Progress in Superconductivity Vol.11 No.1 pp.13-18 31 October 2009

Partial Discharge Measurements of Artificial Defects in HTS Transformer Model using HFCT

S. H. Lee[a], W. J. Shin[a], T. G. Park[a], J. Y. Koo[a], B.W. Lee[*,a]
[a] *Hanayng University, Ansan, Korea*

(Received 3 August 2009; revised or reviewed 9 October 2009; accepted 14 October 2009)

Abstract

Partial discharge measurements in cryogenic dielectric materials of HTS transformer are very important because partial discharge was regarded as primary source for ageing and breakdown of cryogenic materials. But, partial discharge measurement techniques and its effects in low temperature high voltage environments were not suggested and there exist only a few reports on this research fields. Therefore, in order to implement reliable HTS transformers, partial discharge diagnosis techniques for cryogenic materials of HTS transformers were investigated using partial discharge (PD) pattern analysis methods.

In this works, four different types of artificial defects including turn to turn insulation, free moving particle, void and protrusion, have been fabricated since it was commonly regarded that they might cause the sudden service failures of the power apparatus. For this purpose, these defects are installed into the dielectric materials in liquid nitrogen and experimental investigations have been carried out for the diagnosis of HTS transformer. And various PD patterns caused by the amount of quench of superconductors were analyzed. Throughout this works, the different PD patterns in cryogenic dielectric materials in liquid nitrogen, and PD measuring technique could be the fundamental steps to establish diagnosis technologies of HTS transformer for power applications

Keywords : HTS transformer, partial discharge, HFCT

I. Introduction

High temperature superconducting (HTS) power devices such as HTS cables, HTS transformers, and HTS fault current limiters have potential become a core technology of the 21st century in advanced capacity and efficiency, as well as to improve reliability of their power supply and transmission system.

One of the promising HTS devices for electric network is the superconducting transformer. Comparing to conventional power transformers, it could offer several advantages such as reduced size and weight, high efficiency, no oil, nonflammable and free from environmental hazards. For HTS power applications, especially for low temperature, high voltage environments, it was inevitable to cope with cryogenic dielectric issues including low temperature breakdown of materials, partial discharges in Liquid Nitrogen, ageing of dielectric materials, cracks due to cool-down and warm-up situations and bubbling effects due to quench of superconductors.

---

*Corresponding author. Fax : +82 31 400 5665
e-mail : bangwook@hanyang.ac.kr

In case of the transformer, it requires additional equipment and diagnostic measuring techniques in order to detect the abnormal signals and protect the systems from critical hazards because some kinds of internal failures cannot be immediately inspected or observed due to their enclosed and complicated structure, just like conventional transformers. Furthermore, diagnostic techniques to detect and deal with the signals of equipment malfunctions should be established urgently for HTS power equipment especially for high voltage application because small insulation defects in HTS power devices could cause system breakdown which needs a lot of expenses for replacement and superconductors are relatively vulnerable to high voltage applications. But the partial discharges diagnostic techniques for HTS power equipment were in their early stages of research and development around the world.

Therefore, in order to implement reliable HTS transformers, partial discharge diagnosis techniques for cryogenic materials of HTS transformers should be implemented [1].

In this works, four different types of artificial defects including turn to turn insulation, free moving particle, void and protrusion, have been fabricated since it was commonly regarded that they might cause the sudden service failures of the power apparatus.

For this purpose, these defects are installed into the dielectric materials in liquid nitrogen and experimental investigations have been carried out for the diagnosis of HTS transformer. And then various PD patterns caused by the amount of quench of superconductors were analyzed. Especially PRPDA (Phase Resolved Partial Discharge Analysis) was used to diagnose PD in HTS transformers [2].

This method considers the PD magnitude, the phase, and the pulse number for primary measuring parameters by piling up the measured PD quantities of each measuring interval where the phase interval of applied voltage is divided by certain numbers when the PD pulse is generated.

These obtained data from the PD analysis could be used as a database to develop a malfunction detection system when the HTS transformer is implemented for real field application. Identifying the critical insulation defects of liquid nitrogen, cryogenic dielectric materials for superconducting power devices, it could offer the main references to design the optimum insulation levels of superconducting power devices. The different PD patterns in cryogenic dielectric materials in liquid nitrogen, and PD measuring technique could be the fundamental steps to establish diagnosis technologies of HTS transformer for power applications [3].

II. Experimental setup

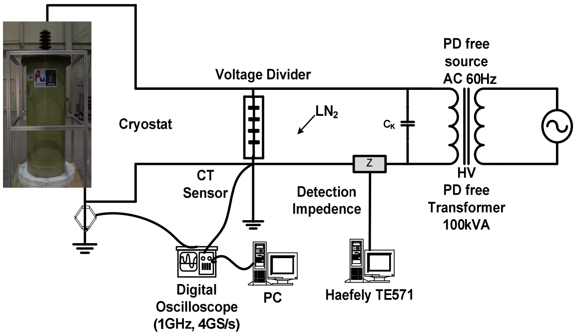


Fig. 1. Block diagram of PD experiments

Figure 1 shows the block diagram of PD experiments. The cryostat which contains liquid nitrogen is made of GFRP (Glass Fiber-Reinforced Plastic) and its inside diameter is 40 cm and its height is 130 cm. The cryostat consists of a vacuum heat insulation layer to hamper the heat transfer, and a flange at its upper part for a freezer connector, a vacuum ventilator, and a 70 kV epoxy busing was installed on the top flange to apply high voltage for the experiment.

The leakage currents from the defect simulated by test cell were detected by the high frequency current transformer (HFCT) sensor (Power Diagnostix, 2-25 MHz) and then measured by oscilloscope (Lecroy LC547AL, 1 GHz, 2 Gs/s). The PD patterns were transmitted through a NI^{TM}-GPIB (general purpose interfacing board with maximum data transmission speed: 4 Ms/sec), and finally analyzed by the LabVIEW program.

High voltage was applied by the test transformer (HAEFLEY, PD Free Test Transformer, 100 kVA), and PD signals from the defects inside the cryostat (Void, Protrusion, Turn to Turn, Free moving particles) were analyzed using the HAEFLEY TE571^{TM} that corresponds to IEC 60270.

The artificial defects installed in the cryostat

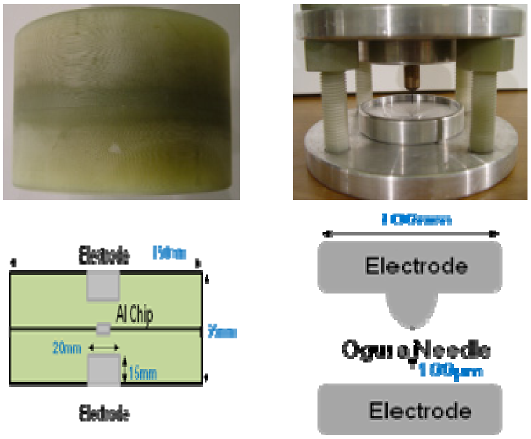
As shown in figure 2, the four artificial defects were fabricated considering potential defects which could be existed in the high voltage transformers in operation.

(A)Void: The void defects were generated inside the GFRP. And the insulation capability may decrease due to deterioration and insulation defects through repeated thermal expansion and contraction. Artificial inner void defect simulated by an aluminium chip of 5 mm in diameter and 5 mm in thickness (the distance between inserted electrodes is 3.5 cm) was fabricated and inserted into the FRP of 15 cm in diameter and 6.5 cm in thickness [4-6].

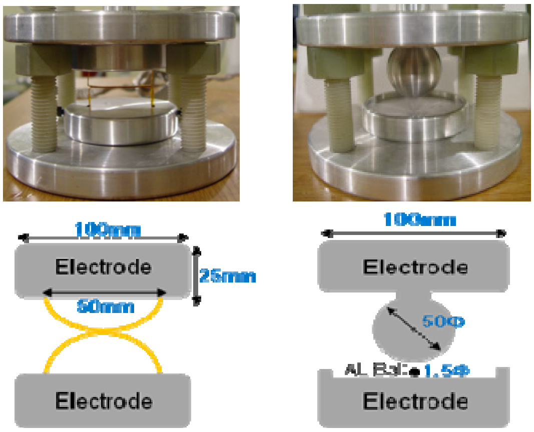
(B)Protrusion: As shown in figure 2(B), the Ogura Needle, a fixed protrusion, of which the radius of curvature, length and gap distance were 100 μm, 5 cm, and 5mm, respectively, has a static needle attached to a high voltage conductor in order to simulate the protrusion and a defect metal while processing the conductor.

(C)Turn to Turn: The surface discharge to Turn to Turn was simulated using a Cu coil (0.3 mm×4 mm), which was wrapped three times with Kapton film (25 μm×10 mm) instead of a superconducting wire, and the complex defects were also simulated when impurities existed between the coils [3].

(D) Free moving particle: An aluminium ball (1.5 Φ) was manufactured for the experiment to simulate charged particles potentially generated inside the HTS transformers. Charged particles may also float on LN_2, causing field concentration as they adhere between coils or lead to dielectric breakdown as they approach the internal conductor.



(A)Void (B) Protrusion

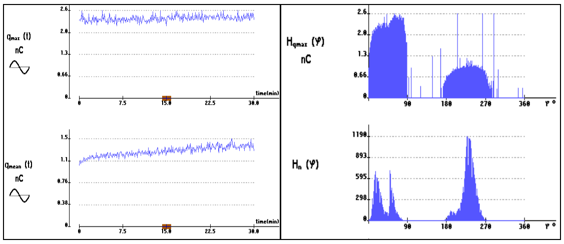


(C) Turn to Turn (D) Free moving particle

Fig. 2. The defects set inside the cryostat

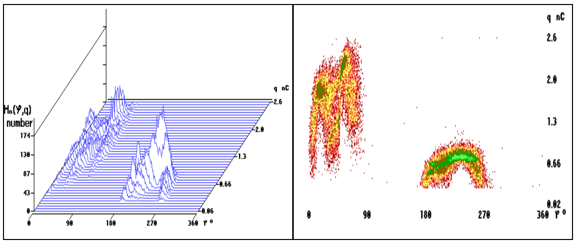
III. PD patterns analysis for each artificial defect inside the cryostat

(A) Void



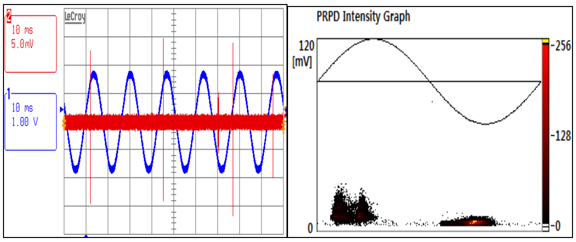
(a) Typical record of PD activity

(b) Typical phase distributions



(c) 3D PRPD pattern (d) PRPD pattern

Fig. 3. Discharge patterns of the inner void measured by the IEC 60270 method

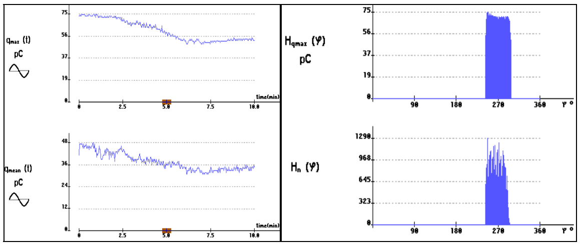


(a) Response of HFCT (b) PRPD pattern

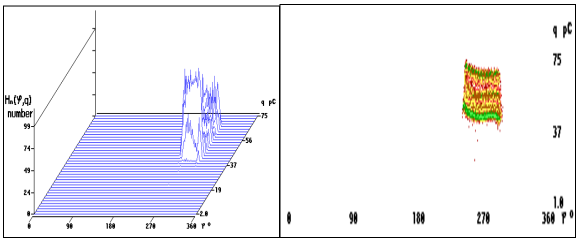
Fig. 4. Discharge patterns of the inner void measured by HFCT

The internal void of solid insulated material has diverse discharge patterns according to its magnitude and location. Figure 3 shows in the void PD pattern, q_{max} and q_{mean} of typical discharge magnitude in figure 3(a), the distribution Hq_{max} of the maximum apparent charge q_{max} to the phase angle Φ, the distribution $H_n(\Phi)$ of the number of discharge pulses to Φ in figure 3(b), and PRPD of the number of discharge pulses to Φ, Φ, magnitude of discharge in figure3(d) [5]. In figure 4, real time data of PD signals was measured by oscilloscope and HFCT in figure 4(a), and analyzed by using the self-developed PRPD analysis program in figure 4(b). As shown in figure 3, a very large discharge was detected for the maximum PD magnitude reaching 2~2.6 nC at 15 kV when it was measured by the IEC 60270 method. The q_{mean} value of discharge tended to increase from below 1.1 nC to 1.5 nC as time went by (Figure3 (a)). The PRPD pattern accumulated for 30 minutes and appeared primarily at around 0~80 ° and 170~280 °. The PD pulses appeared more at negative polarity and PD magnitudes of positive polarity measured higher than negative polarity when the discharge patterns of positive and negative polarities were compared. The result of PD pattern measured by HFCT in figure 4(b) was similar to PRPD pattern of IEC 60270 method in figure 3(d).

(B) Protrusion

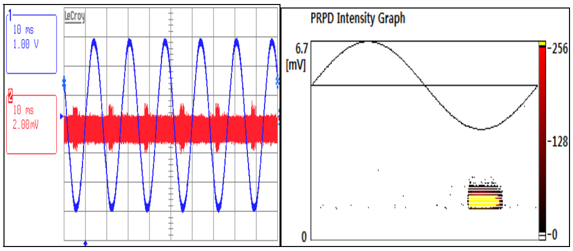


(a) Typical record of PD activity (b) Typical phase distributions



(c) 3D PRPD pattern (d) PRPD pattern

Fig. 5. Protrusion discharge patterns measured by the IEC 60270 method

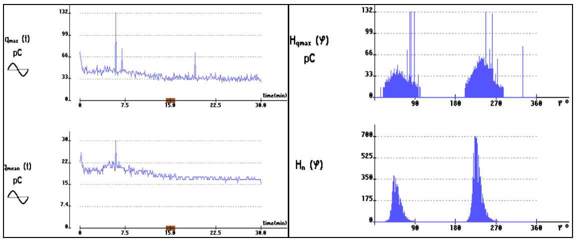


(a) Response of HFCT (b) PRPD pattern

Fig. 6. Protrusion discharge patterns measured by HFCT

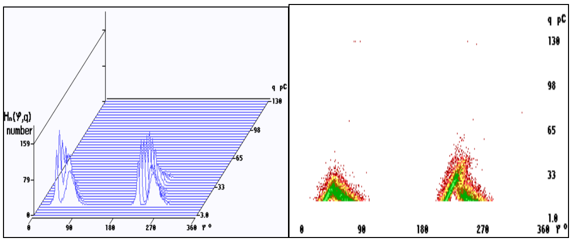
As shown in figure 5 and 6, the result measured by IEC 60270 and HFCT implies that the discharge magnitude at low voltage of 4.7 kV was decreased compared to the time of the early induction, and a constant discharge of nearly 50 pC appeared at around the 270 ° negative polarity. PD pulses appeared at 90 ° positive polarity when increasing applied Voltage, and the more increasing voltage occurred breakdown.

(C) Turn to Turn



(a) Typical record of PD activity

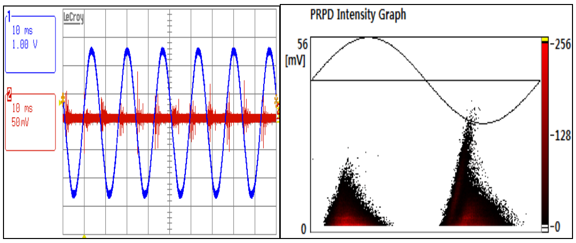
(b) Typical phase distributions



(c) 3D PRPD pattern

(d) PRPD pattern

Fig. 7. Turn to Turn discharge patterns measured by the IEC 60270 method



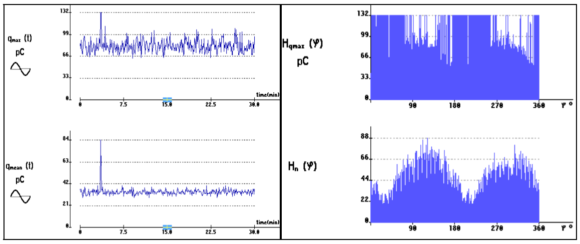
(a) Response of HFCT

(b) PRPD pattern

Fig. 8. Turn to Turn discharge patterns measured by HFCT

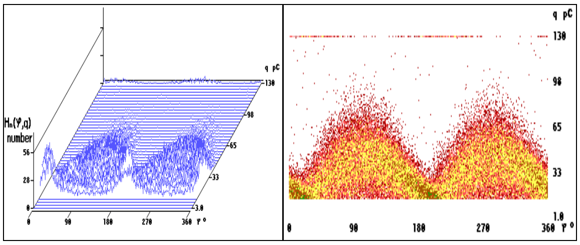
The discharge patterns of turn to turn depend on the size of the contacting surface between coils. As shown in figure 7, the result of PD measured by the IEC 60270 method shows that the discharge of nearly 39~55 pC at the applied voltage of 11kV uniformly occurred at the phase of 30~110 ° and 190~280 °, and a pattern different from that of the void discharge appeared when the pattern was analyzed using PRPD data. In the case defects existing between the coils , different result of the discharge patterns occurred. Also, the analyzed PRPD by measuring HFCT in figure 4(b) accorded with result of IEC 60270 methods in figure 3(d).

(D) Free moving particle



(a) Typical record of PD activity

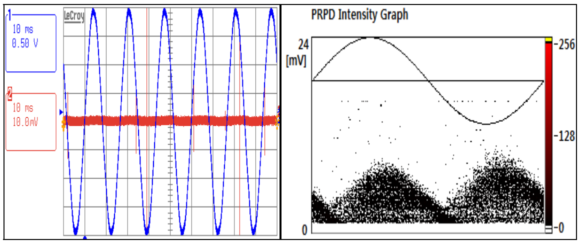
(b) Typical phase distributions



(c) 3D PRPD pattern

(d) PRPD pattern

Fig. 9. Discharge patterns of internal free moving particles measured by the IEC method



(a) Response of HFCT

(b) PRPD pattern

Fig. 10. Discharge patterns of internal free moving particles measured by HFCT

Free moving particles react to the size and quality of the particle and to the size of the electric field so sensitively that sometimes the charged particles move toward the small electric field and no more discharge occurs if the starting voltage of discharge is not constant and the induced electric field is too large (figure 9, 10).

The magnitude of the partial discharge pulses of free moving particles at the applied voltage of 15 kV inconsistently changed, and the partial discharge pulse sporadically occurred at all the phases.

Table 1 shows the comparison of PD test using 4 kinds of artificial defects. And the different characteristics were summarized as follows.

- **Void**: the discharge tended to increase compared to the early pattern of the PD as time proceeded.
- **Protrusion**: constant magnitude of PD after some time passed rather than in the early stage behaviour.
- **Turn to Turn**: the generated phase of the PD pulses showed the same behaviour of the void. But it shows a sharp difference in the magnitude and the PRPD pattern.
- **Free moving particles**: sporadic PD pulses were detected at all the Phases.

Table 1. Result of PD test

Defects	Applied voltage	PD	Phases
Void	15 kV	2~2.6 nC	0~ 80° 170~280°
Protrusion	4.7 kV	45~75 pC	270°
Turn to Turn	11 kV	39~55 pC	30~110° 190~280°
Free moving particle	15 kV	66~132 pC	0~360°

Conclusion

This works focused on the PD measuring skills for superconducting power devices by comparing the partial discharge signals generated by the defects attached inside the cryostat. Various PD patterns in defects in liquid nitrogen were obtained and analyzed by means of artificial defects simulating the defects in HTS power transformers. Different PD patterns in cryogenic dielectric materials could be obtained and this PD measuring technique could be the fundamental steps to establish diagnosis technologies of HTS transformer for power applications

Acknowledgments

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

References

[1] D.R. James, I. Sauers et al., “Breakdown and partial discharge measurements of some commonly used dielectric materials in liquid nitrogen for HTS applications”, IEEE Transactions on Applied Superconductivity, Vol. 17, NO.2, June 2007.
[2] S. M. Strachan, S. Rudd et al., “Knowledge-Based Diagnosis of Parial Discharges in Power Transformers”, IEEE Transaction on Dielectrics and Electrical Insulation, Vol.15, No. 1, February 2008.
[3] S. M. Baek, D. S. Kwag et al., “Insulation test of reciprocal and concentric winding arrangement for a HTS transformer”, IEEE Transaction on Applied Superconductivity , Vol. 15, No. 2, June 2005.
[4] F. Gutfleish and L. Niemeyer, “Measurement and simulation of PD in epoxy voids,” IEEE Trans. Dielectrics El., Vol. 2, no.5, pp.729-743, Oct 1995.
[5] G. Lupo, C. Petrarca et al., “Interpretation and classification of PD in HV Cryogenic Cable Termination”, IEEE Transaction on Dielectrics and Electrical Insulation, Vol. 7, No.1, February 2000.
[6] R. Grabovickic, D. R. James et al., “Measurements of temperature dependence of partial discharge in air gaps between insulated BSCCO tapes”, IEEE Transaction on Applied Superconductivity, Vol. 15, No. 2, June 2005.