Time Variation of Partial Discharge Activity Leading to Breakdown of Magnet Wire under Repetitive Surge Voltage Application

Naoki Hayakawa
EcoTopia Science Institute
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Hiroshi Inano, Yusuke Nakamura and **Hitoshi Okubo**
Department of Electrical Engineering and Computer Science
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

ABSTRACT
This paper discusses partial discharge (PD) propagation, degradation and lifetime characteristics of magnet wires for inverter-fed motor under surge voltage application. Experimental results showed the time variation of PD activity, i.e. intermittent PD, successive PD, critical PD and breakdown (BD), under repetitive surge voltage application with a fixed peak value. Critical PD was a drastic change of PD activity and was identified as the partial BD of magnet wires. Since the final BD was confirmed to be always induced at the critical PD location, the critical PD was regarded as an important indicator to determine the lifetime of magnet wires. The experimental results also clarified that the lifetime of magnet wires could be determined by the total number of PD generation from its inception to breakdown. PD activity was interpreted by the time transition of PD generation frequency, and its mechanisms were discussed.

Index Terms — **Pulse width modulated inverters, Surges, Partial discharges, Space charge, Aging, Magnet wire, Motor drives**

1 INTRODUCTION

BECAUSE of the increase in the demand for low-voltage inverter-fed motors, the operating voltage of inverter-fed motors is being increased for higher performance, e.g. higher power output and compactness. Since inverter-fed motors utilize power electronic devices such as IGBTs with high-speed switching ability, they are exposed to transient surge voltage, known as inverter surge. Inverter surge with the rise time of several tens or hundred nano-seconds in inverter-fed motor coils may cause partial discharge (PD) and degradation of electrical insulation performance. Therefore, rational electrical insulation design and evaluation techniques for inverter-fed motors are strongly required, which should take account of the PD mechanisms under surge voltage conditions [1-5].

The aging process of magnet wires for inverter-fed motors has been investigated in consideration of PD activity and space charge behavior. Monitoring PD activity such as PD magnitude and repetition rate could provide an early warning for the risk of unexpected failure of motors in operation [6, 7]. The relationship between the failure of magnet wires and the type of aging can be established, e.g. by determining the residual dc strength [8].

From the above background, we have investigated the PD inception and propagation characteristics of inverter-fed motor coil samples under surge voltage application [9-10]. In this paper, we focused on the time variation of PD activity after the PD inception under repetitive surge voltage application through electrical and optical observation of PD activity. We found that the PD activity changed drastically just before BD, i.e. generation of "critical PD", and discussed their mechanisms. Moreover, focusing on the breakdown lifetime characteristics, we measured the relationship between the surge breakdown voltage V and the total number of PD generation N (V-N characteristics) under surge voltage application, and verified that the lifetime of magnet wire could be determined by the total number of PD generation from its inception to breakdown. These PD propagation, degradation and lifetime characteristics and their mechanisms were discussed in terms of generation probability of initial electrons, space charge behavior in the wedge-shaped air gap and so on.

Manuscript received on 9 May 2008, in final form 28 September 2008.

Table 1. Specifications of test samples

Sample			Conductor diameter [mm]	Enamel coated thickness [mm]		Relative permittivity
(a)	Twisted pair sample	(a-1)	0.85	AI	0.019	4.1
		(a-2)	0.754	AI (outer) EI (inner)	0.017	3.85
(b)	Point contact sample		0.822	AI	0.03	4.1

AI: polyamide imide, EI: polyester imide

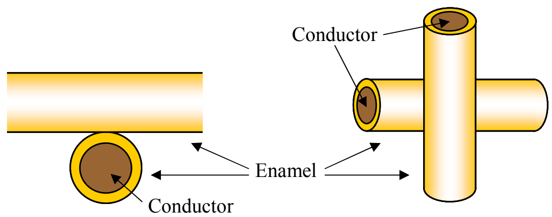


Figure 1. Structure of point contact sample.

2 EXPERIMENTAL SETUP AND PROCEDURE

We used 2 kinds of test samples in this experiment: (a) twisted pair sample and (b) point contact sample. Table 1 shows the specifications of each sample. The point contact sample is the simplified test sample as shown in Figure 1. The insulation configuration and material of the magnet wire is the single layer of AI (polyamide imide) for the samples a-1 and b, and the double layers of AI and EI (polyester imide) for the sample a-2.

Figure 2 shows the experimental setup for the measurement of PD characteristics of the test samples. The inverter surge generation circuit consists of dc high voltage supply, high voltage semiconductor switch, pulse generator and coaxial cable. It can generate damped oscillating surge voltages with different surge parameters such as polarity, peak value, rise time, pulse width and repetition rate. In this paper, the polarity of the applied surge voltage was unipolar and bipolar, the peak value Va was 0 - 5000 V_{peak}, the rise time t_r was 120 ns, the pulse width was 10 μs, and the repetition rate f was 1000 - 10000 pps, respectively.

PD inception voltage (PDIV) of the test samples was measured by the detection of PD light intensity signal using a photo multiplier tube (PMT). PDIV was defined as the applied voltage (0-peak voltage) when PMT detected the first PD signal. PDIV obtained at a temperature T [C] and a pressure P [MPa] was converted into $PDIV_0$ under the standard atmospheric condition (T_0=20 C, P_0=0.1 MPa) by the following equation (1):

$$PDIV_0 = PDIV \times \frac{273+T}{273+20} \times \frac{0.1}{P} \qquad (1)$$

PD light emission images were also taken by a still camera and a high speed video camera (200 frames per second) through an image intensifier. The detected PD light intensity signals were recorded by an oscilloscope (2.5 GHz, 20 GS/s, 64 MWord) and analyzed by the partial discharge current pulse waveform analysis (PD-CPWA) method [11]. PD-CPWA is a PD detection / analysis system developed for the purpose of pursuing the time variation of PD current pulse waveforms, and it was applied to PD light intensity waveforms by PMT in this paper. Figure 3 shows typical applied voltage and PD light intensity waveforms for twisted pair sample. PD can be generated twice at the rise time and fall time for the single surge voltage application. In the following experiments, when the applied voltage was sufficiently higher than PDIV, PD started immediately after the voltage application and continued stably up to BD. After the repetitive surge voltage application, PD generation frequency f_{PD} and the total number of PD generation N were evaluated by PD-CPWA.

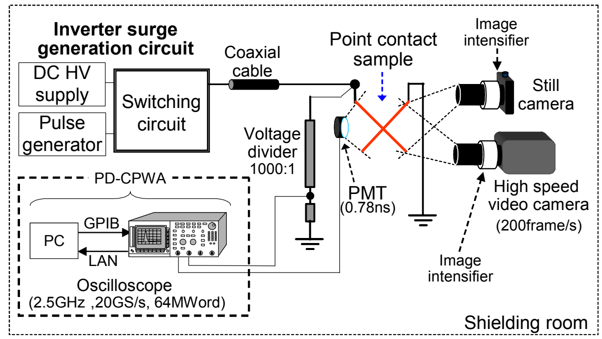


Figure 2. Experimental setup.

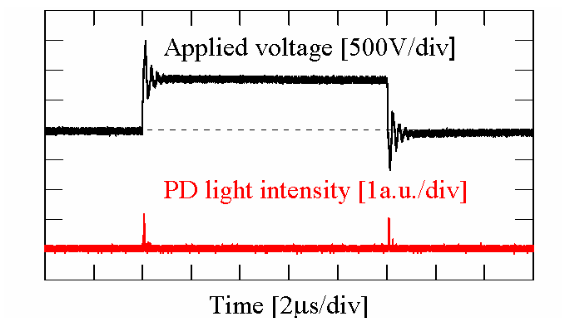
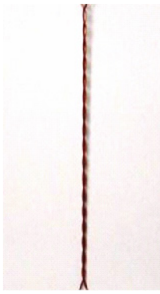


Figure 3. Applied voltage and PD light intensity waveforms for twisted pair sample.

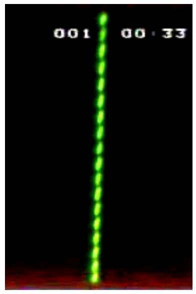
3 PD DEGRADATION CHARACTERISTICS

3.1 TIME VARIATION OF PD ACTIVITY FOR TWISTED PAIR SAMPLE

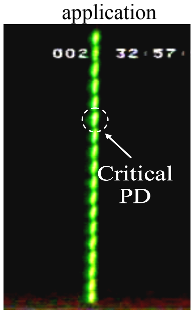
We investigated the time variation of PD activity for twisted pair sample (Sample a-1). The applied surge voltage was kept at Va=3000 V_{peak} (PDIV×1.67) and f=1000 pps with unipolar polarity until BD was induced for twisted pair sample. As the result, BD was induced at t_{BD}=78 min after the voltage application. Figure 4 shows the PD light emission images (a) before voltage application (no PD), at (b) PD inception (t=0 min), (c) 4 min before BD (t=74 min) and (d) BD (t=78 min). In Figure 4b, PD light emission was observed almost uniformly along the whole length of the sample. However, in Figure 4c, a strong PD light emission was locally observed at one point of the sample, which was consistent with the BD point in Figure



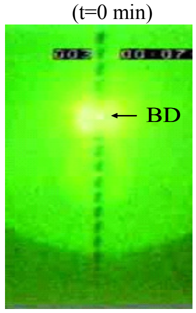
(a) Before voltage application



(b) PD inception (t=0 min)



(c) Critical PD (t=74 min)



(d) BD (t=78 min)

Figure 4. PD and BD light emission images for twisted pair sample (Sample a-1, Va=3000V$_{peak}$=PDIV×1.67, f=1000pps, unipolar).

4d. Such locally strong PD light emission was reproducible for different samples, and was sometimes observed at several points just before BD. In spite of such a change of PD light emission image, there was no change in the PD light intensity observed by PMT, which might be because the strong but local PD light intensity would have been masked under PD light intensity in the other area of the sample. These results suggested that fatal weak points were locally formed on the sample just before BD, and we called this phenomenon "critical PD" as the decisive PD leading to BD, which will be discussed and elucidated in the next sub-sections.

3.2 TIME VARIATION OF PD ACTIVITY FOR POINT CONTACT SAMPLE

In order to discuss the critical PD in detail and elucidate its generation mechanism, we focused on the time variation of PD activity for the simplified point contact sample. The applied surge voltage was kept at Va=3000 V$_{peak}$ (PDIV×2.0) and f=10000 pps with bipolar polarity until BD was induced for point contact sample. Figure 5 shows the time variation of PD light emission images up to BD. PD activity shifted from (a) intermittent PD (0 <t<18.2 min) to (b) successive PD (18.2<t<27.6 min), (c) critical PD (27.6<t<28.2 min), and resulted in BD (t_{BD}=28.2 min). In Figure 5a, PD was generated intermittently in the wedge-shaped air gap. In Figure 5b, PD propagated along the enamel surface into the lower electric field region and generated successively. In Figure 5c, drastic change of PD activity was observed, i.e. "critical PD". PD diminished on the underside wire, whereas extended on the topside wire. This suggests that a fatal weak point was formed on the underside wire.

(a) Intermittent PD (t=0 min)

(b) Successive PD (t=18.2 min)

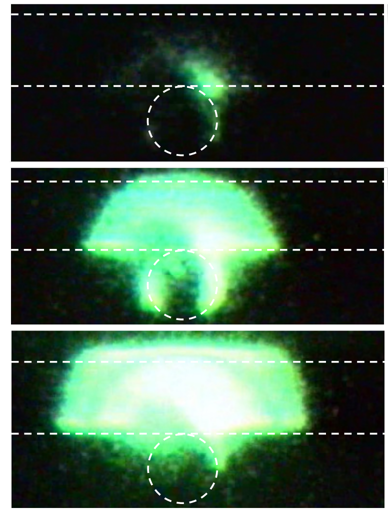


Figure 5. Time variation of PD light emission images for point contact sample (Va=3000V$_{peak}$=PDIV×2.0, f=10000pps, bipolar).

(a) Intermittent PD (t=0 min)

(b) Successive PD (t=27.5 min)

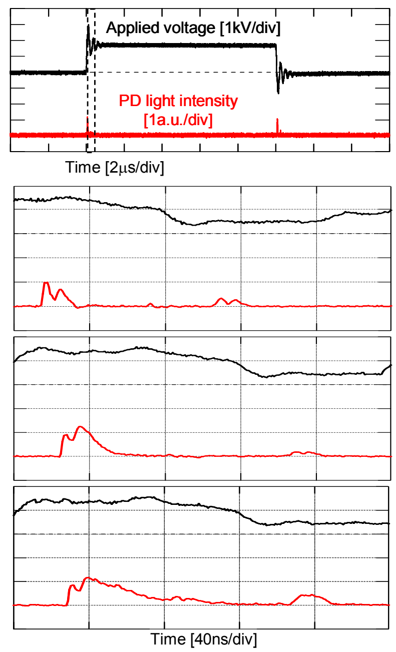
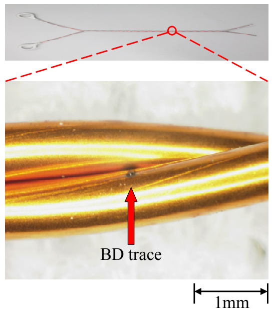


Figure 6. Applied voltage and PD light intensity waveforms for point contact sample (Va=3000V$_{peak}$=PDIV×2.0, f=10000pps, bipolar).

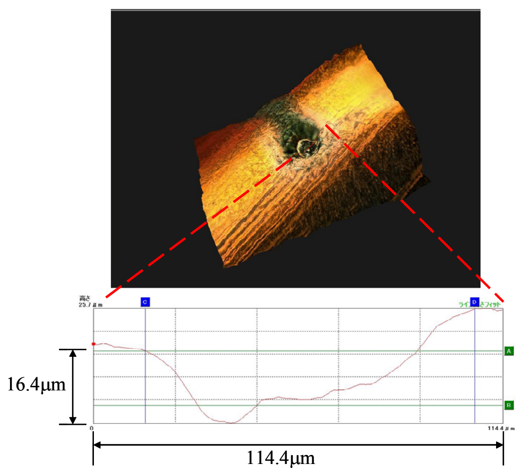
Figure 6 shows typical PD light intensity and applied voltage waveforms corresponding to (a) intermittent PD, (b) successive PD and (c) critical PD. From Figure 6a to Figure 6c, the wave tail of PD light intensity waveform becomes longer, which is consistent with the PD propagation accompanied with the critical PD generation.

3.3 BD TRACE AND CRITICAL PD TRACE ON TWISTED PAIR SAMPLE

The critical PD was also observed under ac voltage application (60 Hz, Va=6000 V$_{peak}$) for twisted pair sample (Sample a-2). The critical PD was confirmed at 2 different points, one of which resulted in BD. Figures 7 and 8 show BD trace and critical PD trace at different points on the same twisted pair sample as observed by optical and digital

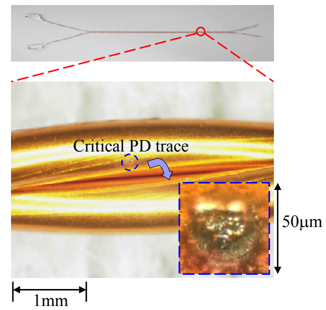


(a) Zoomed view of twisted pair with optical microscope (×100).

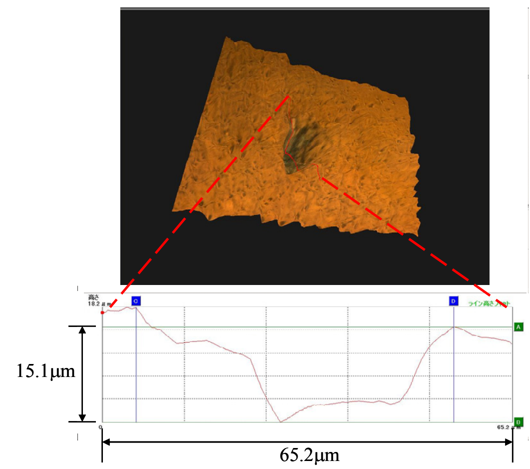


(b) Zoomed view of twisted pair with digital microscope (×500).

Figure 7. BD trace on twisted pair sample (Sample a-2, ac 60Hz, 6000V_{peak}).



(a) Zoomed view of twisted pair with optical microscope (×100).



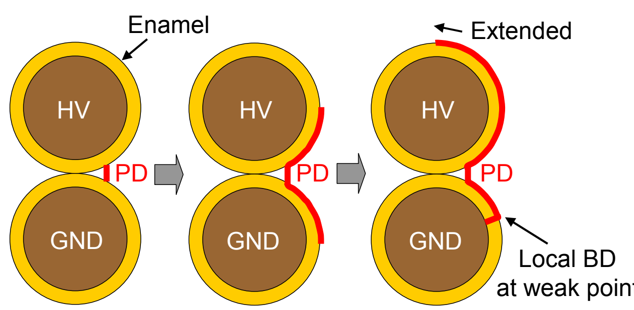
(b) Zoomed view of twisted pair with digital microscope (×500).

Figure 8. Critical PD trace on twisted pair sample (Sample a-2, ac 60Hz, 6000V_{peak}).

microscopes. The depth of BD and critical PD traces is 16.4 μm and 15.1 μm, respectively, which is almost equal to the enamel-coated thickness of the sample (17 μm). This means that the enamel coating of magnet wire was penetrated at the locations of critical PD and BD traces. Therefore, the critical PD was identified as the partial BD, i.e. the insulation on one of the magnet wires was punctured. In addition, since the time to critical PD generation was about 94 ~ 98% of the lifetime (t_{BD}), the critical PD was regarded as a precursor of BD.

3.4 DISCUSSION OF PD PROPAGATION AND DEGRADATION MECHANISMS

From the above experimental results, PD propagation and degradation mechanisms were discussed. Figure 9 shows a model of PD propagation and critical PD. Firstly, intermittent PD is generated because of initial electron shortage in the wedge-shaped air gap. Space charges, e.g., electrons, negative ions (O_2^-, O^-) and positive ions (N_2^+, N^+, O_2^+, O^+), are considered as a source of initial electron for PD inception. Then the number of space charges in the gap, i.e. PD generation probability, increases by intermittent PD, so that successive PD comes to be observed with a sufficient number of initial electrons.



(a) Intermittent PD (b) Successive PD (c)Critical PD

Figure 9. Model of PD propagation and critical PD.

Afterwards, a partial BD is caused at a weak point on one of the magnet wires subjected to PD activity, i.e. critical PD. At that time, the surface potential at the critical PD point becomes equal to that of the conductor, and PD propagates from the critical PD point to lower electric field region on the other magnet wire.

The degradation of insulation performance progresses on the other magnet wire. The enamel coating of magnet wire is penetrated on the other magnet wire, too, i.e. final BD. This is consistent with the experimental results that the final BD was always induced at the critical PD location. Therefore, the critical PD can be regarded as an important indicator to determine the life of magnet wire for inverter-fed motor.

4 LIFETIME CHARACTERISTICS

We verified the time variation from intermittent PD to successive PD in Fig. 5 in terms of PD generation frequency f_{PD} and discussed the lifetime (V-t and V-N characteristics) of magnet wire.

4.1 V-T CHARACTERISTICS

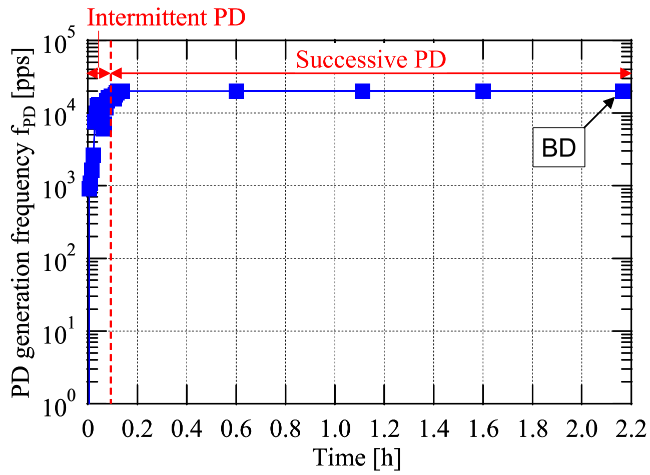
Figure 10 shows the relationship between applied voltage Va and time to BD (t_{BD}) for repetition rate f = 5000 pps and 10000 pps with unipolar polarity (V-t characteristics) for twisted pair sample (Sample a-2). In Figure 10, "Surge PDIV" indicates the dispersion of PDIV (minimum to maximum). The reproducibility of lifetime t_{BD} has been confirmed in the preliminary experiments with different specimens and conditions. t_{BD} decreased with the increase in Va, and the regression line was expressed by the following equation (2):

$$V_a = K \times t_{BD}^{-1/n} \tag{2}$$

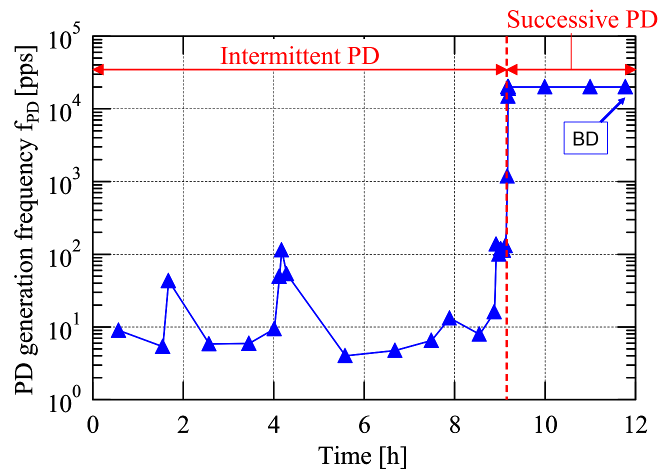
where K is constant and n is life expectancy. In Figure 10, n value at Va<1.5kV (n=23.0) was considerably larger than that value at Va>1.5kV (n=4.04) for f=10000 pps. Accordingly, in the low voltage region near PDIV, the inclination of V-t characteristics became small and longer breakdown lifetime was exhibited.

4.2 TIME VARIATION OF PD GENERATION FREQUENCY

Figure 11 shows the time variation of PD generation frequency f_{PD} for two different twisted pair samples: (a) sample a-2-1 with t_{BD}=2.17 h and (b) sample a-2-2 with t_{BD}=11.8 h (Va=1.2 kV_{peak}). In Figure 11a, f_{PD} increased with time and reached 20000 pps after 7 minutes for sample a-2-1. Since PD can be generated twice for the single surge voltage application just like in Figure 3, f_{PD}=20000 pps means that PD was generated at every single surge voltage application, i.e. successive PD. In Figure 11b, on the other hand, f_{PD} was under 100 pps at first (intermittent PD), then suddenly increased and reached 20000 pps after 9.17 h (successive PD) for sample a-2-2.



(a) Sample a-2-1 (PDIV=1.02 kV_{peak}, t_{BD}=2.17 hours)



(b) Sample a-2-2 (PDIV=1.04 kV_{peak}, t_{BD}=11.8 hours).

Figure 11. Time transition of PD generation frequency f_{PD} (Va=1.2 kV_{peak}, f=10000pps).

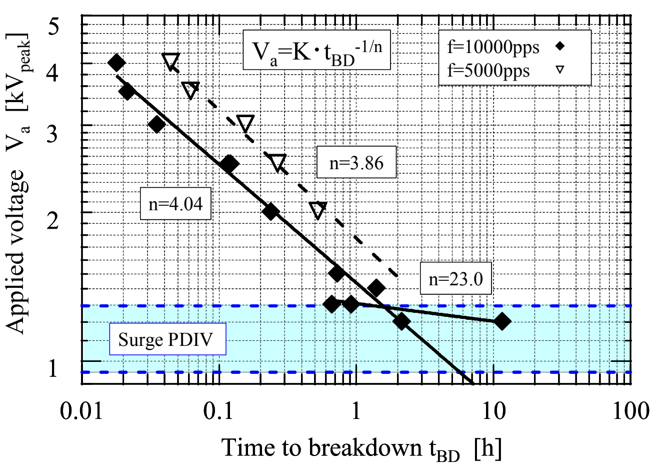


Figure 10. Relationship between applied voltage Va and time to BD t_{BD} (V-t characteristics).

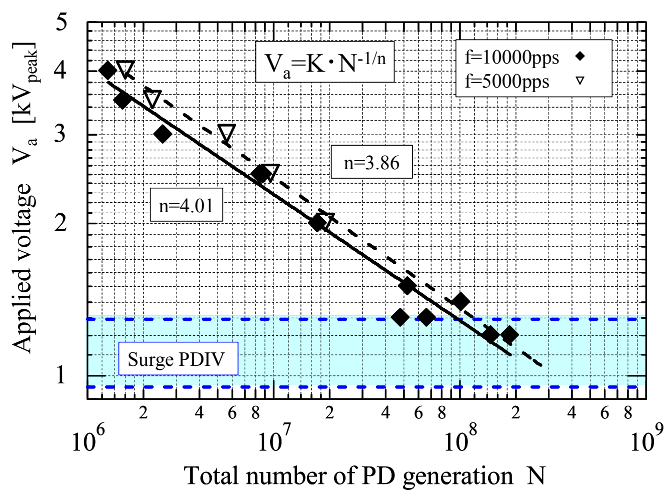


Figure 12. Relationship between applied voltage Va and total number of PD generation N (V-N characteristics).

4.3 V-N CHARACTERISTICS

Figure 12 shows the relationship between applied voltage Va and total number of PD generation N (V-N characteristics). In Figure 12, V-N characteristics could be almost approximated by a straight line, whereas V-t characteristics in Figure 10 had the drastic change of inclination at low voltage region near PDIV. Moreover, V-N characteristics for f=5000 pps and f=10000 pps were almost consistent. These experimental results verify that the lifetime of magnet wire could be determined by N, i.e. the total number of PD generation from its inception to breakdown, which is determined by the generation of successive PD.

During the deterioration process, the residual enamel thickness of non-filled magnet wire decreased linearly with the increase in total number of PD generation N, where PD light intensity and the wire temperature were almost constant [12]. These results also suggest that the transition from intermittent PD to successive PD could be regarded as the main factor of insulation deterioration or lifetime of magnet wire.

5 CONCLUSIONS

PD propagation, degradation and lifetime characteristics of magnet wire for inverter-fed motors under repetitive surge voltage application were obtained and quantitatively evaluated. We summarize the results as shown below:

(1) PD activity shifted from intermittent PD to successive PD, critical PD and resulted in BD under the repetitive surge voltage application.
(2) Critical PD was identified as the partial BD on one of the magnet wires resulting in the final BD. Therefore, critical PD was regarded as the important indicator to determine the life of magnet wire.
(3) D propagation and degradation mechanisms were discussed from the viewpoint of the space charge behavior in the wedge-shaped air gap and the critical PD generation.
(4) Lifetime of magnet wire could be determined by the total number of PD generation from its inception to breakdown, i.e. successive PD.

REFERENCES

[1] M. Kaufhold, K. Schafer and K. Bauer, "Medium & High Power Drive Systems; Requirements and Suitability Proof for Winding Insulation Systems", Intern. Electr. Insul. Conf. (INSUCON), pp.86-92, 2006.

[2] D. Fabiani, A. Cavallini and G.C. Montanari, "The Effect of Environmental Condition on PD Actirivity in PWM-Fed Induction Motors", Intern. Electr. Insul. Conf. (INSUCON), pp.109-114, 2006.

[3] F. Guastabino, A. Dardano, A. Ratto and E. Torello, "PD Measurements During the Degradation of Twisted Pair Enameled Wires Subjected to Repetitive Voltage Impulses", Intern. Sympos. On Electr. Insul. (ISEI), pp.147-150, 2006.

[4] X. Liu, G. Wu, L. Tong, T. Lin and G. Zhang, "Influence of Impulse Frequency on Partial Discharge under PWM", Intern. Sympos. On Electr. Insul. (ISEI), pp. 241-244, 2006.

[5] H. Okubo, N. Hayakawa and G. C. Montanari, "Technical Development on Partial Discharge Measurement and Electrical Insulation Techniques for Low Voltage Motors Driven by Voltage Inverters", IEEE Trans. Dielectr. Electr. Insul., Vol. 14, pp.1516-1530, 2007.

[6] G. C. Montanari, A. Cavallini and A. Caprara, "PD Activity and Ageing of Power-Electronimcs Controlled Motors", Intern. Sympos. Electr. Insul. Materials (ISEIM), Vol.1, pp.168-171, 2005.

[7] D. Fabiani, A. Cavallini and G. C. Montanari, "Aging Investigation of Motor Winding Insulation Subjected to PWM-Supply Through PD Measurements", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp.434-457, 2005.

[8] S. Ul. Haq, S. H. Jayaram and E. A. Cherney, "Evaluation of Medium Voltage Enameled Wire Exposed to Fast Repetitive Voltage Pulses", IEEE Trans. Dielectr. Electr. Insul., Vol.14, pp.194-203, 2007.

[9] N. Hayakawa and H. Okubo, "Partial Discharge Characteristics of Inverter-Fed Motor Coil Samples Under AC and Surge Voltage Conditions", IEEE Electr. Insul. Mag., Vol. 21, No.1, pp.5-10, 2005.

[10] N. Hayakawa, M. Morikawa and H. Okubo, "Partial Discharge Inception and Propagation Characteristics of Magnet Wire for Inverter-Fed Motor under Surge Voltage Application", IEEE Trans. Dielectr. Electr. Insul., Vol.14, pp.39-45, 2007.

[11] H. Okubo and N. Hayakawa, "A Novel Technique for Partial Discharge and Breakdown Investigation Based on Current Pulse Waveform Analysis", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, pp. 736-744, 2005.

[12] N. Hayakawa and H. Okubo, "Lifetime Characteristics of Nanocomposite Enameled Wire Under Surge Voltage Application", IEEE Electr. Insul. Mag., Vol.28, No.2, pp.22-27, 2008.

Naoki Hayakawa was born on 9 September 1962. He received the Ph.D. degree in 1991 in electrical engineering from Nagoya University. Since 1990, he has been at Nagoya University and presently he is a Professor of Nagoya University at the EcoTopia Science Institute. From 2001 to 2002, he was a guest scientist at the Forschungszentrum Karlsruhe, Germany. He is a member of IEEE and IEE of Japan.

Hiroshi Inano was born on 29 September 1982. He received the B.S. degree in 2006 in electrical engineering from Nagoya University. Currently, he is a Master Course student at Nagoya University in the Department of Electrical Engineering and Computer Science.

Yusuke Nakamura was born on 2 March 1982. He received the B.S. degree in 2007 in electrical engineering from Nagoya University. Currently, he is a Master Course student at Nagoya University in the Department of Electrical Engineering and Computer Science.

Hitoshi Okubo (M'81) was born on 29 October 1948. He received the Ph.D. degree in 1984 in electrical engineering from Nagoya University. He joined Toshiba Corporation, Japan in 1973 and was a Manager of HV laboratory of Toshiba. From 1976 to 1978, he was at the RWTH Aachen, Germany and the TU Munich, Germany. In 1989 he became an Associate Professor and presently he is a Professor of Nagoya University in the Department of Electrical Engineering and Computer Science. He is a member of IEE of Japan, VDE and CIGRE.