakdown strength (by both correlation based on Swanson's theory and ANN) are shown on the same graph. It can be seen from the graph that breakdown strength predicted by ANN is more close to the measured values for most of the test specimen considered. Fig.8 shows the comparison of errors in prediction by Eq. (7) and by ANN implementation.

CONCLUSION

Empirical formula suggested as given by Eq (7) for estimation of electric strength of solid insulating material is simple and gives results with errors within 10% and thus may be useful provided thickness is small. It is expected that the equation obtained will help the designers as a handy tool for quick estimation of breakdown strength of solid dielectrics. Mean absolute error in prediction of breakdown strength by this method is found to be 4.0797 percent (Table -1).

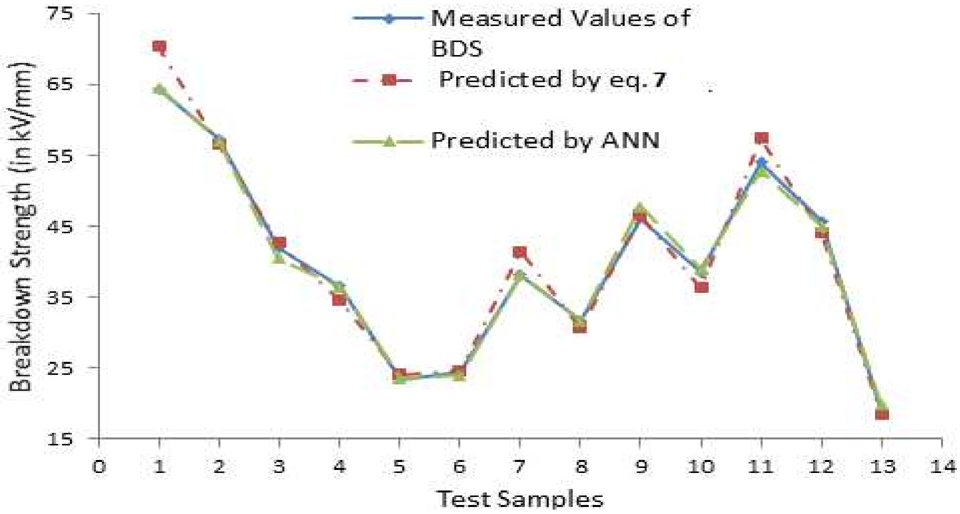

Fig. 8 Comparison of Breakdown Strength predicted by ANN and eq. (7)

In the second part of the work various ANN architectures were studied for finding an alternate way to predict breakdown strength. Performance of 4 – 2 – 9 – 1 ANN architecture is found to be quite satisfactory with the modelled value of the breakdown strength closely following the measured value having a mean absolute error of 1.5129 percent only (Table -3).

It can be seen from Fig.8 that breakdown strength predicted by ANN is more close to the measured values for most of the test specimen considered suggesting ANN model is found to be more satisfactory than predicted equation.

The proposed model suggesting the effectiveness of ANN particularly as the behaviour of insulation breakdown strength is non-linear.

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