고온초전도 변압기를 위한 턴간 모델의 V-t 특성 및 생존 확률

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V-t Characteristics and Survival Probability of Turn-to-Turn Models for HTS Transformer

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Abstract

Using multi wrapped copper by polyimide film for HTS transformer, the breakdown and V-t characteristics of two type models for turn-to-turn, one is point contact model, the other is surface contact model, were investigated under ac and impulse voltage at 77 K. A material that is Polyimide film (Kapton) 0.025 mm thickness is used for multi wrapping of the electrode. Statistical analysis of the results using Weibull distribution to examine the wrapping number effects on V-t characteristics under ac voltage as well as breakdown voltage under ac and impulse voltage in LN_2 was carried. Also, survival analysis was performed according to the Kaplan-Meier method. The breakdown voltages for surface contact model are lower than that of the point contact model, because the contact area of surface contact model is wider than that of point contact model. At the same time, the shape parameter of the point contact model is a little bit larger than the of the 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.

Key Words : V-t Characteristics; Survival Probability; Turn-to-Turn Models; HTS transformer

1. Introduction

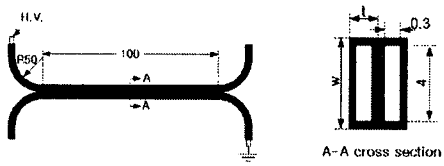
High temperature superconducting (HTS) transformers have been developing in many countries because of its lighter weight, smaller volume, and higher efficiency than those of the conventional transformer as well as the ability to overload without loss of insulation life, decreased environmental impact, 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 normal 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 LN2 as well as the degradation of these composite insulations after breakdown.

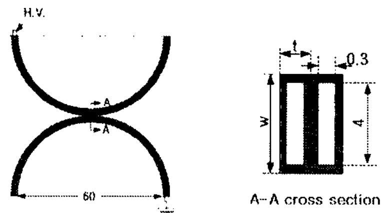
Therefore, we investigated breakdown characteristics and V-t characteristics of point and surface contact model under ac and impulse high voltage in liquid nitrogen (LN2) for insulation design of turn-to-turn of HTS transformer immersed LN2. And we analyzed experiment data with Weibull distribution [12]. 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 different 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 Setup and Procedure

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

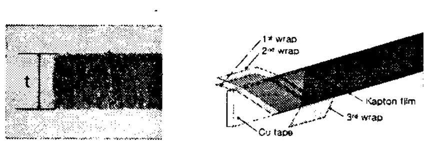


(a) Surface contact model



(b) Point contact model

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



(a) Cu tape (b) Overlap method

Fig. 2. Schematic drawings of the Cu tape and a overlap method.

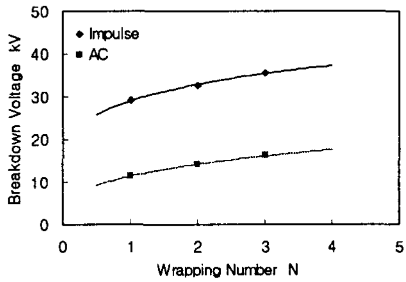
One end of each sample had the conductor insulation revolved to make the electrical connection to the test voltage or to ground. The copper was wrapped by the Kapton film for a 10 % over-wrapping method.

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 LN2-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.

Table 1. Parameters of virgin and insulated Cu tape.

Electrode	Virgin	Insulated Cu tape		
Parameter	Cu tape	1 layer	2 layers	3 layers
t (mm)	0.3	0.36	0.42	0.49
W (mm)	4	4.23	4.29	0.439

The turn-to-turn model was set in a FRP cryostat of LN2 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 LN2. 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 ㎲, 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 (BDV50) from Weibull plot and then measured the time to breakdown with the applied voltage in the range of 100% to 60% of BDV_{50}.



(a) Point contact model

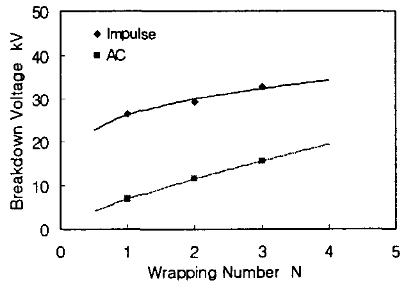


Fig. 3. AC and impulse breakdown strength of the two type models.

3. Result and Discuss

2.1 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 a point 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 progression equation to get an average failure line. As shown in the Fig. 3, the breakdown voltage increases non-linearly versus the wrapping number and the standard deviation of breakdown voltage is nearly the same value as the number of layer increases. And Fig. 3 shown that the breakdown voltages of the point contact model is higher than that of the surface contact model under impulse as well as ac. This results are explained as following. If a contacting area in models is increasing, a number of weak spots is increasing. Thus, the surface contact model is considered that the breakdown voltages are lowwer than that of the point contact model because the contacting area of surface contact model is wider than that of point contact model.

Table 2. Weibull statictical data for breakdown voltages of turn-to-turn models.

Model	Voltage	Layer	Parameter	
			Sphere (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	30.91
		3	17.10	36.61
Surface contact	AC	1	6.27	7.44
		2	11.26	12.08
		3	20.29	16.14
	Impulse	1	9.88	27.65
		2	15.7	30.12
		3	16.30	33.99

Table 2 lists Weibull scale parameter V_0 and shape parameter m estimated from the slope of Weibull plots for each model. As seen in Table 2 the scale parameter values increase for ac and impulse voltage under point and surface contact model, when the wrapping number is increased from 1 layer to 3 layers.

Weibull shape parameters m for point contact and surface contact model under ac voltage were estimated to be about 26-28 and 6-20, respectively. And Weibull shape parameters m for point contact and surface contact model under Impulse voltage were estimated to be about 15-17 and 9-16, respectively. At the same time, the shape parameter of the point contact model is a little bit larger than that of the surface contact model.

2.2 V-t Characteristics

Fig. 6 and Fig. 7 show V-t characteristics of the models for 2 and 3 layers under AC voltage.

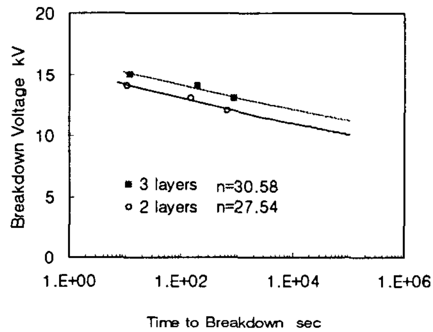


Fig. 6. Relationship time to breakdown and breakdown voltage for the point contact model.

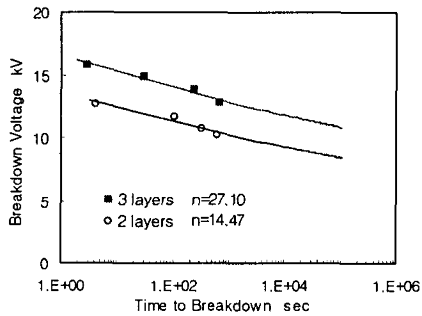


Fig. 7. Relationship time to breakdown and breakdown voltage for the surface contact model.

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 V-t characteristics is slightly dependent on applied voltage as well as the number of layers. In Fig. 6, n=27.54 and n=30.58 were obtained in

LN2 on 2 and 3 layers, respectively. And in Fig. 7, n=14.47 and n=27.10 were obtained in LN2 on 2 and 3 layers, respectively. In case of point contact model, n value is similar. However, in case of surface contact model, n value is different. As referred above, this result is considered that an electrode effect of breakdown voltage increased according to increase of contact area. The relation between breakdown voltage of point contact model and time to breakdown t50 of point contact model for 2 layers and 3 layers is shown by

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

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

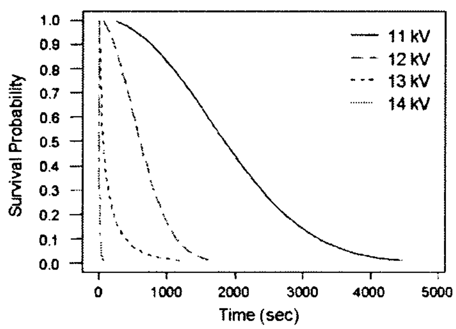
Similarly, the breakdown voltage of contact model can be expressed by

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

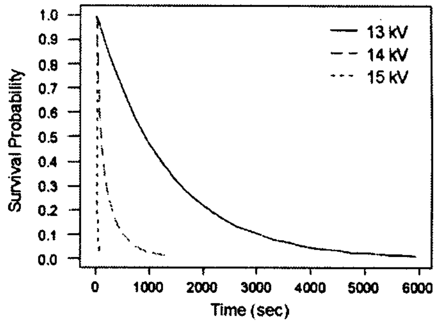
$$BDV = 13.67\, t_{50}^{-1/14.47} \text{ (for 3 } \textit{lalayers}) \quad (4)$$

The overall survival estimates for point contact and 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.

And as the wrapping number is increased, the survival probability is increased.

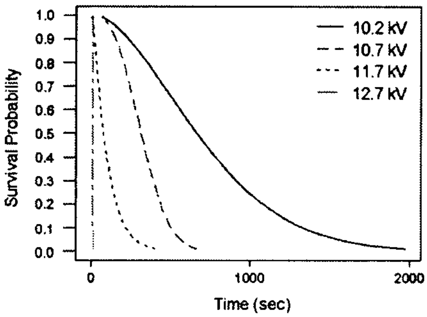


(a) 2 layers

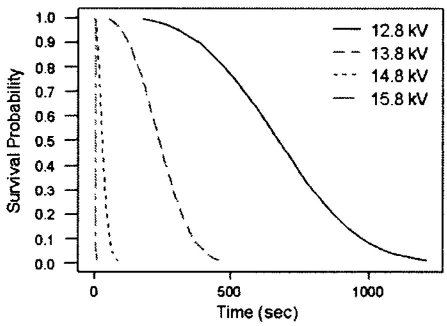


(b) 3 layers

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



(a) 2 layers



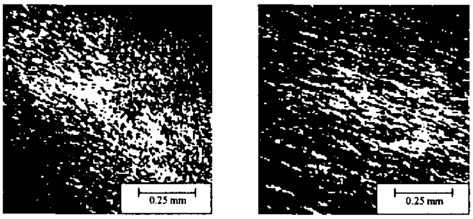
(b) 3 layers

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

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 %) on 2 layers under 13 kV is lower than the survival probability (48 %) on 3 layers under 13 kV at 1000sec. Therefore, both electrical stress and wrapping number have significant effect on the survival provability. It is also clear that the increasing electrical stress leads to the reducing breakdown initiation time.

The erosion areas were further observed using microscope. The photos are shown in Fig. 10. It displays that a numerous micro cracks develop on the surface of Kapton. On the case of the 15 kV applied voltage the micro cracks are longer and deeper compare to 13 kV applied voltage. However in 13 kV applied voltage, the micro cracks are denser than those of the 15 kV applied voltage.



(a) 13 kV (b) 15 kV

Fig. 10. Microscope photographs of erosion area of Kapton tape.

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

4. Conclusion

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

As the number of layer is increased, the breakdown voltage of the models is increased proportionally and the shape parameter *m* of Weibull plots for the breakdown voltage is decreased. Lifetime indices *n* of point and surface contact model are decreased from 30.58 for 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 V-t characteristics increases slightly as the number of layer becomes increase.

The survival probability is increased as the wrapping number is increased and/or applied voltage is decreased. The results are shown that the increasing electrical stress and decreasing number of layer lead to the reducing breakdown initiation time. Therefore, both electrical stress and wrapping number have significant effect on the survival provability.

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