TRANSACTIONS ON ELECTRICAL AND ELECTRONIC MATERIALS
Vol. 18, No. 6, pp. 338-340, December 25, 2017

Regular Paper

pISSN: 1229-7607 eISSN: 2092-7592
DOI: https://doi.org/10.4313/TEEM.2017.18.6.338
OAK Central: http://central.oak.go.kr

Breakdown Strength Estimation of Non-Cellulosic Insulating Materials Used in Electrical Power Equipment

Sakshi Singh†, Mirza Mohd. Mohsin, and Aejaz Masood
Department of Electrical Engineering, Z.H. College of Engineering & Technology, Aligarh Muslim University, Aligarh 202002, India

Received October 27, 2016; Revised June 17, 2017; Accepted June 19, 2017

Breakdown of solid insulating materials in power equipment could result in undesired outages and replacements, and may be due to an increase in electric stress on the material. Therefore, it is necessary to conduct a proper diagnosis of materials before their practical use. In this work, a few inherent properties of different non-cellulosic insulating materials, such as Nomex, Teflon, laminated Nomex, glass bonded mica, epoxy resin bonded mica paper, and epoxy resin bonded fiberglass, have been evaluated by performing non-destructive dielectric diagnostic measurements, and an attempt has been made to correlate these basic parameters to evaluate the breakdown strength (BDS). An equation has been proposed using a basic theory which defines the correlation between the BDS, dielectric constant, dissipation factor, sample thickness, and volume resistivity. The results obtained from the equation are also compared with the experimental values. The suggested equation will be helpful to predict the BDS of any non-cellulosic material without experimentation in the laboratory.

Keywords : Non-cellulosic materials, Breakdown strength, Dielectric constant, Dissipation factor

1. INTRODUCTION

Insulating material is a vital part of any electrical power apparatus. The performance of the electrical system is governed by a number of factors, including the physical state of the insulating material involved, its physical, electrical, and mechanical properties, the environmental conditions in which the insulation is subjected to a test voltage, type of voltage applied, and its rate of increase.

A large number of cellulosic and non-cellulosic insulating materials are used in the electric power industry. Cellulose insulation has been a preferred choice for solid insulation in power equipment because it is available in plenty from natural resources. However, these materials are hygroscopic in nature and need to be used in dry conditions. Moreover, their electrical and mechanical properties deteriorate rapidly under excessive temperature, and are therefore generally used after treatment with a varnish or impregnation with oil. These are the main disadvantages of cellulosic material for their use in the electric power industry [1–4].

Unlike cellulosic materials, non-cellulosic materials have better electrical properties, considerably higher thermal ratings, and lower moisture absorption. Generally, inorganic or synthetic insulating solids are non-cellulosic materials. A few examples are Nomex (aramid), glass, mica, epoxy resins, asbestos, and phenols [4].

Millions of power equipment devices currently in use worldwide utilize non-cellulosic material as insulation; therefore, proper diagnosis of these materials has become a high priority to estimate their life span and performance.

Studies of the breakdown strength (BDS) of solid insulating materials are of extreme importance in insulation studies. BDS is found to depend on a number of factors including intrinsic material properties, test conditions, and external environmental factors. Intrinsic material properties include the dielectric constant ξ_r, dissipation factor tan δ, sample thickness t, mobility of charge carriers μ, number of charge carriers n, free volume of the material V_f, and mean free path among molecules λ. Among these parameters, the dielectric constant, dissipation factor, and thickness can be measured directly. The mean free path depends on the free volume of the material, which is temperature dependent. To determine mobility, a volume resistivity ρ_v measurement can be used through

† Author to whom all correspondence should be addressed:
E-mail: sakshisingh3009@gmail.com

the relation $\rho_v = 1/ne\mu$, where, e is the elementary charge [5–9].

In this work, some important properties of a few non-cellulosic materials are measured, and an equation is developed which defines the relationship between BDS and the other properties of the materials under study. The equation obtained is based on the empirical relation suggested by F. C. Dall and Samson [10], in which the different properties of the dielectric materials are correlated in the given form

$$BDS = A + B \log_{10} (\rho_v / (\xi_r \tan \delta)) \quad (1)$$

The relation obtained would be useful in testing these types of materials before their practical use. Parameters like loss tangent tan δ, permittivity ξ_r, and breakdown strength are measured according to ISI, ASTM and IEEE standards [11–13].

2. EXPERIMENTAL TECHNIQUES

2.1 Preparation of sample

In this work, measurements have been done for non-cellulosic materials like Teflon, Nomex, laminated Nomex, glass bonded mica, epoxy resin bonded mica paper, and epoxy resin bonded fiber glass.

No additional effort was made to modify or clean the materials under observation in this work. It was assumed that any contaminant or impurity that could influence the dielectric strength would also influence other properties of material. The materials were tested as available in the laboratory [10].

2.2 Measurement of breakdown strength

The ASTM point-to-plane electrode assembly [14] to obtain the breakdown voltage of materials is shown in Fig. 1. It is comprised of cylindrical brass rods of 0.64 cm in diameter with edges rounded to a 0.08-cm radius, mounted vertically one above the other, so that the sample could be held between the faces of the rods. In the setup, five such electrode fixings are available. Lower electrodes are connected to a flat plate (0.64 cm wide and 10.8 cm long with square edges) which is connected to the ground during the experiment. High voltage is applied to the upper electrode using a 150 kV, 50 Hz transformer, shown in Fig. 2.

Fig. 1. ASTM point to plane electrode system.

Fig. 2. Primary and secondary sides of transformer in lab to apply high voltages to the electrode system.

From the observed values of breakdown voltage, breakdown strength can be calculated by using the relation given as

Breakdown Strength= (Breakdown Voltage [kV])/ (Thickness of insulation [mm]).

2.3 Measurement of dielectric constant and dissipation factor

The parallel plate method is commonly employed to measure the permittivity and capacitance of any insulating material [11,12]. Dielectric constant ξ_r and dissipation factor tan δ are calculated for materials placed between the plates of the ASTM electrode assembly, using an advanced version of capacitance and dissipation factor bridge which is named as automatic capacitance and dissipation factor (tan-delta) test system (Model PE-ACDF-1), shown in Fig. 3.

ACDF was used for on-the-spot anti-interference high voltage dielectric diagnostic measurements in the lab. Experiments can be performed on voltage ranges from 0.5~12 kV (200 mA maximum) with 1% ± 4-digit accuracy for dissipation factor, and 1% ± 1-digit accuracy for capacitances which range between 3 pF to 50,000 pF at 12 kV and 60 pF to 1 μF at 0.5 kV. This test set is an all-in-one structure containing frequency conversion power unit, in-built high-voltage generators, standard reference capacitor (SF_6 gas filled), etc. with fully automatic intelligent and stable measurements even under heavy interferences It is a user-friendly system which allows all settings and display of results on the same big back-lighted colored LCD display, and the feather touch membrane key panel. One-time connection can measure capacitance and dielectric loss simultaneously [15].

Values of capacitance and dissipation factor, obtained from the ACDF Bridge, for the non-cellulosic materials under study are used for further calculations. The dielectric constant can be calculated by using the following relation:

$$\xi_r = (t * C) / (A * \xi_0) \quad (2)$$

where, C is an equivalent insulation parallel capacitance of the sample (F), t is the average thickness of the sample insulation (m), A is the surface area of the parallel plate electrodes (m^2), and ξ_0 is permittivity of free space (8.8542×10^{-12} F/m).

Fig. 3. Parallel plate electrode cell with ACDF-1 present in HV lab.

3. RESULTS

Parameters like dissipation factor, dielectric constant, and breakdown strength for all the non-cellulosic materials under

Table 1. Measured values of intrinsic properties of different non-cellulosic materials.

Non-cellulosic materials	Density (gm/ cm^3)	Thick-ness (mm)	Dielectric constant (ξ_r)	Dissipation factor ($\tan\delta$)	log ($\rho_v/\xi_r \tan\delta$)	Measured BDS (kV/mm)
Teflon*	1.0796	0.17	1.57 1.60	0.210 0.230	14.48 14.43	35.29 35.29
Nomex	0.831	0.134	1.05 1.08	0.050 0.055	17.28 17.23	48.50 48.50
Laminated Nomex*	1.036	0.16	1.07 1.04	0.021 0.023	17.62 17.62	53.12 53.12
Glass Bonded Mica Paper	1.251	0.168	1.15 1.18	0.082 0.091	13.03 12.97	29.41 29.41
Epoxy resin mica paper	1.754	0.517	1.72 1.74	0.040 0.040	14.16 14.16	38.68 39.65
Epoxy resin fiber glass	1.789	0.583	2.75 2.75	0.023 0.019	13.89 13.99	36.02 36.81

*value of volume resistivity has been taken as provided by the manufacturer

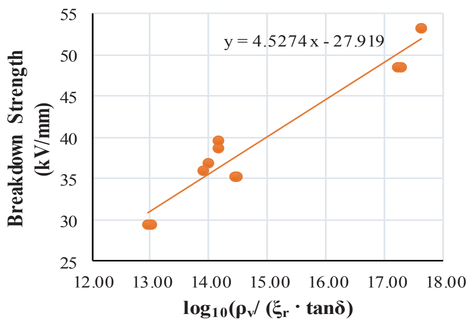

Fig. 4. Plot between breakdown strength and log (ρ_v / ($\xi_r \cdot \tan\delta$)).

Table 2. Measured and calculated values of breakdown strength and their comparison.

Non-cellulosic materials	Measured BDS (kV/mm)	Calculated BDS (kV/mm)	% Error
Teflon	35.29 35.29	37.65 37.43	-6.27 -5.73
Nomex	48.50 48.50	50.31 50.07	-3.60 -3.14
Laminated nomex	53.12 53.12	51.84 51.86	2.48 2.44
Glass bonded mica paper	29.41 29.41	31.06 30.80	-5.31 -4.52
Epoxy resin mica paper	38.68 39.65	36.21 36.19	6.82 9.56
Epoxy resin fiber glass	36.02 36.81	34.99 35.42	2.94 3.93

study are obtained by performing the experiments discussed in section 2.2 and 2.3. All the measured values are tabulated in Table 1. Volume resistivity for most of the materials have been taken from the literature [16,17] or taken as provided by the manufacturer.

Values of all the inherent properties are chronicled and computed to achieve $\log_{10}(\rho_v/(\xi_r \cdot \tan\delta))$ for each material. Measured values of breakdown strength were plotted against $\log_{10}(\rho_v/(\xi_r \cdot \tan\delta))$ for each sample, as shown in Fig. 4.

From the plot, the equation of a straight line is obtained in the form of y = mx + c, as stated below.

$$BDS = -27.919 + 4.527 \log_{10} (\rho_v / (\xi_r \tan\delta)) \quad (3)$$

The form of the obtained equation (3) is similar to equation (1) suggested by Swanson. BDS is again calculated for each material using proposed equation (3) and the percentage error observed between the calculated and measured BDS is shown in Table 2. The error is found to be within the range of ±10%.

In the opinion of the authors, this range of percentage error can be acceptable to predict the approximate value of breakdown strength of any non-cellulosic material if other inherent properties of the material are known.

4. CONCLUSION

Reliability and lifetime of electrical equipment are highly influenced by the condition of insulating material used. Therefore, dielectric diagnosis has always been very important to maintain the equipment sustainability.

Breakdown tests are performed to identify a potential dielectric material and determine its insulating properties. Results of these experiments can be used as a design tool for electrical power equipment. An attempt thus has been made using the physical parameters predicted by the basic theory, suggesting an equation that defines the correlation between breakdown strength and volume resistivity, dielectric constant, dielectric loss, and thickness of material.

The electric strength calculated by equation (3) for Teflon, Nomex, laminated Nomex, glass bonded mica, epoxy resin bonded mica paper, and epoxy resin bonded fiber glass are quite in agreement with the experimentally measured values. Percentage error is also calculated, which is within ±10%. Therefore, it is expected that the proposed equation will aid in the estimation of breakdown strength of non-cellulosic insulating materials used in electrical equipment.

REFERENCES

[1] T. A. Prevost and T. V. Oommen, *IEEE Elect. Insul. Mag.*, **22**, 28 (2006). [DOI: https://doi.org/10.1109/MEI.2006.1618969]

[2] M. Schwartz, *Encyclopedia of Materials, Parts and Finishes*, Ed. 2 (CRC Press, London, 2002) p. 190.

[3] R. Arora and W. Mosch, *High Voltage Insulation Engineering: Behavior of Dielectrics; Their Properties and Applications* (New Age International (P) Ltd., New Delhi, 2008) p. 236.

[4] M. S. Naidu and V. Kamaraju, *High Voltage Engineering* (Tata McGraw-Hill Publishing Company Ltd., New Delhi, 1989) p. 77.

[5] M. A. Laughton and D. F. Warne, *Electrical Engineer's Reference Book*, Ed. 16 (Newnes-An Emprint of Elsivier Science, Oxford, 2003) p. 3.

[6] F. Cardarelli, *Materials Handbook: A Concise Desktop Reference*, Ed. 2 (Springer Science & Business Media, 2008) p. 519.

[7] J. Mort, *Proc. 8th Symposium on Electrical Insulation* (Tokyo, Japan, 1975).

[8] E. Husain, M. M. Mohsin, and R. S. Nema, *Proc. Conference on Electrical Insulation and Dielectric Phenomena* (IEEE, Leesburg, USA, 1989) p. 453. [DOI: https://doi.org/10.1109/CEIDP.1989.69588]

[9] A. Masood, M. U. Zuberi, and E. Husain, *IEEE Trans. Dielectr. Electr. Insul.*, **15**, 1051 (2008). [DOI: https://doi.org/10.1109/TDEI.2008.4591227]

[10] J. W. Swanson and F. C. Dall, *IEEE Trans. Electr. Insul.*, **12**, 142 (1977). [DOI: https://doi.org/10.1109/TEI.1977.297967]

[11] *Recommended methods for the determination of the permittivity and dielectric dissipation factor of electrical insulating materials at power, audio and radio frequencies including metre wavelengths*, **IS 4486**, p. 17 (1967).

[12] *Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation*, **ASTM D150 - 98**, p. 3 (2004).

[13] *IEEE Guide for the Statistical Analysis of Electrical Insulation Breakdown Data*, **IEEE Standard 930**, p. 1 (2004).

[14] Operation Manual-Model PE-ACDF-1 (Power Electronical).

[15] *Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies*, **ASTM D149 - 09**, p. 2 (2013).

[16] E. W. Washburn, *International Critical Tables of Numerical Data, Physics, Chemistry and Technology*, Vol. 2 (National Academy of Science, USA, 1927) p. 310.

[17] R. Von Hippel, *Dielectric Materials and Applications* (The Technology Press of M. I. T. and Wiley, New York, 1954) p. 219.