Probabilistic determination of failure of solid insulation paper used in a transformer under external environmental influence

Pratyush Verma[1], R.K. Jarial[2]

1 School of Electrical Engineering, VIT-Vellore, India

2 Electrical Engineering Department, NIT-Hamirpur, India

Abstract

In high voltage equipments say a transformer, the use and need of solid insulating materials is an indispensable necessity. This is because these materials not only provide mechanical support but also help insulate high voltage conductors effectively. Hence it is of paramount importance to select most suitable insulating material keeping all key characterising parameters intact for smooth functionality of the apparatus. This is equally important in substation transformers which are important elements of a power system network. Should a transformer's conductors get shorted due to a winding paper of extremely low breakdown strength, it would end up damaging the entire transformer and thus interrupt the flow of power from the generating end to the consumer end of power system network. In this paper an investigation has been carried out to study statistical nature of newer and commonly used solid insulation paper based on breakdown voltage and dielectric strength of three different winding paper samples under the influence of temperature and humidity.

Keywords – *breakdown voltage, dielectric strength, probability of failure, transformer.*

1. INTRODUCTION

The dielectric materials are integral part of an electric apparatus and require thorough investigations related with its characterising properties before their use in any electrical power apparatus. The functional life of any electrical apparatus has direct bearing on the quality of insulation used by the manufacturer. It should therefore be selected appropriately. The different properties of the insulating material are mentioned below:

a) It should have a high dielectric strength.
b) It should be thermally stable at high temperatures.
c) The material should have high resistivity and low dissipation factor.
d) Its thermal conductivity should be high.
e) The material should be compatible with other materials present in the transformer.

There are two types of insulation used in the transformer – solid and liquid. The focus of this paper is on the solid insulation – specifically the winding insulation paper that is used in power transformer. Majority of the solid insulating materials are made of fibres which contain cellulose $(C_6H_{10}O_5)_n$. Here subscript 'n' represents the degree of polymerization and it is different for each type of plant. The value of 'n' for fibres made of cotton is typically 1200 or more and for fibres obtained from wood pulp, it is typically 2500 or more. In the transformer, the solid insulators used are impregnated in oil and are used to provide insulation between the different parts of the transformers. During a short circuit these insulators also provide mechanical support to the windings and deal with axial and radial forces [1].

Frequently practical insulation structures consist of combinations of solids with liquid and/or gaseous media. Therefore, the knowledge of failure mechanisms of solid dielectrics under electric stress is of great importance. The types of breakdown that occurs in Solid Insulators is mentioned below [2]:

- Intrinsic Breakdown
- Streamer Breakdown
- Electromechanical Breakdown
- Edge Breakdown & Treeing
- Thermal Breakdown

In this paper, the breakdown voltage and dielectric strength of three different types of winding insulation papers have been shown to vary under the influence of temperature and humidity and their respective probabilities of failure have been presented. The results from the probabilistic analysis can be used to decide which type of paper is best suited for which type of distribution systems. The bell curve has been employed to find out the probabilities of failure of insulation paper.

2. EXPERIMENTAL EQUIPMENT USED AND SAMPLE DESCRIPTION

2.1 Solid Insulation Test Kit:

The equipment consists of a rectangular fibre glass chamber, a high voltage transformer and a control panel. The high voltage transformer provides a maximum voltage of 60 kV (rms) between the two terminals of the high voltage winding which is connected to the testing electrodes. The primary of the transformer is connected to 230 Volts (ac, variable voltage) from the output of the control panel, so that the secondary voltage can be varied from 0 to 60 kV at a constant rate of rise. The variable voltage is provided by a motor operated variac, which is housed inside the control panel.

The control panel is provided with zero voltage interlock, protection against short circuit and tripping off of the high voltage when the specimen under test fails. It is also provided with a reset switch and indicating lamps. The rectangular fibre glass chamber is fixed above the high voltage transformer. It is used for conducting break down studies on solid insulating materials [3]. Fig. 1 shows the circuit diagram of the test kit.

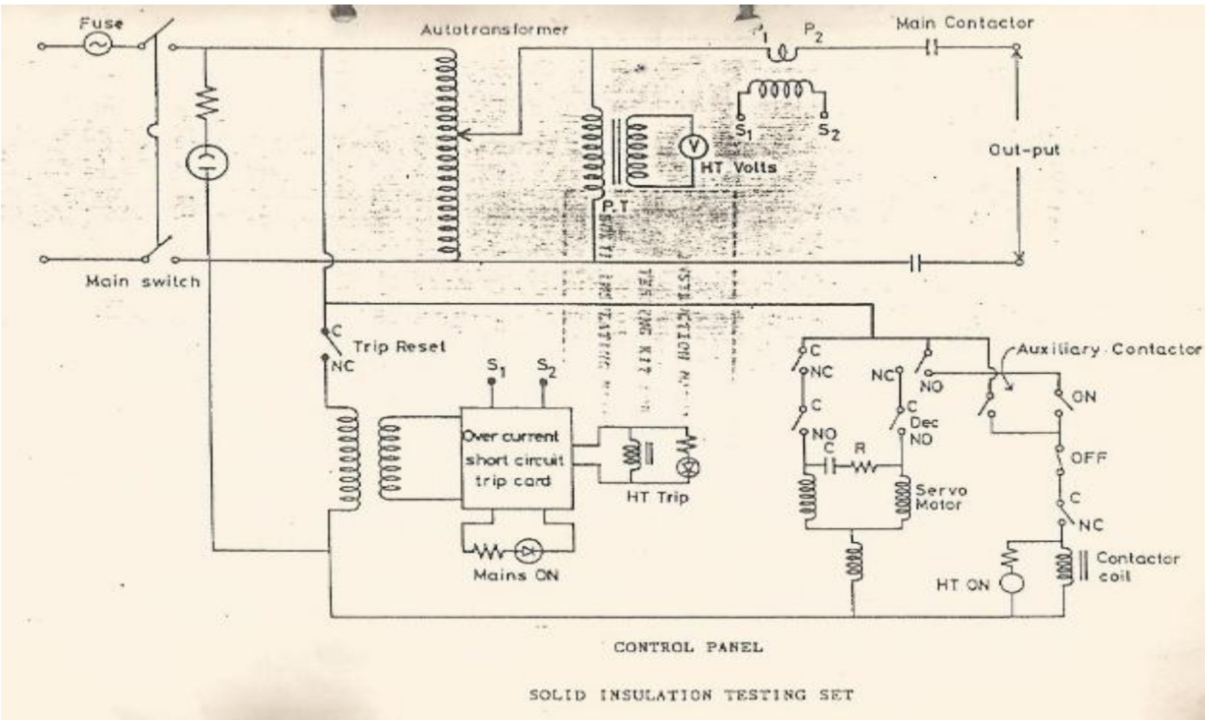

Fig. 1. Solid Insulation Test Kit [3].

2.2 Insulation Paper Sample

2.2.1 Flexilam Nomex 50N

This paper has a high dielectric strength and high breakdown voltage (ranging from 18kV to 22kV). It is also lightweight, tear proof and has along life. It can be used in High voltage systems, such as 22 kV, 33 kV and higher systems.

2.2.2 Polymer based paper

This insulation paper also known as Thermally Upgraded Kraft (TUK) paper has non-uniform thickness, high dielectric strength and high breakdown voltage (ranging from 12 kV to 18 kV). This paper finds application in several electrical systems conformal to needs of low rating transformers.

2.2.3 Wax based insulation paper

Humidity and temperature have marginal effects on this paper. It has a very low dielectric strength and low breakdown voltage (1.9kV to 2kV). Due to this, it can only be used in those distribution systems which supply low voltages in the order of 1kV or below.

Break down tests of solids are generally conducted with the test specimen immersed in oil inside the fibre glass chamber. [3] The testing equipment is in adherence with ASTM D149 standard.

3. RESULTS & DISCUSSION

The tests have been performed twice in a day for five consecutive days, for three single layered samples. Readings of temperature, humidity and breakdown voltage have been taken down. Using a screw gauge of least count 0.01mm, the thickness of each sample has been measured.

The formula used to calculate the dielectric strength is

$$D = \frac{V}{1000 * t} \qquad (1)$$

where,

a) D is the dielectric strength in V/mm.
b) V is the breakdown voltage in kV.
c) t is the thickness of the sample in mm.

Table 1 shows us the readings for temperature, humidity, breakdown voltage (BDV) and dielectric strength (DS) for Flexilam Nomex 50N

Table 1. Flexilam Nomex 50N insulation paper readings of average thickness 0.34 mm

Temperature (K)	Humidity (%)	BDV (kV)	DS (V/mm)
301	-	20	57.14286
301	88	19	57.57576
302	72	21	61.76471
302	74	22	64.70588
303	54	20	59.70149
303	80	18.5	54.41176
307	-	20.25	59.55882
308	57	22	64.70588
310	54	22	64.70588

In this table, the highest breakdown voltage is 22 kV and the highest dielectric strength is 64.70588 V/mm. Both these values occur at different values of temperature and humidity, i.e. highest breakdown voltage doesn't necessarily correlate to highest dielectric stress.

Fig. 2 shows the relation between dielectric stress and temperature for Flexilam nomex 50N paper. It can be observed that the highest value of dielectric strength occurs at temperatures of 302 K, 308 K and 310 K and that the relation can be mapped by a polynomial function of order 4.

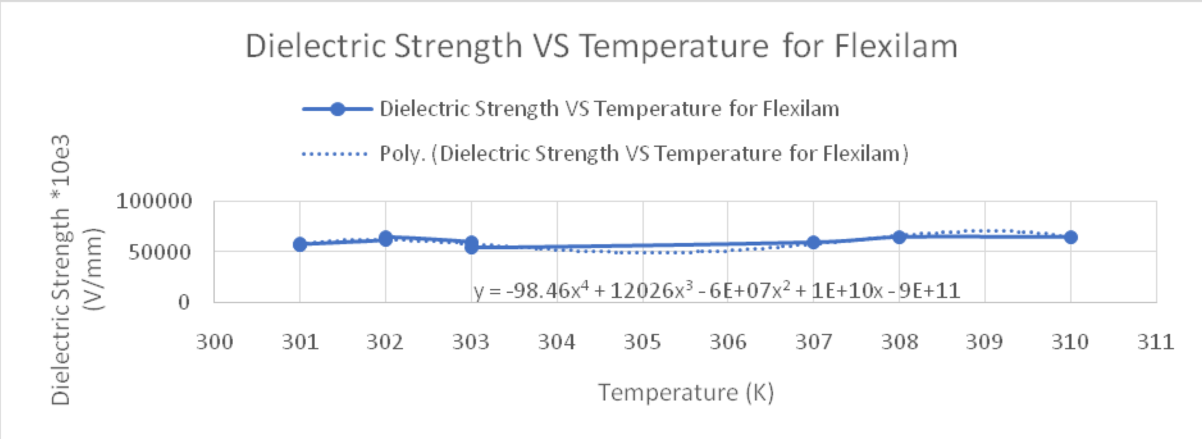

Fig. 2. Dielectric Stress VS Temperature for Flexilam nomex 50N insulation paper

Similarly, the relation between dielectric strength and humidity is shown in Fig. 3 Here at the highest point of humidity (88%), the dielectric strength is nearly 58 V/mm. Whereas dielectric strength has attained its highest values at different humidity levels (54%, 57% and 74% respectively). The relation between the two can be mapped by a polynomial function of order 4.

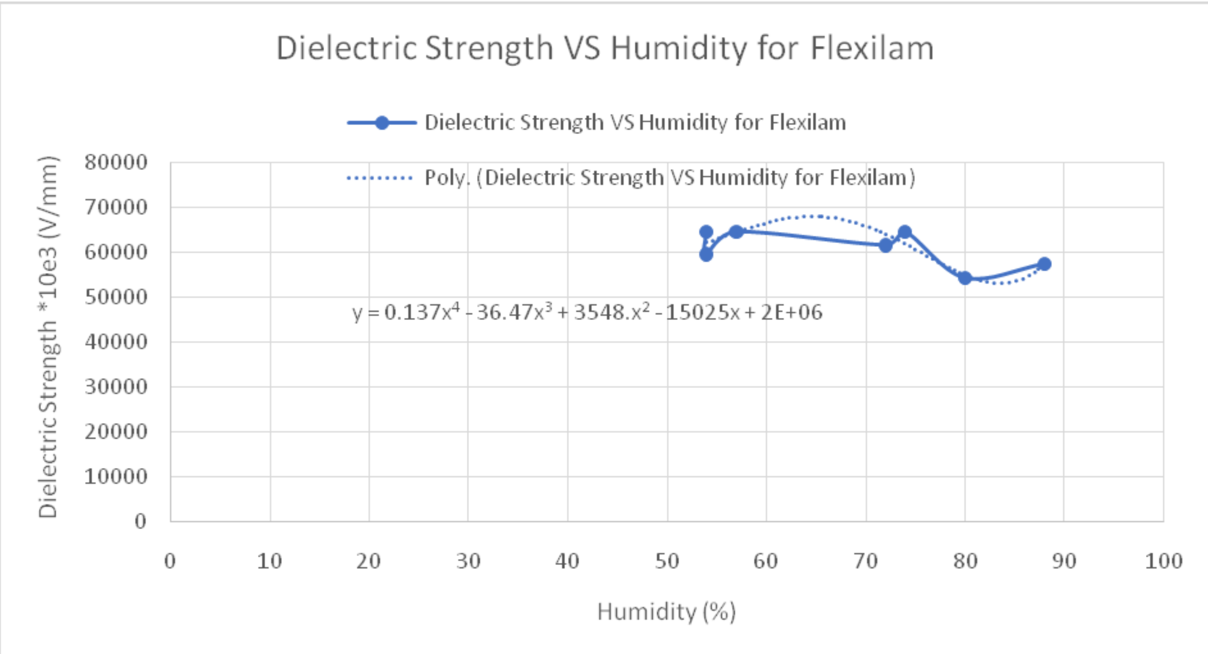

Fig. 3. Dielectric Strength VS Humidity for Flexilam nomex 50N insulation paper

Table 2 shows the readings of temperature, humidity, breakdown voltage (BDV) and dielectric strength (DS) for polymer based paper.

Table 2. Polymer based insulation paper readings of average thickness 0.24 mm

Temperature (K)	Humidity (%)	BDV (kV)	DS (V/mm)
301	-	12.25	58.33333
301	88	12.2	55.45455
302	72	13	61.90476
302	74	18	66.66667
303	54	17	62.96296
303	80	14	66.66667
307	-	12.25	72.05882
308	57	16	61.53846
310	54	18.1	58.38710

The highest value of breakdown voltage is 18.1 kV and it corresponds to a temperature of 310 K and humidity of 54%. The highest value of dielectric strength is found to be nearly 72 V/mm and it corresponds to a temperature of 307 K.

Fig. 4 shows the relation between the dielectric strength and temperature for polymer based insulation paper.

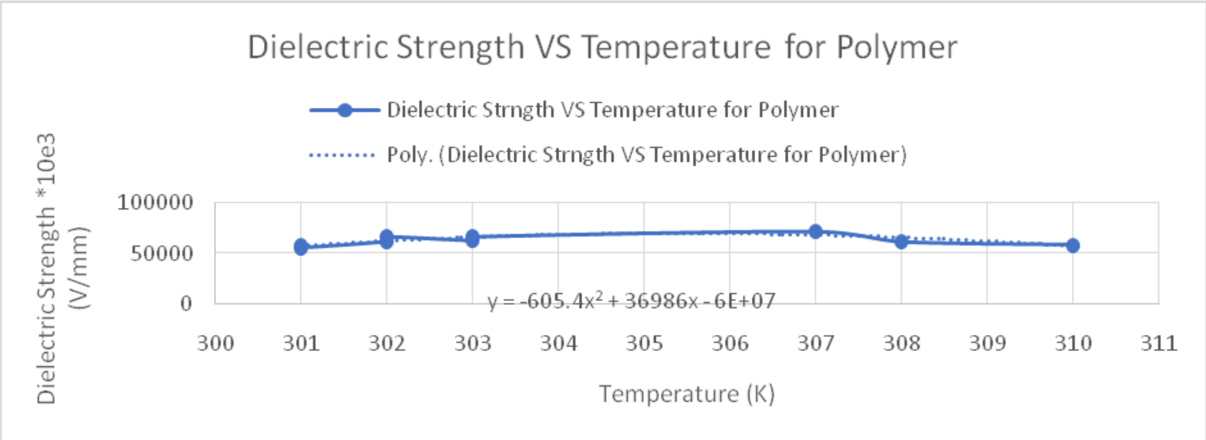

Fig. 4. Dielectric Strength VS Temperature for polymer based insulation paper

The relation between the two can be mapped by a quadratic function shown in Fig. 4. Fig. 5 shows the relation between dielectrics strength and humidity. The relation between the two parameters can be mapped by a polynomial function of order 4.

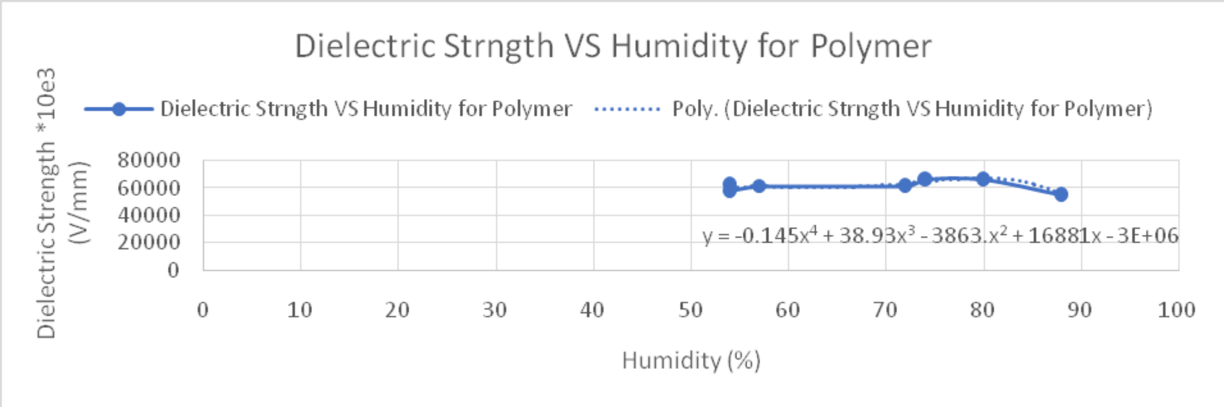

Fig. 5. Dielectric Strength VS Humidity for polymer based insulation paper

Table 3 shows us the readings of temperature, humidity, breakdown voltage (BDV) and dielectric strength (DS). The lowest value of breakdown voltage is 1.9 kV, while the highest value of 2 kV is attained frequently and irrespective of temperature. It can be inferred that temperature and humidity have marginal effect on the breakdown voltage of wax based insulation paper.

Table 3. Wax based insulation paper readings of average thickness 0.14 mm

Temperature (K)	Humidity (%)	BDV (kV)	DS (V/mm)
301	-	2	16.66667
301	88	1.9	12.66667
302	72	2	14.28571
302	74	2	13.33333
303	54	2	14.28571
303	80	2	14.28571
307	-	2	14.28571
308	57	2	14.28571
310	54	2	13.33333

Another observation that can be made is of the material’s dielectric strength. The highest value it attains is nearly 16.7 V/mm, while the most frequent value is nearly 14.3 V/mm for temperature of 302 K, 303 K, 307 K and 308 K. The humidity values for the most frequent value of dielectric strength are 72%, 54%, 80% and 57% respectively. Fig. 6 shows the relation between dielectric strength and temperature. This relation can be mapped by a cubic function.

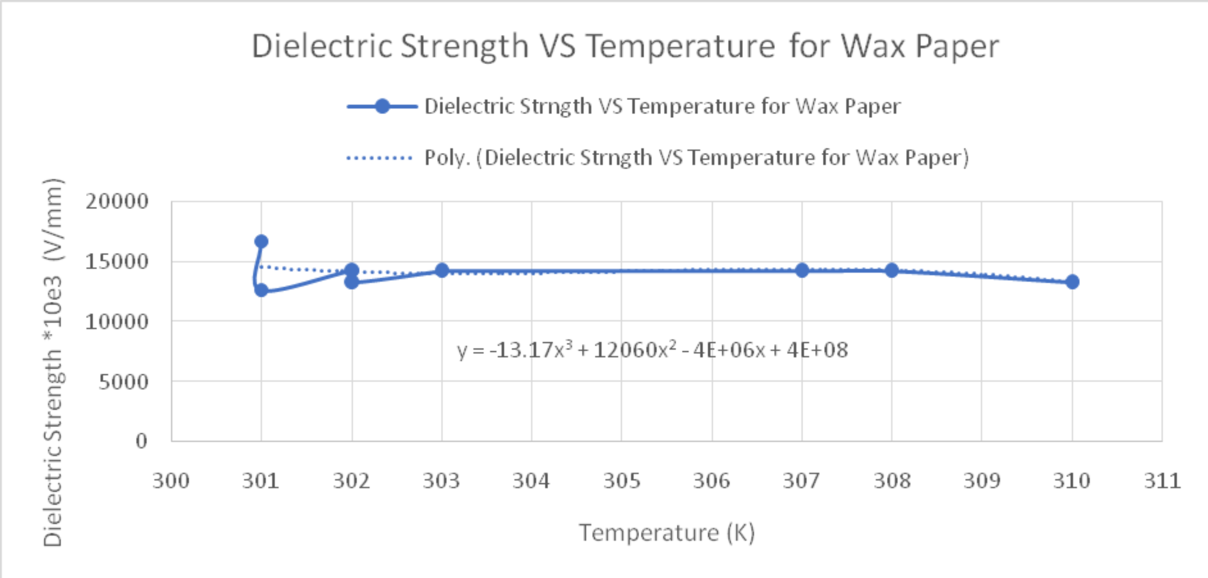

Fig. 6. Dielectric Strength VS Temperature for Wax based insulation paper

The relation between dielectric strength and humidity can be seen in Fig. 7, which can be mapped a polynomial function of order 5.

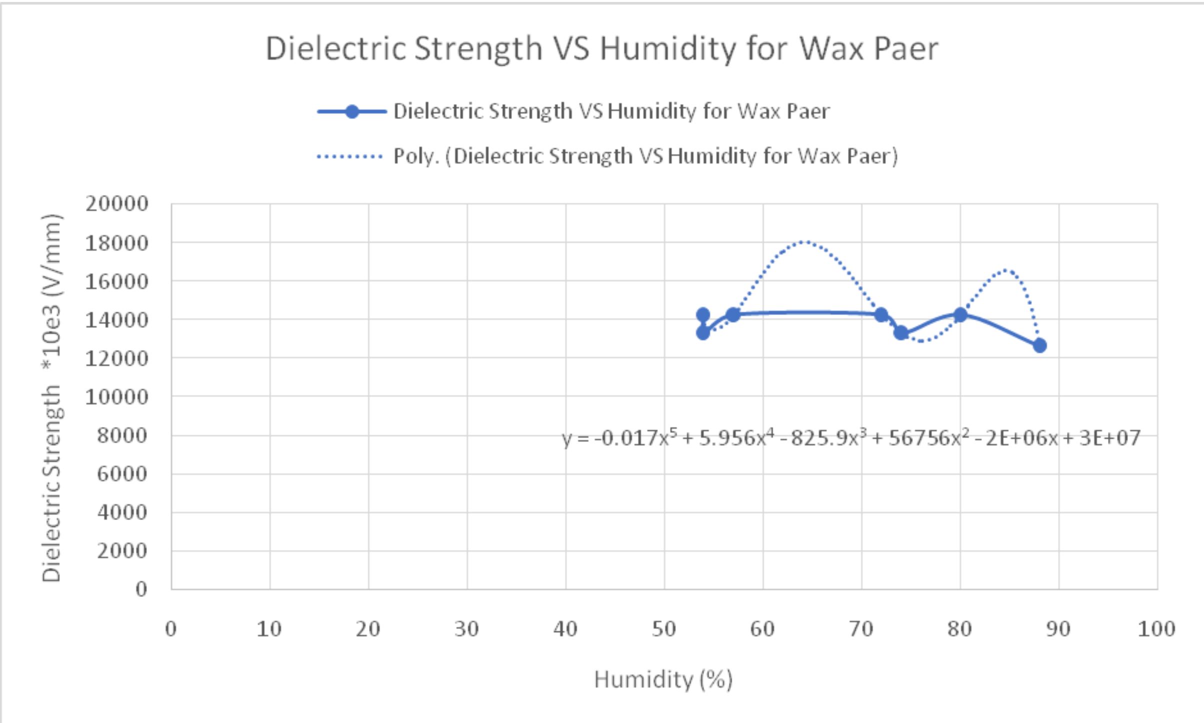

Fig. 7. Dielectric Strength VS Humidity for Wax based insulation paper

4. PROBABILISTIC ANALYSIS

The probability distribution curves of each sample type have been designed separately for two variables – breakdown voltage and dielectric strength. The formula used are

$$\mu = \frac{U_d}{n} \tag{2}$$

$$\sigma = \sqrt{\frac{\sum(U_d - \mu)^2}{n}} \tag{3}$$

$$COV = \frac{\sigma}{\mu} \tag{4}$$

where,

i. μ is mean of breakdown voltage and dielectric strength (separately calculated)

ii. n is number of readings taken for each paper sample

iii. U_d is the value of an individual reading (both breakdown voltage and dielectric strength)

iv. σ is the standard deviation of breakdown voltage and dielectric strength (separately calculated)

v. COV is the coefficient of variation of breakdown voltage and dielectric strength (separately calculated)

The normal distribution curve has been implemented on the values of breakdown voltage and dielectric strength for each of the insulation paper samples. Then using the Z-table the probability of failure of each paper has been calculated. Table 4 shows the values of breakdown voltage (BDV), dielectric strength (DS) and their respective probabilities of failure (PoF) for Flexilam Nomex 50N insulation paper.

Table 4. Flexilam Nomex 50N insulation paper failure probabilities

BDV (kV)	PoF (%)	DS (V/mm)	PoF (%)
18.5	6.06	54.41176	5.37
19	12.10	57.14286	18.67
20	34.46	57.57576	22.06
20	34.46	59.55882	40.52
20.25	42.07	59.70149	41.68
21	64.06	61.76471	63.31
22	86.86	64.70588	87.08
22	86.86	64.70588	87.08
22	86.86	64.70588	87.08

Fig. 8 shows the relation between probability of failure and breakdown voltage for Flexilam Nomex 50N insulation paper under different temperature and humidity conditions. As the value of breakdown voltage or dielectric strength increases then the probability of failure of the material will increase as well. The relation between the two parameters can be mapped using a polynomial function of order 5.

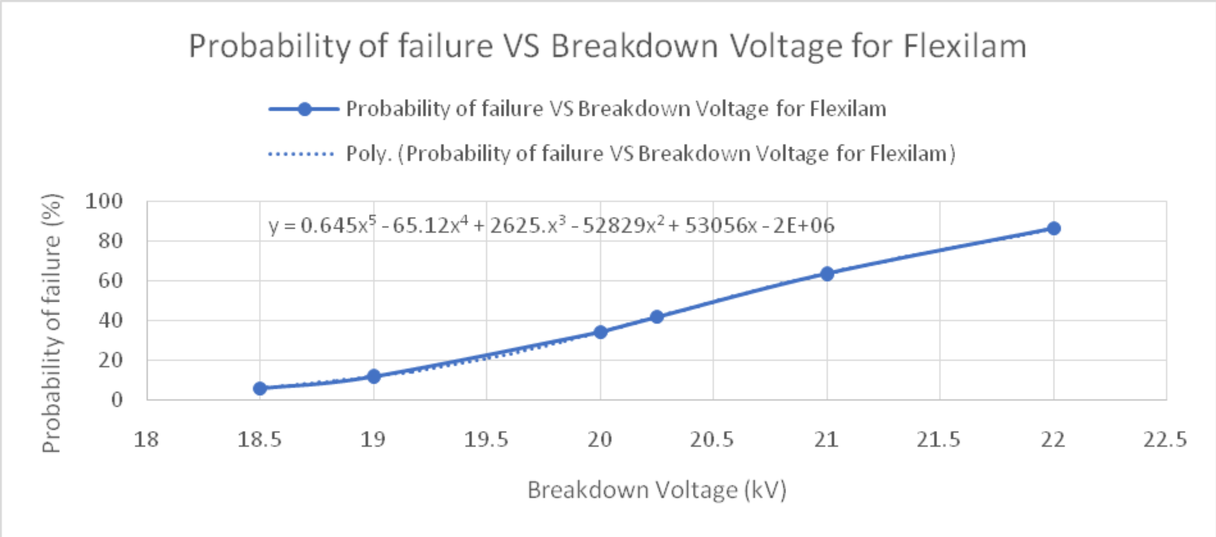

Fig. 8. Probability of failure VS Breakdown voltage for Flexilam nomex 50N insulation paper

Similarly, Fig. 9 shows the relation between probability of failure and dielectric strength for Flexilam nomex 50N insulation paper. The relation between the two parameters can be mapped by a cubic function. Table 5 shows us the values of breakdown voltage (BDV), dielectric strength (DS) and their respective probabilities of failure (PoF) for Polymer based insulation paper.

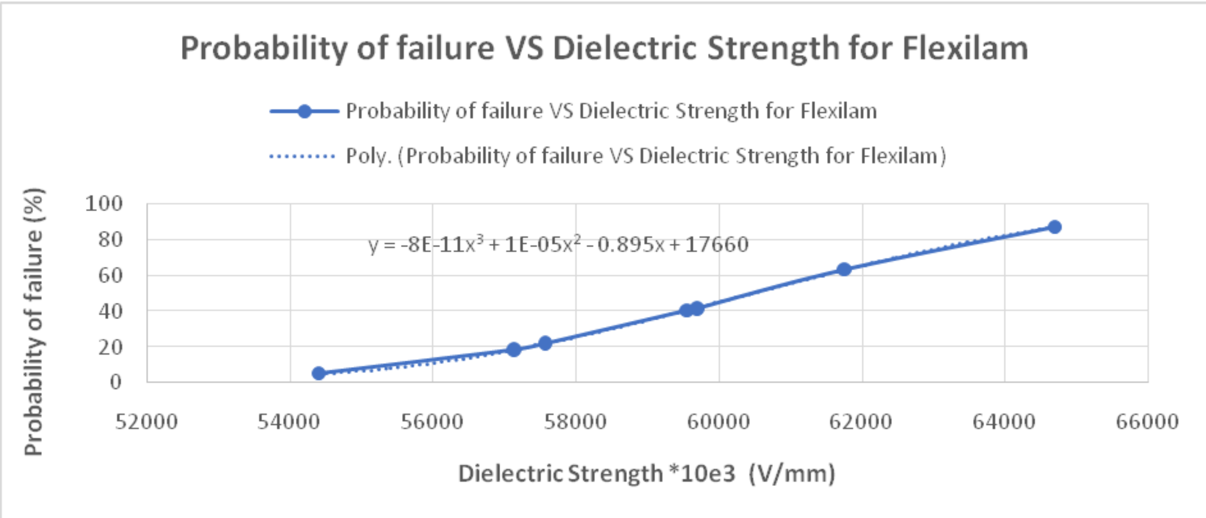

Fig. 9. Probability of failure VS Dielectric strength for Flexilam nomex 50N insulation paper

Table 5. Polymer based insulation paper failure probabilities

BDV (kV)	PoF (%)	DS (V/mm)	PoF (%)
12.2	15.62	55.45455	8.08
12.25	16.11	58.33333	20.05
12.25	16.11	58.38710	20.33
13	24.20	61.53846	41.29
14	38.21	61.90476	44.04

16	68.79	62.96296	52.39
17	81.33	66.66667	78.23
18	89.97	66.66667	78.23
18.1	90.66	72.05882	96.64

A direct relation can be found to exist between probability of failure and its respective parameter. Fig. 10 shows the relation between probability of failure and breakdown voltage for polymer based insulation paper. The relation between the two parameters can be mapped by a cubic function.

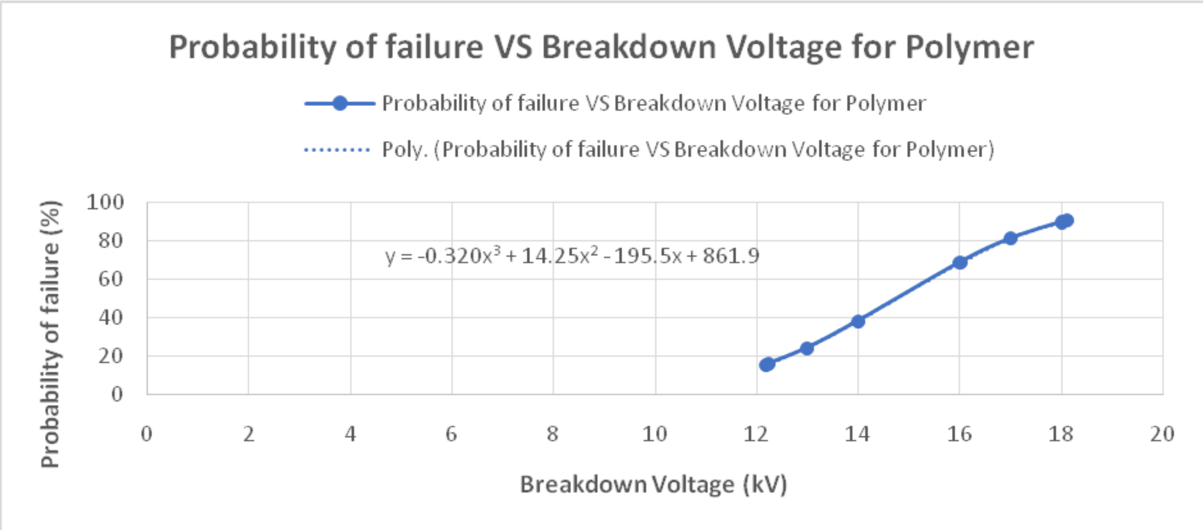

Fig. 10. Probability of failure VS Breakdown voltage for polymer based insulation paper

Fig. 11 shows the relation between probability of failure and dielectric strength for polymer based insulation paper. The relation between these two parameters can be mapped by a polynomial function of order 5. Table 6 shows the values of breakdown voltage (BDV), dielectric strength (DS) and their respective probability of failure for Wax based insulation paper.

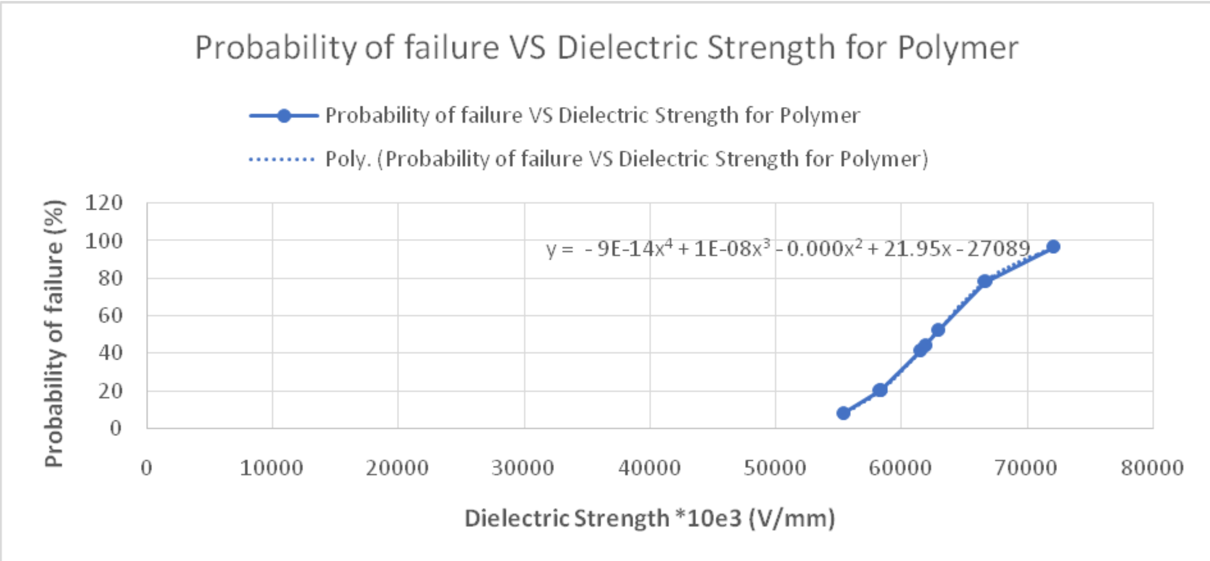

Fig. 11. Probability of failure VS Dielectric strength for polymer based insulation paper

Like the previous two samples, a direct relation exists between probability of failure & breakdown voltage and probability of failure & dielectric strength.

Table 6. Wax based insulation paper failure probabilities

BDV (kV)	PoF (%)	DS (V/mm)	PoF (%)
1.9	0.10	12.66667	9.01
2	62.93	13.33333	22.96
2	62.93	13.33333	22.96
2	62.93	14.28571	55.57
2	62.93	14.28571	55.57
2	62.93	14.28571	55.57
2	62.93	14.28571	55.57
2	62.93	14.28571	55.57
2	62.93	16.66667	98.78

Fig. 12 shows the relation between probability of failure and breakdown voltage for wax based insulation paper. The relation between the two parameters can be mapped by a linear function.

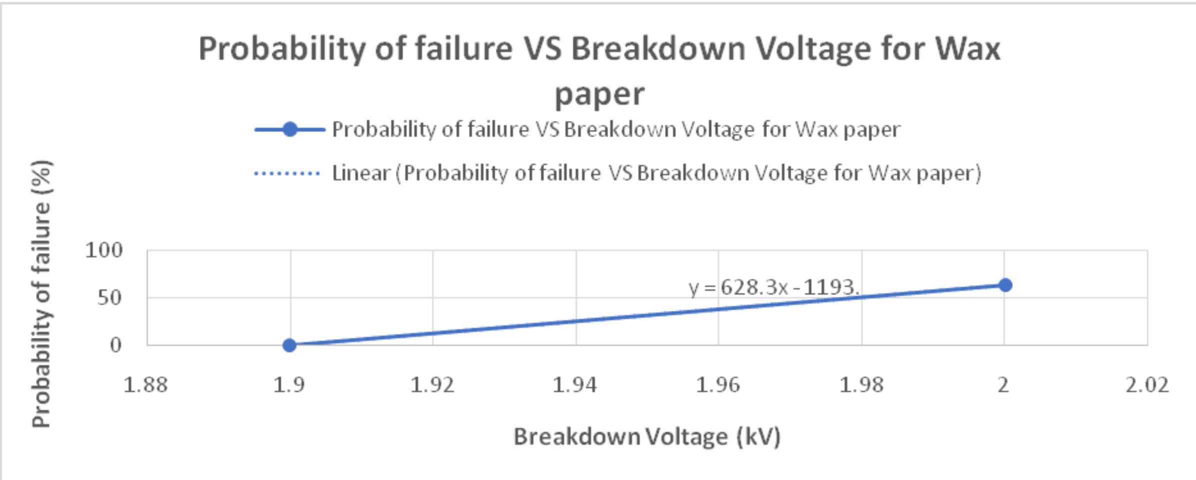

Fig. 12. Probability of failure VS Breakdown voltage for Wax based insulation paper

Fig. 13 shows the relation between probability of failure and dielectric strength for wax based insulation paper. The relation between the two parameters can be mapped by a quadratic function.

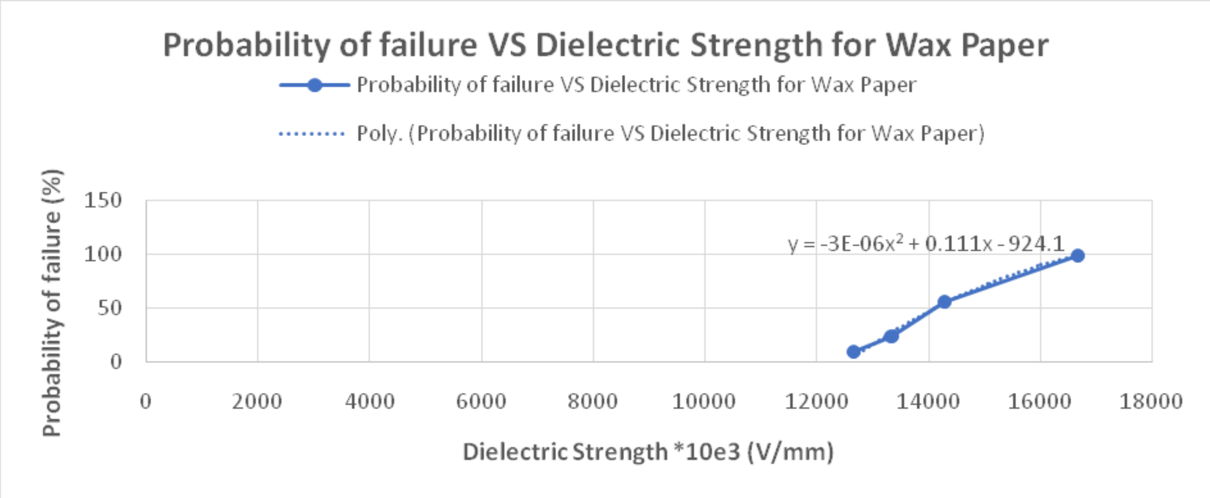

Fig. 13. Probability of failure VS Dielectric strength for Wax based insulation paper

5. CONCLUSION & FUTURE SCOPE

The tests on the breakdown strength of three insulation papers has been carried out successfully and the results have been presented in this paper. Through such findings, one can understand the differences in the three samples on the basis of breakdown voltage and dielectric strength under the effect of temperature and humidity. The probability distribution curve for each sample can be used to determine the suitability of using a particular sample in any high voltage system. Flexilam nomex 50N insulation paper has the highest breakdown voltage and should be used in high voltage based distribution systems. The polymer based TUK sample is of relatively poorer quality and has lower breakdown voltage value. It may be used in High voltage distribution systems but the paper will have a lower life compared to flexilam. The wax based insulation paper is ideal for use in low voltage based systems. Further research work in this field can be done by testing more samples and including the effects of oil degradation factors under combined thermal and electric stresses on the breakdown strength of insulation papers to ascertain their operational life.

6. ACKNOWLEDGEMENTS

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APPENDIX

Table 7 shows the values of sample thickness measured using screw gauge.

Table 7. Thickness of each sample (in mm)

S.No.	Flexilam Nomex 50N (mm)	Polymer Based (mm)	Wax paper based (mm)

1	0.35	0.21	0.12
2	0.33	0.22	0.15
3	0.34	0.21	0.14
4	0.34	0.27	0.15
5	0.335	0.27	0.14
6	0.34	0.21	0.14
7	0.34	0.17	0.14
8	0.34	0.26	0.14
9	0.34	0.31	0.15

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