Partial Discharge Propagation and Degradation Characteristics of Magnet Wire for Inverter-Fed Motor under Surge Voltage Application

N. Hayakawa[1], H. Inano[1], K. Inuzuka[1], M. Morikawa[1] and H. Okubo[2]
[1]Department of Electrical Engineering and Computer Science, Nagoya University, Japan
[2]EcoTopia Science Institute, Nagoya University, Japan

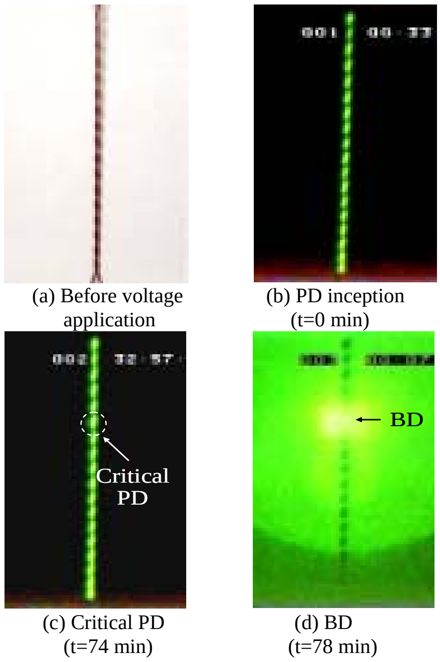
Abstract: In this paper, we investigated the PD generation, propagation, degradation and breakdown (BD) characteristics of magnet wire for inverter-fed motor under surge voltage application. Experimental results revealed the transition of PD activity, i.e. intermittent PD, successive PD, critical PD and BD, under repetitive surge voltage application with a fixed peak value. The transition from intermittent PD to successive PD was associated with the PD propagation along the enamel surface into the lower electric field region. Critical PD was a drastic change of PD activity and identified as the local BD of magnet wire. Since the final BD was confirmed to be always induced at the critical PD location, critical PD was regarded as an important indicator to determine the life of magnet wire for inverter-fed motor.

Introduction

Surge voltages with the rise time of several tens or hundreds of nano second in inverter-fed motor may cause partial discharge (PD) and degradation of electrical insulation performance of the motor coils. Therefore, rational electrical insulation design and evaluation techniques for the inverter-fed motors are strongly required, which should take account of the PD mechanism under surge voltage condition [1-3].

From the above background, we have been investigating the PD inception, propagation, degradation and breakdown (BD) characteristics of inverter-fed motor coil samples under surge voltage application [4,5]. We have already found that a strong PD light emission (critical PD) was locally observed in the twisted pair sample just before BD, and the final BD was always induced at the critical PD location [6,7]. Figure 1 shows typical PD light emission images from PD inception to BD through critical PD generation.

In this paper, we focused on the critical PD characteristics and clarified their transition process through electrical and optical observation of PD activity. These PD generation, propagation, degradation and BD 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.



(a) Before voltage application
(b) PD inception (t=0 min)
(c) Critical PD (t=74 min)
(d) BD (t=78 min)

Figure 1: PD and BD light emission images for twisted pair sample.

Experimental setup

We used 3 kinds of test samples in this experiment: (a) twisted pair sample, (b) 1 twisted sample, (c) point contact sample. Table 1 shows the specifications of each sample. 1 twisted sample has only 1 twisted part, whereas twisted pair sample has 18 twists. Point contact sample is the simplified test sample as shown in Fig. 2.

Figure 3 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 generates damped oscillating surge voltages with different surge parameters such as polarity, peak value, rise time, pulse width and repetition rate. In this paper, 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 single shot with positive polarity, or 10000pps with bipolar polarity, respectively.

Table 1: Specifications of test samples.

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

AI: polyamide imide, EI: polyester imide

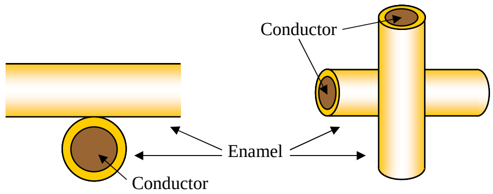


Figure 2: Structure of point contact sample.

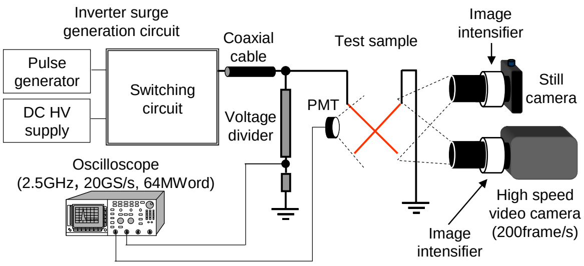


Figure 3: Experimental setup.

PD inception voltage (PDIV) of the test samples were measured by the detection of PD light intensity signal using a photo multiplier tube (PMT). 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. PDIV was defined as the peak value of the applied voltage, and converted into the value at the standard atmosphere condition (20 ℃, 0.1 MPa). PDIV for twisted pair sample was 980 V_{peak}, and PDIV for 1 twisted sample and point contact sample was 1500 V_{peak} (bipolar polarity, 10000pps)

Experimental results and discussions

PD propagation characteristics

Figures 4 and 5 show PD propagation images for different applied voltages higher than PDIV for point contact sample and 1 twisted sample. Note that the applied surge voltage was single shot with positive polarity at each Va. PD propagates from the contact point of two magnet wires along the surface of the magnet wire. PD extends to the lower electric field region on the backside of the magnet wire along with the rise of applied voltage Va. Therefore, even in the lower electric field region, the degradation of insulation performance of magnet wire can progress.

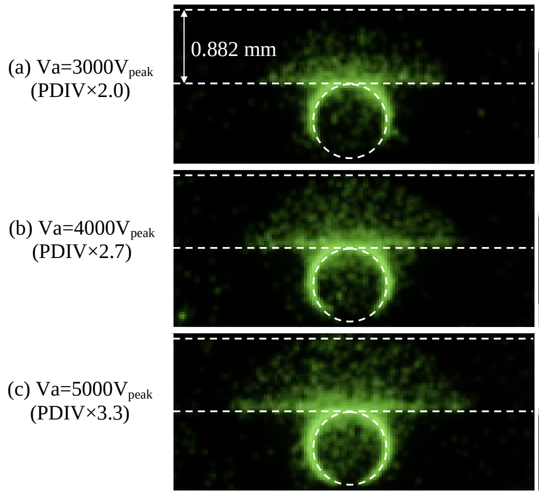
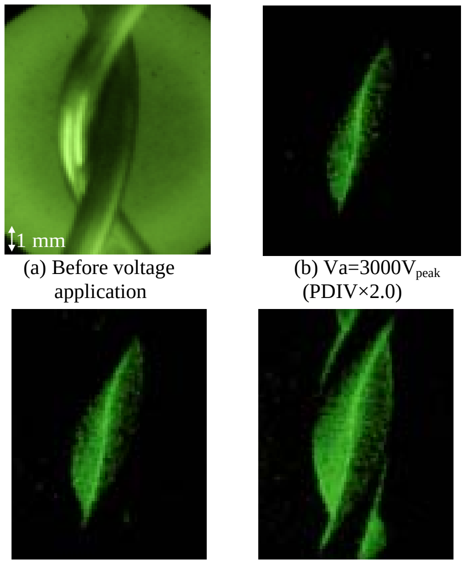


Figure 4: PD propagation images for point contact sample (single shot).



(a) Before voltage application

(b) Va=3000V_{peak} (PDIV×2.0)

(c) Va=4000V_{peak} (PDIV×2.7)

(d) Va=5000V_{peak} (PDIV×3.3)

Figure 5: PD propagation images for 1 twisted sample. (single shot)

Transition characteristics of PD activity

The applied surge voltage was kept at Va=3000 V_{peak} and f=10000pps with bipolar polarity until BD was induced for point contact sample. Figure 6 shows the time transition 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 Fig.6 (a), PD was generated intermittently in the wedge-shaped air gap. In Fig.6 (b), PD propagated along the enamel surface into the lower electric field region and generated successively. In Fig.6 (c), the drastic change of PD activity was observed, to be

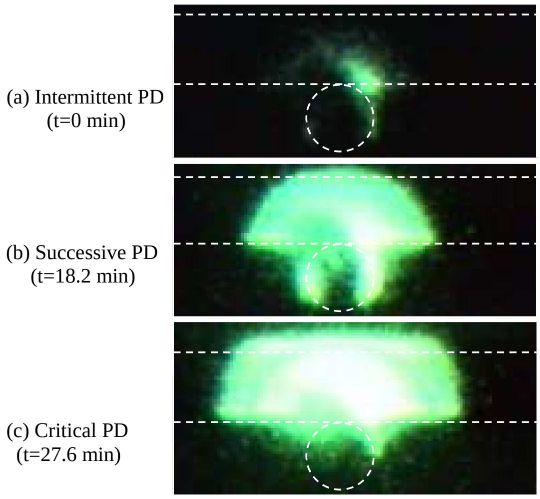


Figure 6: Time transition of PD light emission images for point contact sample. (Va=3000V$_{peak}$, f=10000pps, bipolar)

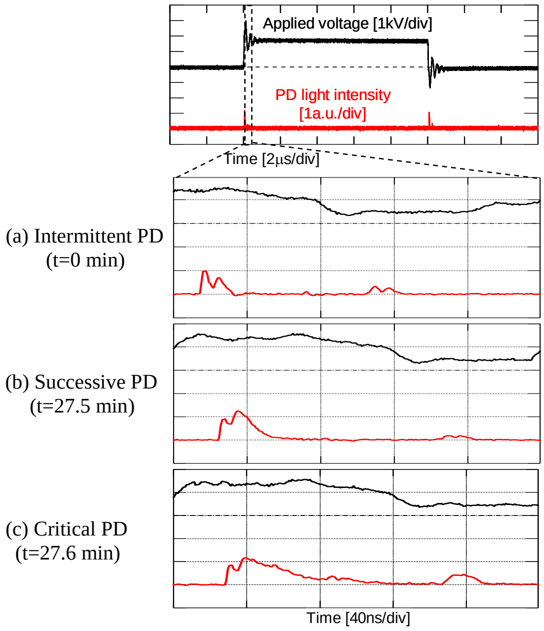
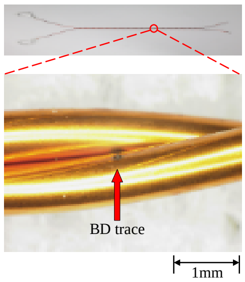


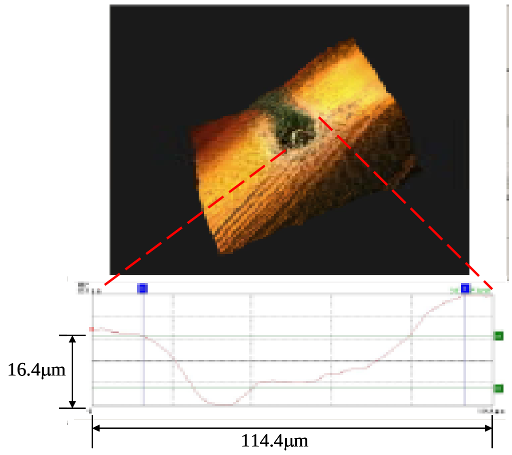
Figure 7: Applied voltage and PD light intensity waveforms for point contact sample.

referred to the “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.

Figure 7 shows typical PD light intensity and applied voltage waveforms corresponding to (a) intermittent PD, (b) successive PD and (c) critical PD. From Fig.7 (a) to Fig.7 (c), the wave tail of PD light intensity waveform becomes longer, which is consistent with the PD propagation accompanied with the critical PD generation.

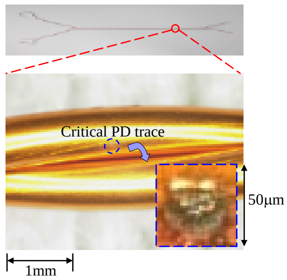


(a) Zoomed view of twisted pair with optical microscope (×100).

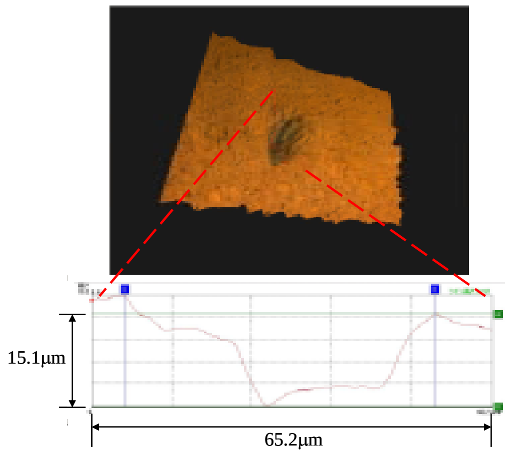


(b) Zoomed view of twisted pair with digital microscope (×500).

Figure 8: BD trace on twisted pair sample. (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 9: Critical PD trace on twisted pair sample. (ac 60Hz, 6000V$_{peak}$)

BD characteristics

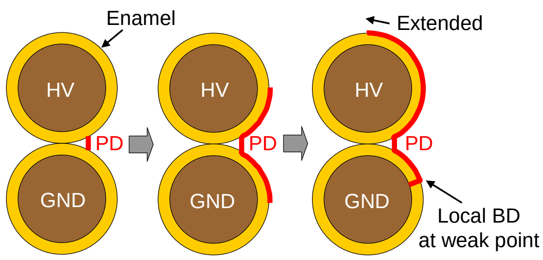
The critical PD was also observed under ac voltage application (60Hz, Va=6000 V_{peak}). The critical PD was confirmed at 2 different points, one of which resulted in BD. Figures 8 and 9 show BD trace and critical PD trace at different points on the same twisted pair sample observed by optical and digital 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 through at the locations of critical PD and BD traces. Therefore, the critical PD was identified as the local BD on one of magnet wire. In addition, since the time to critical PD generation, t_{CPD}, was about 94 ~ 98% of t_{BD}, the critical PD was regarded as a precursor of BD.

Discussion on PD propagation and degradation mechanisms

From the above experimental results, PD propagation mechanisms were discussed. Figure 10 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. The number of space charges in the gap, i.e. PD generation probability, increases by intermittent PD. Then, successive PD comes to be observed with enough number of initial electrons.

Afterwards, a local BD is caused at a weak point on one of magnet wire 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 through 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 the important indicator to determine the life of magnet wire for inverter-fed motor.



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

Figure 10: Model of PD propagation and critical PD.

Conclusions

PD propagation and degradation characteristics of magnet wire under surge voltage condition were obtained. We summarize the results as shown below:

(1) PD propagated along the enamel surface to the lower electric field region on the backside of the magnet wire.

(2) PD activity shifted from intermittent PD to successive PD, critical PD and resulted in BD under the repetitive surge voltage application.

(3) Critical PD was identified as the local BD on one of magnet wire resulting in the final BD. Therefore, critical PD was regarded as the important indicator to determine the life of magnet wire for inverter-fed motor.

(4) PD 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.

References

[1] M.Kaufhold, K. Schafer, K. Bauer and M.Rossmann "Medium and High Power Drive Systems; Requirements and Suitability Proof for Winding Insulation Systems", INSUCON, pp. 86-92, 2006

[2] S. Grzybowski and N. P. Kota, "Lifetime Characteristics of Magnet Wires under Multistress Conditions", CEIDP, pp.605-608, 2005

[3] D. Fabiani, A. Cavallini and G. C. Montanari,, "The Effect of Environmental Conditions on Activity in PWM-Fed Induction Motors", INSUCON, pp. 115-119, 2006

[4] H. Okubo, Y. Lu, M. Morikawa and N. Hayakawa, "Partial Discharge Inception Characteristics Influenced by Stressed Wire Length of Inverter-Fed Motor", CEIDP, pp.442-445, 2004

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

[6] M. Morikawa, N. Hayakawa and H. Okubo, "Partial Discharge Inception and Degradation Characteristics of Inverter-Fed Motor Sample under Surge Voltage Condition", CEIDP, pp.426-429, 2005

[7] H. Okubo, M. Morikawa, K. Inuzuka and N. Hayakawa, "Partial Discharge Inception and Breakdown Characteristics of Inverter-Fed Motor under Inverter Surge Voltage Condition", INSUCON, pp.109-114, 2006.

Author address: Naoki Hayakawa, Department of Electrical Engineering and Computer Science, Nagoya University, Furo-Cho, Chikusa-ku, Nagoya, 464-8603, Japan. Email: nhayakaw@nuee.nagoya-u.ac.jp