고온초전도 변압기를 위한 액체질소 중 절연 파괴, V-t, 열화 특성

論 文
53C-6-5

Breakdown, V-t and Degradation Characteristics of Insulation in Liquid Nitrogen for HTS Transformer

류엔반둥[*] · 鄭 鍾 萬[**] · 白 承 明[***] · 李 昶 和[*] · 宋 僖 錫[§] · 金 相 賢[§§]
(Van Dung Nguyen · Jong-Man Joung · Seung-Myeong Baek · Chang-Hwa Lee · Song-Hee Suck · Sang-Hyun Kim)

Abstract – HTS transformer is one of the most promising devices to supply enough electric energy for quick increase consumption. However, for practical design of the HTS transformer, it is necessary to establish the research on breakdown, V-t characteristics, degradation, and so on. In this paper, we discussed breakdown characteristics and V-t characteristics of polyimide/LN_2 and glass fiber reinforced plastic/LN_2 composite insulations. These composite insulations have been used as turn-to-turn and layer-to-layer insulations for HTS transformer respectively. Moreover, we investigated the degradation of these insulation samples after breakdown using microscope and SEM photograph.

Key Words : HTS transformer, Breakdown, V-t characteristics, Composite insulations, Degradation

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 RD Program in Korea. 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 [3-5]. 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 [6-8] and breakdown mechanism in gaseous and liquid nitrogen [9-10], 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.

In this paper, we investigated breakdown characteristics and V-t characteristics of Kapton/LN_2 and GFRP/LN_2 composite insulations under ambient pressure and degradation of these insulation samples after breakdown. We also analyzed experiment data with Weibull distribution [11]. The breakdown voltage (V_B) is dependent on number of Kapton tape and the thickness of GFRP while the time to breakdown was conditioned on applied voltage. Moreover, we discussed lifetime indices n of different layers of Kapton tape and different applied voltages as well as different thickness of GFRP.

2. Experimental Apparatus and Procedures

Figure 1 shows the cryostat and experimental set-up. The experiment apparatus consists of a cryostat, a high voltage power supply, an electrode system and some auxiliary devices. The cryostat was made of two dewar flasks; inner one is for testing and outer one is filled with atmospheric liquid nitrogen (1 atm, 77K) to prevent the temperature rise of the liquid nitrogen in the inner dewar flask. Electrode system was set in the inner dewar flask with a high voltage bushing. The dewars were painted

[*] 正 會 員 : 慶尙大 電氣電子工學部 碩士科程
[**] 正 會 員 : 韓國電力公社 電力硏究員 配電技術그룹 硏究員
[***] 正 會 員 : 慶尙大 電氣電子工學部 博士科程
[§] 正 會 員 : 曉星重工業 硏究所 首席硏究員
[§§] 正 會 員 : 慶尙大 電氣電子工學部 敎授 · 工學阮 硏究員
接受日子 : 2004年 1月 20日
最終完了 : 2004年 5月 14日

with silver for blocking up radiant heat. The power supply, made of Kyonan Electric CO., LTD, is AC 100 kV, 1 kVA capacity.

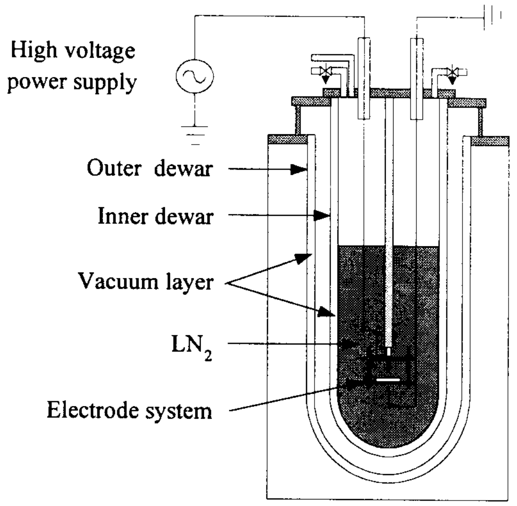
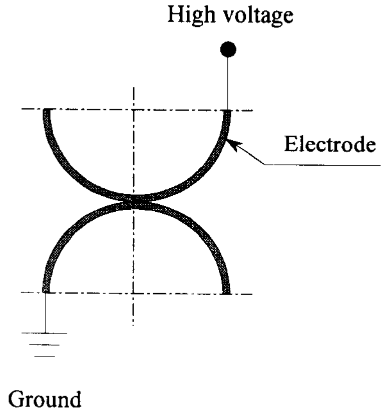
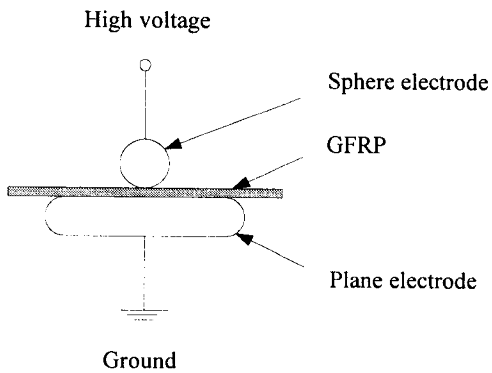


Fig. 1 Cryostat and experimental set-up



(a) Turn-to-turn insulation



(b) Layer-to-layer insulation

Fig. 2 Electrode system

Figure 2-a shows the electrode system for testing turn-to-turn insulation. The Cu electrodes are circular in shape with 65 mm diameter and 0.3 mm 4 mm cross-section. The Kapton tape, having 2.8% of moisture absorption, with dimensions of 0.025 mm 10 mm cross-section was wound and overlapped around the Cu electrodes with 1, 2, 3, and 4 layers.

Figure 2-b shows the electrode system for testing layer-to-layer insulation. The GFRP sample having a dimension of 80 mm 80 mm and has a 0.09% moisture content was laid between sphere and plane electrodes. The thickness of GFRP samples was varied from 0.3 mm to 2.5mm (0.3 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm and 2.5 mm). All the electrodes are made from stainless steel with a diameter of 7 mm and 60 mm for sphere and plane electrode respectively.

For measuring breakdown voltage, the 60 Hz ac high voltage was applied to the electrodes and increased with the rate of 1 kVrms/s until it breakdown, ten samples of insulation materials were used in this experiment. In order to investigate V-t characteristics, we first measured the breakdown voltage and calculated 50% cumulative probability of breakdown voltage (V_{B50}) from Weibull plot and then measured the time to breakdown with the applied voltage in the range of 100% to 60% of V_{B50}.

3. Experimental Results and Discussion

3.1 Breakdown Characteristics

Figure 3 shows the ac average V_B in LN_2 as a function of Kapton's layer number (N). As shown in the figure, the V_B increases nonlinearly versus the number of layer N and the standard deviation of V_B is nearly the same value as the number of layer increases. The relation between V_B and N is expressed by

$$V_B = 11.2N^{0.36} \quad (1)$$

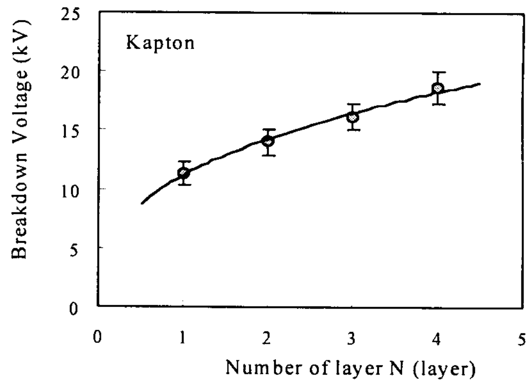


Fig. 3 Ac breakdown characteristics of Kapton/LN_2 composite insulation

Figure 4 shows Weibull plots of V_B in LN_2 with 1 layer, 2 layers, 3 layers, and 4 layers of Kapton tape. Table 1 lists the Weibull scale parameter Vo and shape parameter mestimated from the slope of Weibull plots. It is seen from this table that the scale parameter Vo increases from 11.3 kV to 19 kV when the number of layer increase from 1 layer to 4 layers, and the shape parameter m decreases from 32.5 to 26.4. It means that when the number of layer is larger, the scattering of breakdown voltage is broader.

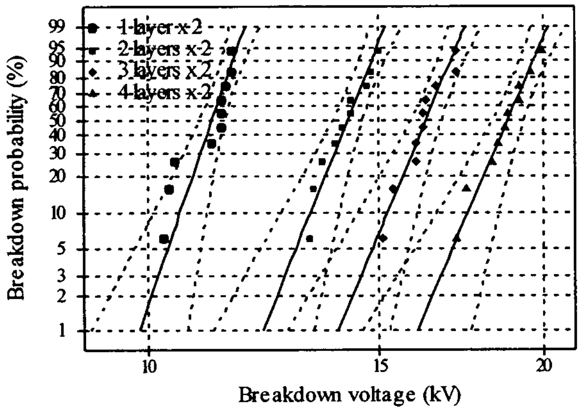


Fig. 4 Weibull plots of breakdown voltage of Kapton tape in LN_2

Table 1 Parameters of Weibull plots for breakdown voltage of Kapton tapes

1	32.5	11.3
2	28.5	14.4
3	27.5	16.5
4	26.4	19

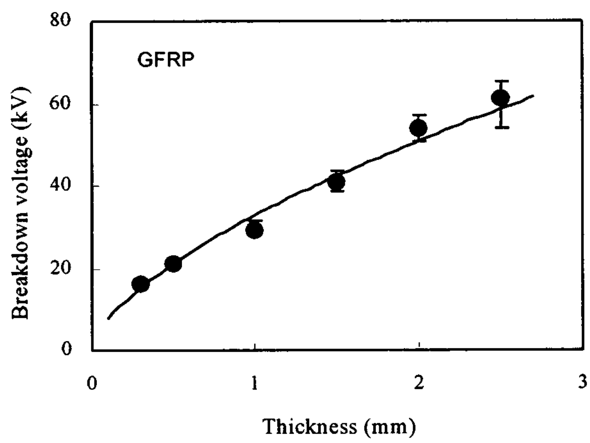


Fig. 5 Ac breakdown characteristics of GFRP/LN_2 composite insulation

Similarly, figure 5 shows the ac average V_B in LN_2 as a function of thickness of GFRP (t). It shows that the V_B increases nonlinearly with increasing the thickness t and the standard deviation of V_B also increases as the thickness increases. The relation between V_B and tis expressed by

$$V_B = 32.8t^{0.6} \qquad (2)$$

The Weibull plots of breakdown strength of GFRP with 0.3 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm, and 2.5 mm thickness are indicated in figure 6 and the parameters of these plots are listed in table 2. From the table, the scale parameter (Eo) decreases from 53 kV/mm to 24.8 kV/mm as the thickness increases from 0.3 mm to 2.5 mm. This means that the dielectric strength of GFRP decreases when the thickness is to be higher. The shape parameter (m) also reduces from 42.7 to 27.2 as the thickness increases from 0.3 mm to 2.5 mm. It is obvious that the dispersion of breakdown voltage becomes larger as the thickness gets higher value. Due to increasing thickness, it leads to increase the non-uniform degree of material components in the bulk.

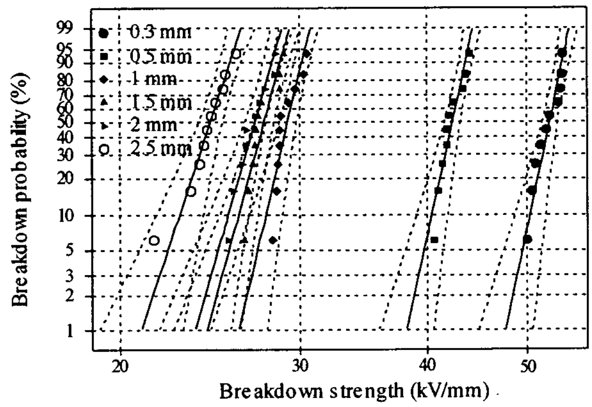


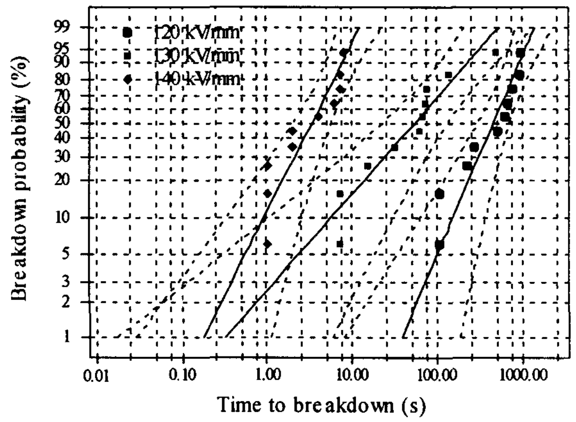
Fig. 6 Weibull plots of breakdown strength of GFRP

Table 2 Parameters of Weibull plots for breakdown strength of GFRP

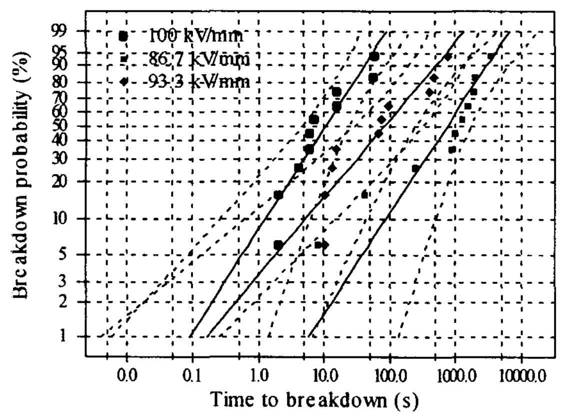
0.3 mm	42.7	53
0.5 mm	40.9	42.7
1 mm	37.9	29.5
1.5 mm	32.7	28
2 mm	31	27.5
2.5 mm	27.2	24.8

3.2 V-t Characteristics

Figure 7 (a) and (b) show Weibull plots of time to breakdown in LN_2 for 2 layers and 3 layers respectively. Table 3 lists the Weibull scale parameter to, shape parameters m and 50% probability breakdown time (t50) for 2 layers and 3 layers of Kapton tape. The results indicate that the shape parameter m is very small leading to a very large scattering of time to breakdown. Moreover, the value of m is fluctuating hence the time to breakdown is slightly dependent on the applied electric stress and number of layers.



(a) 2 layers



(b) 3 layers

Fig. 7 Weibull plots of time to breakdown of Kapton tapes

V-t characteristics of Kapton tape for 2 layers and 3 layers are shown in figure 8 based on the data of table 3. It is seen that the time to breakdown t50 (s) decreases as the applied electric stress E (kV/mm) increases, and the lifetime indices nslightly decreases as the number of layer increases. Thus, the slope of V-t characteristics is slightly dependent on the number of layer. The relation between electric stress E and time to breakdown t50 for 2 layers and 3 layers of Kapton tape is shown by

$$E = 121.6 t_{50}^{-1/32.3} \quad \text{(for 2 layers)} \qquad (3)$$

$$E = 90 t_{50}^{-1/30.6} \quad \text{(for 3 layers)} \qquad (4)$$

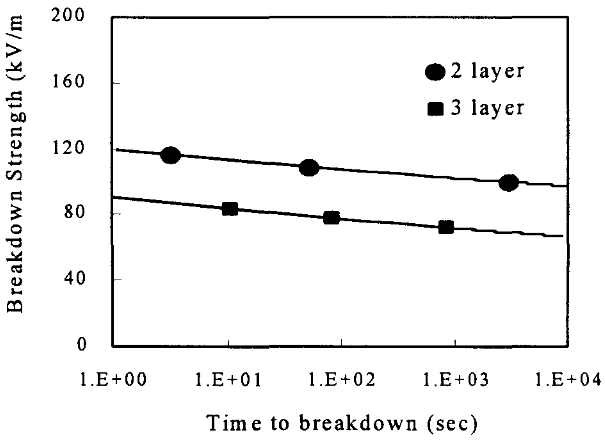


Fig. 8 V-t characteristics of Kapton tapes

Table 3 Parameters of Weibull plots for time to breakdown of Kapton tape

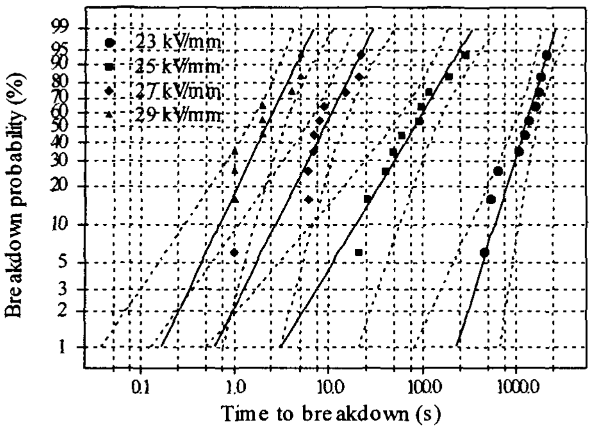
No. of layer	2 layers			3 layers		
Applied electric stress (kV/mm)	120	130	140	86.7	93.3	100
m	1.7	0.8	1.4	0.9	0.67	0.88
t_o(s)	565	84	4.3	1244	144.7	15.8
t_{50}(s)	455	54	3.3	839	84	10.5

The Weibull plots of time to breakdown for 1 mm and 2 mm thickness GFRP are shown in figure 9. Table 4 lists the Weibull scale parameter to, shape parameter m and 50% probability breakdown time (t50) for 1 mm and 2 mm thickness of GFRP. The results show the shape parameter m is small so the dispersion of time to breakdown of GFRP is large. Moreover, parameter m has not much different, therefore the time to breakdown is slightly dependent on the applied electric stress and thickness.

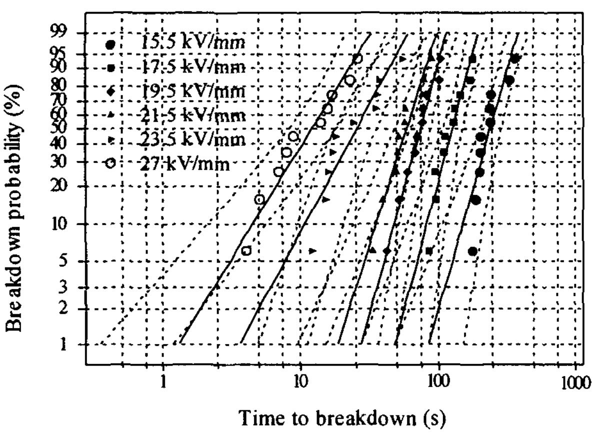
The V-t characteristics of GFRP are shown in figure 10, which was based on the data of table 4. The expression of E (kV/mm) as a function of time to breakdown t50(s) for 1 mm and 2 mm thickness are given as follows:

$$E = 29.4 t_{50}^{-1/28.8} \quad \text{(for 1 mm thickness)} \qquad (5)$$

$$E = 44 t_{50}^{-1/53} \quad \text{(for 2 mm thickness)} \qquad (6)$$



(a) 1 mm thickness



(b) 2 mm thickness

Fig. 9 Weibull plots of time to breakdown of GFRP

Table 4 Parameters of Weibull plots for time to breakdown of GFRP

Thickness (mm)	Applied electric stress (kV/mm)	m	t_0 (s)	t_{50} (s)
1	23	2.5	1452	1254
	25	1.3	106.3	80.4
	27	1.6	11.4	9.0
	29	1.65	2.7	2.2
2	15.5	4	265.8	242.8
	17.5	4.4	138.6	127.5
	19.5	4.3	81	74.4
	21.5	3.7	65	58.8
	23.5	2.2	30	25.5
	27	1.9	14.6	12

Figure 10 shows that the lifetime indices nof V-t characteristics were 28.8 and 5.3 for 1 mm and 2 mm thickness, respectively. It means that the lifetime indices ndecreases quickly as the thickness increases. Thus, the slope ofV-t characteristics rises rapidly when the thickness increases. This is due to the fact increasing the thickness will develop non-uniform degree of material components in the bulk, and increase the number of impurities and voids.

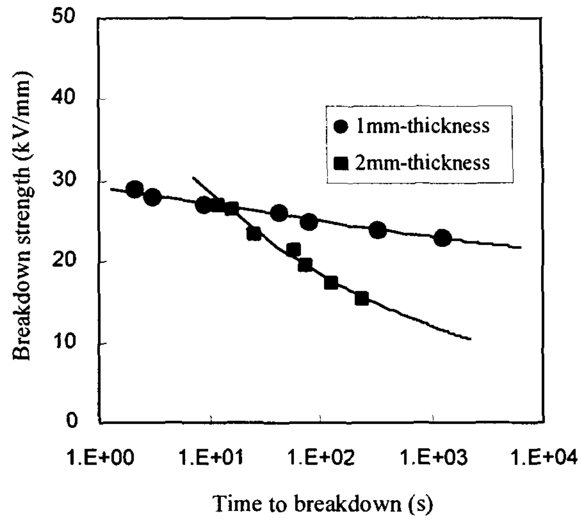
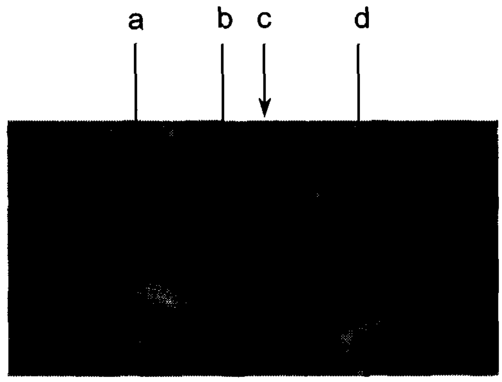


Fig. 10 V-t characteristics of GFRP

3.3 Degradation

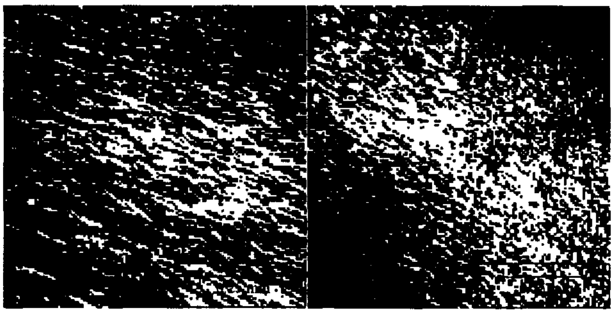


(a) 13 kV

(b) 15 kV

Fig. 11 Photographs of Kapton tape after breakdown; a : erosion area, b : non-erosion area, c : contact line, d : breakdown hole

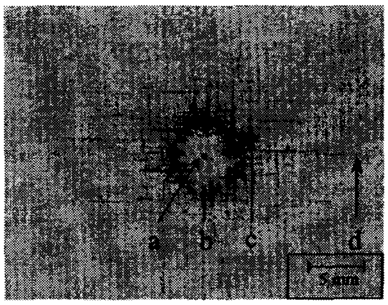
Figure 11 (a) and (b) show the pictures of 3 layers Kapton tape samples after breakdown for 13 kV and 15 kV-applied voltages. It can be seen that erosion areas are rectangular shapes and axis-symmetric to the contact line. While the breakdown holes occur inside the erosion area near the contact line and it is almost at edge of Kapton tape. The erosion areas were further observed using microscope. The photos are shown in figure 12. It displays that a numerous micro cracks develop on the surface of Kapton. On the case of 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 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 or vice versa. With the higher electric stress and smaller breakdown's time, the micro cracks will be deeper and longer but less dense.



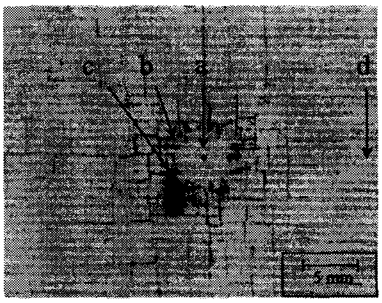
(a) 13 kV (b) 15 kV

Fig. 12 Microscope photographs of erosion area of Kapton tape

Figure 13 shows the pictures of 2 mm thickness GFRP sample after breakdown for 31 kV and 43 kV- applied voltages. The erosion area has circular shape with cracks along the interface between the glass fiber and epoxy on the surface of GFRP sample while the breakdown hole is near the boundary of non-erosion and erosion area, which is far from the contact point (CTP) between sphere electrode and GFRP sample. Moreover, the GFRP has no damage around the CTP. The reason is that, the occurrence of partial discharge (PD) around the CTP at the small radius protrusions on the surface of sphere electrode. It will lead to the bombardment of energetic electron to insulation and erode the insulation. Discharges in LN_2 at the interfaces between glass fiber and epoxy can initiate creeping and puncture. The SEM photographs of eroded area are shown in figure 14. Many deep pits on the surface of GFRP can be seen in the figure. The pits are deeper and larger for 43 kV-applied voltage in comparison to the 31 kV-applied voltage.



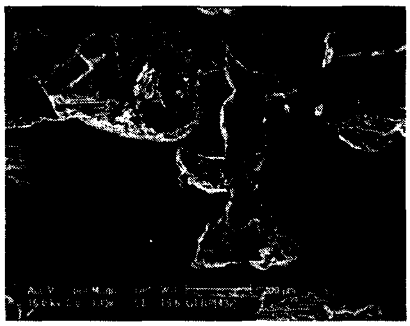
(a) 31 kV



(b) 43 kV

Fig. 13 Pictures of GFRP sample after breakdown; a : contact point, b : erosion area, c : breakdown hole, d : non-erosion area

(a) 31 kV



(b) 43 kV

Fig. 14 SEM photographs of erosion area of GFRP

4. Conclusions

In this paper, we investigated the breakdown and V-t characteristics of Kapton/LN_2 and GFRP/ LN_2as well as the destruction of insulation samples after breakdown. The main results are summarized as follow:

The breakdown voltage of Kapton tape increases nonlinearly when the number of Kapton layer increases but the shape parameter m of Weibull plots for breakdown voltage decreases. The scattering of breakdown voltage is proportional with the layer's number. Lifetime indices nof Kapton tape decreases from 32.3 for 2 layers to 30.6 for 3 layers. Thus, the slope of V-t characteristics increases slightly as the number of layer become bigger.

The breakdown voltage of GFRP increases nonlinearly as the thickness increases, while its breakdown strength decreases rapidly and the shape parameter mof Weibull plots for breakdown strength also decreases quickly. Lifetime indices n of GFRP decreases quickly from 28.8 for 1 mm thickness to 5.3 for 2 mm thickness, so the slope of V-t characteristics increases rapidly as the thickness increases.

The breakdown holes and erosion areas of Kapton tape and GFRP sheet do not occur at the contact line or contact point, which have the maximum value of electric field. It occurred inside the erosion area (for Kapton case) or around the boundary between erosion and non-erosion area (for GFRP case) because of the partial discharge and the degradation degree of erosion areas depends on the applied voltage.

Acknowledgements

This research was supported by a grant from the Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

References

[1] J.K. Sykulski, C. Beduz, R. L. Stoll, M. R. Harris, K. F. Goddard, Y. Yang, "Prospects for Large High-temperature Superconducting Power Transformers: Conclusions from a Design Study", Proceeding of IEEE on Electrical Power Application, vol.146, no.1, pp.41-52, January 1999.

[2] B.W. McConnell, S. P. Mehta, M. S. Walker, "HTS transformers", IEEE power Engineering Review, vol.20, no.6, pp.7-11, June 2000.

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

[4] 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.

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

[6] 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.

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

[8] 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 Transacsion on Applied Superconductivity, vol.11, no.1, pp.1486-1489, 2001.

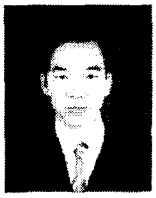
[9] S. M. Baek, J. M. Joung, J. H. Lee, S. H. Kim, "Electrical Breakdown Properties of Liquid Nitrogen for Electrical Insulation Design of Pancake Coil Type HTS Transformer", IEEE Transaction on Applied Superconductivity, vol.13, no.2, pp.2317-2320, 2003.

[10] 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 Transaction on Applied Superconductivity, vol.13, no.2, pp.2321-2324, 2003.

[11] 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.

저 자 소 개

Van-Dung Nguyen (류엔반둥)



He was born in Vietnam on December 13, 1976. He received his B.S degrees in Mechanical Engineering from Cantho University, Vietnam, in 2000. He is currently working toward his M.S degree in Electrical Engineering at Gyeongsang National University. His research interests are in the areas of electrical material, high voltage engineering and cryogenic insulation.

Tel : 055-751-5345, Fax : 055-761-8820
E-mail : nvdung131276@yahoo.com

Jong-Man Joung (鄭 鍾 萬)

He was born in Korea on Sept. 16, 1971. He received his B.S and M.S degrees in Electrical Engineering from Gyeongsang National University, Korea, in 1997 and 1999 respectively. He is currently working toward his Ph.D degree in Electrical Engineering at Gyeongsang National University. His research interests are in the areas of electrical material, high voltage engineering and cryogenic insulation.

Tel : 042-865-5915, Fax : 042-865-5804
E-mail : jjmany@keri.re.kr

Seung-Myeong Baek (白 承 明)

He was born in Korea on March 10, 1973. He received his B.S and M.S degrees in Electrical Engineering from Gyeongsang National University, Korea, in 1998and 2000 respectively. He is currently working toward his Ph.D degree in Electrical Engineering at Gyeongsang National University. His research interests are in the areas of electrical material, high voltage engineering and cryogenic insulation.

Tel : 055-751-5345, Fax : 055-761-8820
E-mail : trebari@hanmail.net

Chang-Hwa Lee (李 昶 和)

He was born in Korea on January 03, 1973. He received his B.S. degrees in Electrical Engineering from Gyeongsang National University, Korea, in 1997. He is currently working toward his M.S degree in Electrical Engineering at Gyeongsang National University and working at Otis-LG Elevator Company as an assistant manager. His research interests are in the areas of high voltage engineering and cryogenic insulation.

Tel : 055-751-5345, Fax : 055-761-8820
E-mail : chleec@otis.co.kr

Song-Hee Suck (宋 憘 錫)

He was born in Korea on May 15, 1951. He received M.S degree in Electrical Engineering from Kyungnam University, Korea, in 1990.He joined Hyosung Corporation in 1977 and was a head researcher of R D center for transformers. He is a director of the Korea Institute of Applied Superconductivity and Cryogenics.

Tel : 055-268-9370, Fax : 055-268-9926
E-mail : song@hyosung.com

Sang-Hyun Kim (金 相 賢)

He was born in Korea on Feb. 7, 1950. He received his B.S and M.S degrees in Electrical Engineering from Inha University, Korea, in 1974 and 1979 respectively, and his Ph.D degree in Electrical Engineering from Osaka University, Japan, in 1986. From 1986 to 1989, he was the head of the Applied Superconductivity Research Group at the Korea Electrotechnology Research Institute (KERI). He was President of the College of Engineering, Gyeongsang National University, from 1999 to 2001. During 2000-02, he was a Director at the Korea Institute of Electrical Engineers (KIEE). He was also Chairman of the KIASC from 2001 to 2003. Since 1989, he has been a Professor in the College of Engineering, Gyeongsang National University. His research interests are in the areas of electrical material, high voltage engineering and cryogenic insulation.

Tel : 055-751-5345, Fax : 055-761-8820
E-mail : shkim@ganu.ac.kr