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Breakdown Characteristics and Survival Probability of Turn-to-Turn Models for a HTS Transformer

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Abstract— **Breakdown characteristics and survival probability of turn-to-turn models were investigated under ac and impulse voltage at 77K. For experiments, two test electrode models were fabricated: One is point contact model and the other is surface contact model. Both are made of copper wrapped by 0.025mm thick polyimide film(Kapton). The experimental results were analyzed statistically using Weibull distribution in order to examine the wrapping number effects on voltage-time characteristics under ac voltage as well as under impulse voltage in LN_2. Also survival analysis were performed according to the Kaplan-Meier method. The breakdown voltages of surface contact model are lower than that of point contact model, because the contact area of surface contact model is wider than that of point contact model. Besides, the shape parameter of point contact model is a little bit larger than that of surface contact model. The time to breakdown t_{50} is decreased as the applied voltage is increased, and the lifetime indices slightly are increased as the number of layers is increased. According to the increasing applied voltage and decreasing wrapping number, the survival probability is increased.**

1. INTRODUCTION

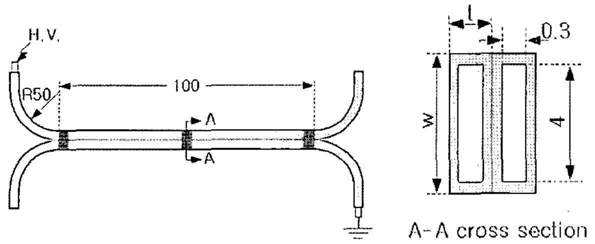
High temperature superconducting (HTS) transformers have been developing in many countries because of its lighter weight, smaller volume, and higher efficiency than those of the conventional transformer as well as the ability to overload without loss of insulation life, decreased environmental impact, and ease of sitting [1-2]. Recently, research for development and application of high temperature superconducting transformer has been motivated and supported with the Applied Superconductivity Technology of 21st Century Frontier R&D Program in Korea [3].

HTS transformer is consisted of various insulation factors such as turn-to-turn, layer-to-layer, section-to-section, coil-to-tank and so on. Many researchers have been investigated for the dielectric characteristics of the insulation factors that are driven under high voltage and cryogenic temperature conditions. However, although basis of winding insulation design is turn-to-turn insulation, useful data for practical insulation design have not been obtained enough. A voltage of turn-to-turn is very low in superconducting state, but it is very high in abnormal state. Thus, to achieve the most suitable insulation design for the HTS transformer operating cryogenic temperature, it is important to evaluate dielectric strength for insulation factors such as turn-to-turn as well as others insulation factors. Also, for designing electrical insulation of HTS power apparatus, it is very important to know the V-t characteristics and breakdown characteristics of insulation materials as well as the degradation after breakdown [4-6]. Moreover, V-t characteristic is one of the most important factors to establish the testing level and estimate the lifetime of electrical insulation materials in electrical power devices. Unfortunately, most of researches focus on construction design, benefits, and testing of HTS transformer [7-9] and breakdown mechanism in gaseous and liquid nitrogen [10-11], and lack of the researches on breakdown characteristics, V-t characteristics of solid insulations, which used as turn-to-turn and layer-to-layer insulation, in LN_2 as well as the degradation of these composite insulations after breakdown.

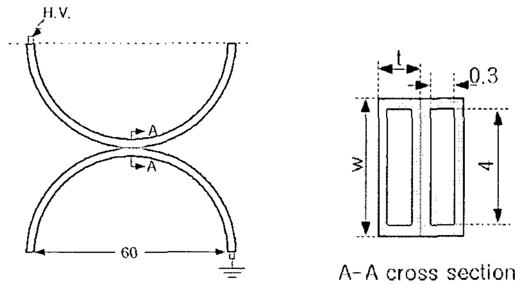
Therefore, we investigated breakdown characteristics and V-t characteristics of point and surface contact model under ac and impulse high voltage in liquid nitrogen (LN_2) for insulation design of turn-to-turn of HTS transformer immersed in LN_2. And we analyzed experimental data with Weibull distribution [12]. The breakdown voltage is dependent on the number of layer as well as voltage configuration. Moreover, we discussed lifetime indices n of number of layers and various applied voltages. And we investigated the survival probability of each turn-to-turn models. Survival analysis was performed according to the Kaplan-Meier method. Differences between the curves were confirmed or rejected by the long-rank test.

2. EXPERIMENTAL SET UP

Among many methods, two methods have been selected. One is surface contact method and the other is point contact method. Fig. 1 (a) and (b) show the turn-to-turn models. The turn-to-turn insulation models are

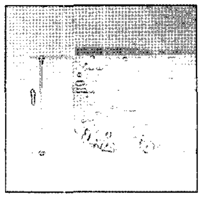


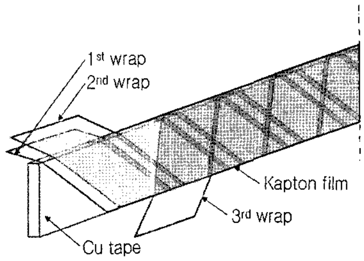
(a) Surface contact model



(b) Point contact model

Fig. 1. The models for turn-to-turn (all unit: mm).





(a) Cu tape (b) Schematic drawings of over lap method

Fig. 2. Schematic drawings of electrode and insulating method.

TABLE I
PARAMETERS OF VIRGIN AND INSULATED CU TAPE.

Electrode	Virgin Cu tape	Insulated Cu tape		
Parameter		1 layer	2 layers	3 layers
t (mm)	0.3	0.36	0.42	0.49
w (mm)	4	4.23	4.29	4.39

impregnated film insulation. In this experiment, the turn-to-turn insulation models were made by a square-section copper tape (0.3×4 mm) which is wrapped by Kapton tape (0.025 mm×10 mm). In order to study the relation between the insulation strength of liquid-film and the film thickness, wrapping number of the copper wire is 1, 2 and 3, respectively.

One end of each sample had the conductor insulation revolved to make the electrical connection to the test voltage or to ground. The copper was wrapped by the Kapton film for a 10 % over-wrapping method.

Fig. 2 (a) and (b) illustrate the copper tape and insulating method of it. A range of total insulation thickness was chosen in the turn-to-turn test to develop design information across the spectrum of thicknesses used in LN_2 -filled HTS transformers. The three turn-to-turn thicknesses used in this series were 0.36, 0.42 and 0.49 mm. The base material for the tests was Kapton.

The turn-to-turn model was set in a FRP cryostat of LN_2 in the innermost layer of the cryostat with a high voltage bushing. The outer layer is extracted by about 10^{-6} Torr to prevent the temperature ride of the LN_2. In this experiment, an ac power source (KYONAN ELECTRIC CO., LTD, MODEL: YPAS-01100, 0-100 kV) was used and impulse voltage tester system, which made of Dae Yang Electric CO., LTD (1.2×50 μs, 400 kV, 15 kJ). The high voltage lead connected to the one copper electrode and the other copper electrode was connected ground. The ac voltage was increased at a constant rate of 1 kV/sec until breakdown occurred. In case of impulse test, firstly a voltage which is estimated to be 70% of breakdown value was applied to a test object. The voltage was then increased in steps of 4 kV until a breakdown occurred. For both of ac and impulse test, the breakdown experiment was repeated 10 times for each sample to obtain an average value of breakdown voltage. In order to investigate V-t characteristics, we first measured the breakdown voltage and calculated 50% cumulative probability of breakdown voltage (BDV_{50}) from Weibull plot and then measured the time to breakdown with the applied voltage in the range of 100% to 60% of BDV_{50}.

3. RESULTS AND DISCUSSION

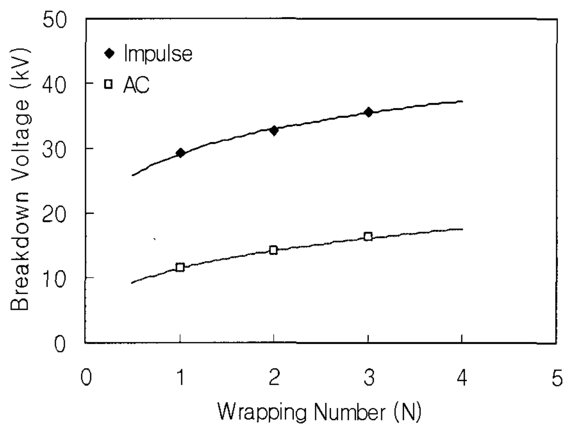
3.1. Breakdown Characteristics

Fig. 3 (a) and (b) present the results of the point and surface contact models ac and impulse tests. The average breakdown voltages are illustrated as points in the Fig. 3. The lines were obtained by averaging the data for each turn-to-turn wapping number and then applying those averages to a linear pregression equation to get an average failure line. As shown in Fig. 3, the breakdown voltage increases nonlinearly versus the wrapping number and the standard deviation of the breakdown voltage is nearly the same as the number of layer increases. Fig. 3 also shows that the breakdown voltages of the point contact model is higher than that of the surface contact model under impulse as well as ac. These results can be explained as follows. If the contact area in the model is increased, the number of weak spots also increases. Thus, in the surface contact model it is considered that the breakdown voltages are lower than these of the point contact model because the contact area of the surface contact model is larger than that of point contact model.

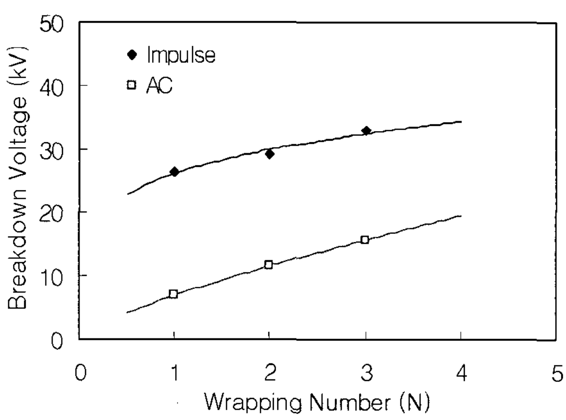
Fig. 4 (a) and (b) show the Weibull plot of the breakdown voltage under the ac and impulse ramp to failure in LN_2 for the point contact model. Fig. 5 (a) and (b) show Weibull plots of breakdown voltage under the ac and impulse ramp to failure in LN_2 for the surface contact model. It is obvious from Figs. 4 and 5 that the Weibull plots of ac and impulse breakdown voltage give straight lines. Thus, the Weibull distribution can be applied to the breakdown voltage for the turn-to-turn models in LN_2.

Table 2 lists the Weibull scale parameter *Vo* and the shape parameter *m* estimated from the slope of the Weibull plots for each model. As seen in Table I the scale parameter values increase for ac and impulse voltage in the point and surface contact models, when the wrapping number is increased from 1 layer to 3 layers.

The Weibull shape parameters *m* for point contact and surface contact models under ac voltage were estimated to be about 26-28 and 6-20, respectively. Also the Weibull shape parameters *m* for the point contact and surface contact model under Impulse voltage were estimated to be about 15~17 and 9-16, respectively. In general, the shape parameter of the point contact model is a little bit larger than that of the surface contact model.

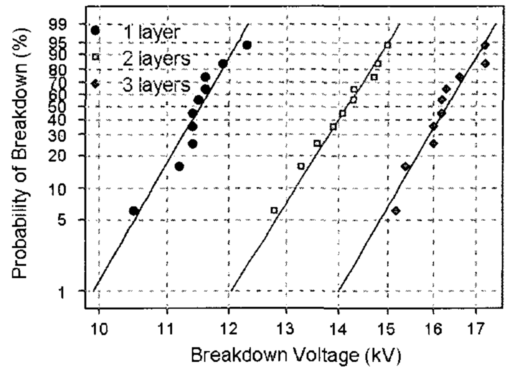


(a) Point contact model

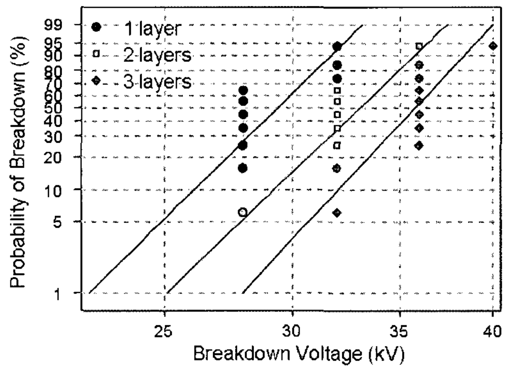


(b) Surface contact model

Fig. 3. AC and impulse breakdown strength of the two type models.

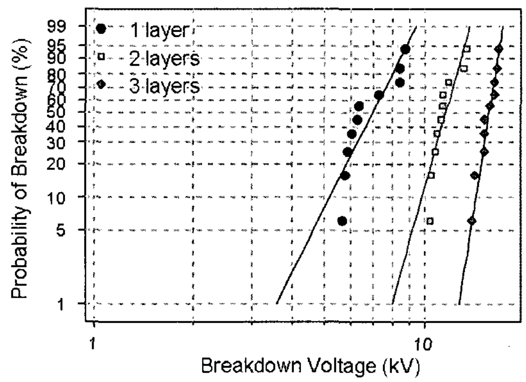


(a) Under AC

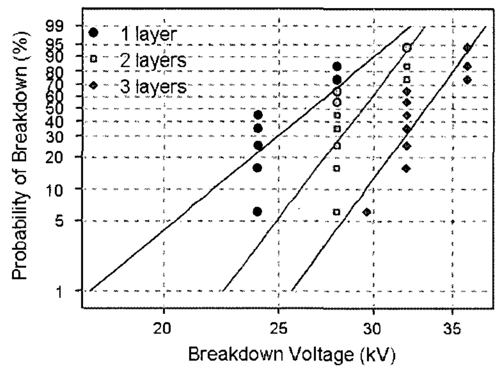


(b) Under Impulse

Fig. 4. Weibull plots of breakdown voltage for the point contact model.



(a) Under AC



(b) Under Impulse

Fig. 5. Weibull plots of breakdown voltage for the surface contact model.

TABLE II
WEIBULL STATICTICAL DATA FOR BREAKDOWN VOLTAGES OF TURN-TO-TURN MODELS.

Model	Voltage	Layer	Parameter	
			Shape (m)	Scale (V_0)
Point contact	AC	1	28.17	11.69
		2	26.06	14.38
		3	27.89	16.53
	Impulse	1	15.70	30.12
		2	15.29	33.91
		3	17.10	36.61
Surface contact	AC	1	6.27	7.4432
		2	11.26	12.08
		3	20.29	16.14
	Impulse	1	9.88	27.65
		2	15.70	30.12
		3	16.30	33.99

3.2. V-t Characteristics

Fig. 6 and Fig. 7 show V-t characteristics of the models for 2 and 3 layers under ac voltage. It is seen that the time to breakdown t_{50} (s) decreases as the applied voltage (kV) increases, and the lifetime indices slightly increase as the number of layers increase. Thus, the slope of the V-t characteristics is slightly dependent on applied voltage as well as the number of layers. In Fig. 6, life time index (n)=27.54 and n=30.58 were obtained in LN_2 on 2 and 3 layers, respectively. Also in Fig. 7, n=14.47 and n=27.10 were obtained in LN_2 on 2 and 3 layers, respectively. In the case of the point contact model, the n value is similar. However, in the case of the surface contact model, the n value is different.

As referred to above, this result is considered that an electrode effect of the breakdown voltage increased according to the increase of the contact area. The relation between the breakdown voltage of the point contact model and the time to breakdown t_{50} of the point contact model for 2 layers and 3 layers is shown by

$$BDV = 16.37t_{50}^{-1/30.58} \quad \text{(for 2 layers)} \qquad (1)$$

$$BDV = 15.34t_{50}^{-1/27.53} \quad \text{(for 3 layers)} \qquad (2)$$

Similarly, the breakdown voltage of the surface contact model can be expressed by

$$BDV = 16.59t_{50}^{-1/27.1} \quad \text{(for 2 layers)} \qquad (3)$$

$$BDV = 13.67t_{50}^{-1/14.47} \quad \text{(for 3 layers)} \qquad (4)$$

The overall survival estimates for the point contact and the surface contact model within the total observation are shown in Fig. 8 and Fig. 9, respectively. As the applied voltage is increased, the survival probability is decreased at all times.

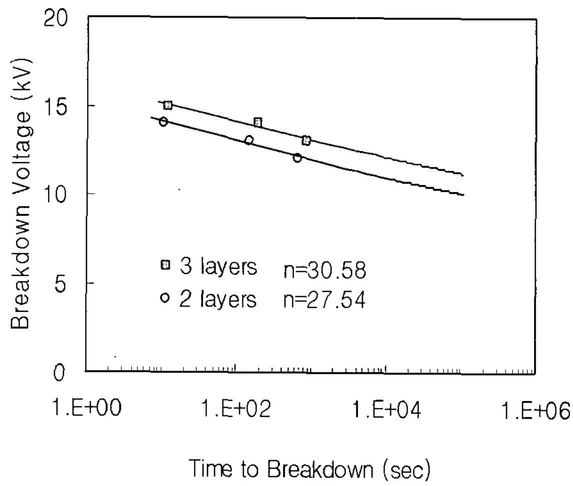


Fig. 6. Relationship of time to breakdown and breakdown voltage for the point contact model.

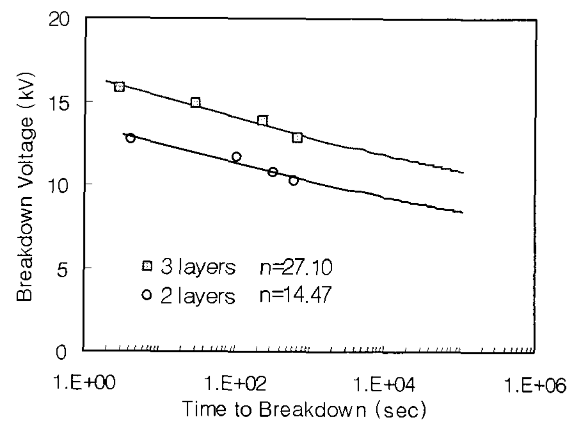
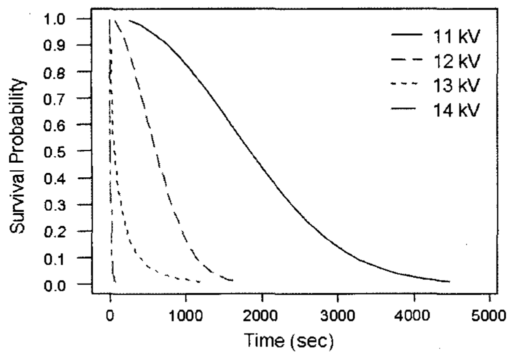


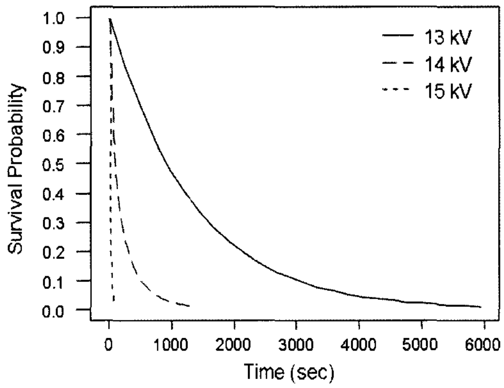
Fig. 7. Relationship of time to breakdown and breakdown voltage for the surface contact model.

As the wrapping number is increased, the survival probability is increased. For example, in Fig. 8 (a), the survival probability (84 %) under 11 kV at 1000sec is higher than the survival probability (17 %) under 12 kV at 1000sec. In Fig. 8 (a) and (b), the survival probability (2 %) for 2 layers under 13 kV is lower than the survival probability (48 %) for 3 layers under 13 kV at 1000 sec. Therefore, both electrical stress and wrapping number have a significant effect on the survival provability. It is also clear that the increasing electrical stress leads to the reduced breakdown initiation time.

Fig. 10 (a) shows erosion position. And Fig. 10 (b) and (c) show the pictures of 3 layer Kapton tape samples after breakdown for the 13 kV and 15 kV applied voltages. It can be seen that the erosion areas are rectangular shapes and axis-symmetric to the contact line, while the breakdown holes occur inside the erosion area near the contact line almost at the edge of the Kapton tape.

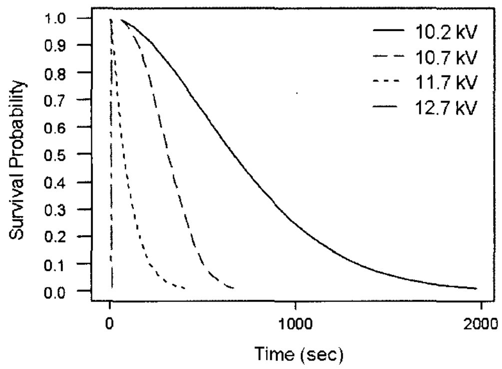


(a) 2 layers

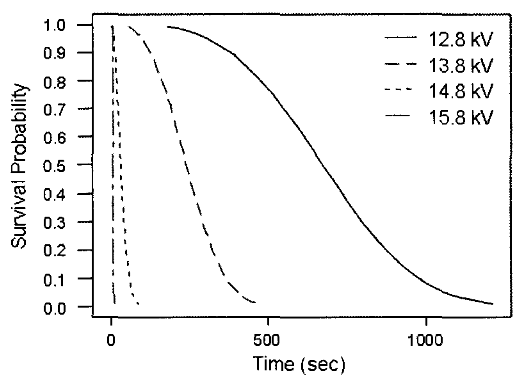


(b) 3 layers

Fig. 8. Overall survival estimates for the point contact model.

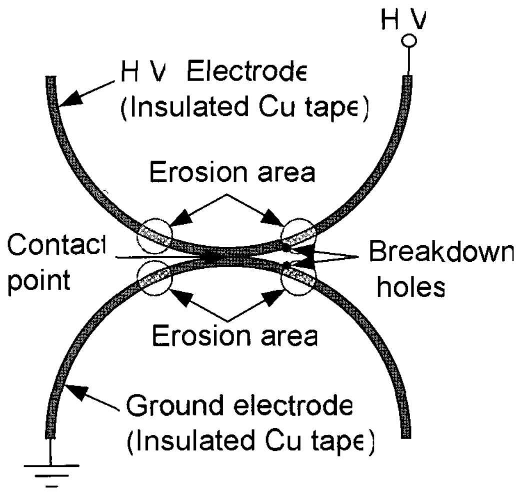


(a) 2 layers

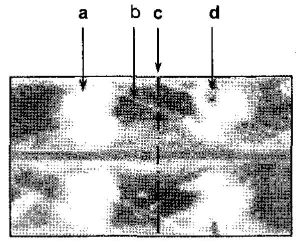


(b) 3 layers

Fig. 9. Overall survival estimates for the point contact model.



(a) Erosion position



(b) Erosion traces at13 kV

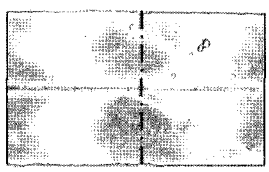
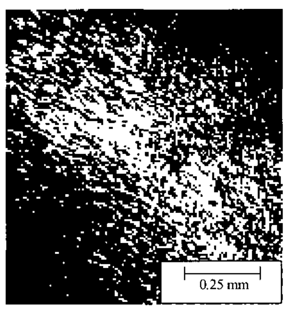

(c) Erosion traces at 15 kV

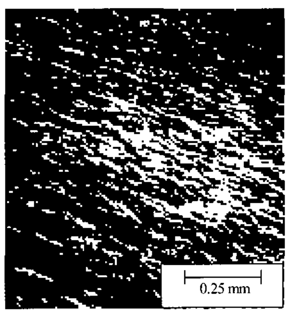
Fig. 10. Photographs of Kapton tape after breakdown;
a: erosion area, b: non-erosion area, c: contact line, d: breakdown hole.

The erosion areas were further observed using microscope. These photos are shown in Fig. 11. Numerous micro cracks develop on the surface of Kapton. In the case of the 15 kV applied voltage the micro cracks are longer and deeper compare to 13 kV applied voltage. However for 13 kV applied voltage, the micro cracks are denser than those of the 15 kV applied voltage.

This can be explained that when the applied voltage is higher, the electric stress is larger and the time to breakdown is smaller and vice versa. With the higher electric stress and smaller breakdown's time, the micro cracks will be deeper and longer but less dense.



(a) 13 kV



(b) 15 kV

Fig. 11. Microscope photographs of erosion area of Kapton tape.

4. CONCLUSION

In this paper the breakdown and V-t characteristics of two types of turn-to-turn models insulated by Kapton/LN2 were investigated. The main results are summarized as follow:

As the number of layer is increase, the breakdown voltage of the models increase proportionally, but the shape parameter m of Weibull plots for the breakdown voltage decreased. Lifetime indices n of the point and surface contact model decreased from 30.58 for the 3 layers to 27.58 for 2 layers and from 27.1 for 3 layers to 14.47 for 2 layers, respectively. Thus, the slope of the V-t characteristics increases slightly as the number of layers is increased.

The breakdown holes and erosion areas of the point contact model do not occur at the contact line or contact point, which has the maximum value of electric field. They occurred inside the erosion area or around the boundary between the erosion areas because of the partial discharge and the degradation of the erosion areas depends on the applied voltage. The survival probability is increased as the wrapping number is increases and/or applied voltage is decreased. The results are shown that the increasing electrical stress and decreasing number of layers leads to reduced breakdown initiation time. Therefore, both electrical stress and wrapping number have a significant effect on the survival probability.

ACKNOWLEDGMENT

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REFERENCES

[1] B.W McConnell, " Transformers - A successful Application of High Temperature Superconductors," IEEE Transactions on Applied Superconductivity, Vol. 10, No. 1, pp. 716-720, 2000.

[2] S.W.Schwenterly, et al, " Development of HTS power transformers for the 21st century: Waukesha Electric Systems/IGC-SuperPower/RG&E/ORNL SPI collaboration," Physica C 382, pp. 1-6, 2002.

[3] H.M Chang, et al, "Cryogenic cooling temperature of HTS transformers for compactness and efficiency," IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, pp. 2298-2301, June 2003.

[4] M. Kosaki, M. Nagao, N. Shimizu, and Y. Mizuno, "Solid Insulation and Its Deterioration," Cryogenics, vol.38, no.11, pp.1095-1104, 1998.

[5] T. Suzuki, K. Kishi, T. Uozumi, K. Yatsuka, N. Yashuda, T. Fukui, "Study on V-t Characteristics for XLPE Cable," Proceeding of the 1994 IEEE power Engineering Society, pp.192-199, April 1994.

[6] H. Okubo, M. Hikita, H. Goshima, H. Sakakibara, N. Hayakawa, "High Voltage Insulation Performance of Cryogenic Liquids for Superconducting Power Apparatus," IEEE Transactions on Power Delivery, vol.11, no.3, pp.1400-1406, July 1996.

[7] C. T. Reis, S. P. Mehta, B. W. Mc Connell, R. H. Tones, "Development of High Temperature Superconducting Power Transformers," IEEE power engineering society winter meeting, vol.1, pp.151-156, 2002.

[8] T.L. Baldwin, J.I. Ykema, C.L. Allen, J.L. Langston, "Design Optimization of High Temperature Superconducting Power Transformers," IEEE Transactions on Applied Superconductivity, vol.13, no.2, pp.2344-2347, 2003.

[9] H. J. Lee, G .S. Cha, J. K. Lee, K. D. Choi, K. W. Ryu, S. Y. Hahn, "Test and characteristic analysis of an HTS power transformer," IEEE Transactions on Applied Superconductivity, vol.11, no.1, pp.1486-1489, 2001.

[10] S. M. Baek, J. M. Joung, J. H. Lee, S. H. Kim, "Electrical Breakdown Properties of Liquid Nitrogen for Electrical Insulation Design of Pancake Coil Type HTS Transformer," IEEE Transactions on Applied Superconductivity, vol.13, no.2, pp.2317-2320, 2003.

[11] J. M. Joung, S. M. Baek, C. S. Kim, S. H. Kim, "Electrical Insulation Characteristics in The Simulate Electrode System of HTS Double Pancake Coil," IEEE Transactions on Applied Superconductivity, vol.13, no.2, pp.2321-2324, 2003.

[12] H. Goshima, N. Hayakawa, M. Hikita, H. Okubo, "Weibull Statistical Analysis of Area and Volume Effects on The Breakdown Strength in Liquid Nitrogen," IEEE Transactions on Dielectrics and Electrical Insulation, vol.2, no.3, pp.385-393, June 1995.