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Partial discharge characteristics of inverter-fed motor coil samples under ac and surge voltage conditions

Hitoshi Okubo[1], Yonghu Lu[2] and Naoki Hayakawa[2]
[1]Center for Integrated Research in Science and Engineering, Nagoya University, Japan
[2]Department of Electrical Engineering, Nagoya University, Japan

Abstract: We discussed the partial discharge (PD) characteristics of inverter-fed motor coil samples under surge voltage condition and compared with those under ac voltage application. PD light emission images and PD light intensity waveforms were simultaneously measured to obtain the PD inception characteristics. The differences in the PD characteristics under ac and surge voltage conditions were investigated for the insulation design of inverter-fed motors. It was found that the PDIV under surge voltage condition was 1.6~1.8 times and 2.3~2.7 times higher than those under ac voltage application for the used and virgin samples respectively, and the PD inception mechanisms were clarified.

Introduction

Since conventional inverter-fed motors for electric vehicles and hybrid vehicles have been operated under a low voltage stress [1-4], an electrical insulation performance has not been critical for the basic design. However, the operating voltage of the inverter-fed motors is being enhanced for the higher performance, e.g. high power output and compactness, which requires the rational electrical insulation design. Especially, the inverter-fed motors utilize power electronics devices such as IGBT with high-speed switching ability [3], and then exposed to transient surge voltage stress with a steep wave front. Such a surge voltage stress can cause partial discharge in the motor insulation system and deteriorate the electrical insulation performance leading to breakdown failure.

From the above background, in this paper, we investigated PD inception characteristics of twisted pair as a simplified inverter-fed motor coil sample. We discussed the difference in the PD inception characteristics of the twisted pair under 60 Hz ac voltage and surge voltage with a steep wave front.

Experimental setup

Figure 1 shows the experimental setup for the measurement of PD characteristics of the twisted pair. The twisted pair consists of two enamel coating wires with the following specifications: diameter=0.845 mm (conductor), coating thickness =0.03 mm (dielectric constant ε_r=4.2), twisted pitch=7mm, and total length=130mm. One of the wires was grounded, and ac or surge high voltage was applied to the other wire. The frequency of ac voltage was 60 Hz, and the surge voltage had the rise time of 20ns and the duration of 1μs for the single shot and the repetitive shot of 6 pps or 60 pps.

PD inception voltage (PDIV) was detected by PD light intensity under both ac and surge voltage applications. PD light intensity signal was observed using a photo multiplier tube (P.M.T.). The PD light emission images were taken by a still camera through an image intensifier (I.I.) with setting the exposure time to 5 seconds. We also measured the PD current pulse under ac voltage application through high frequency CT (1GHz); CT1 for the twisted pair, and CT2 for the coupling capacitor.

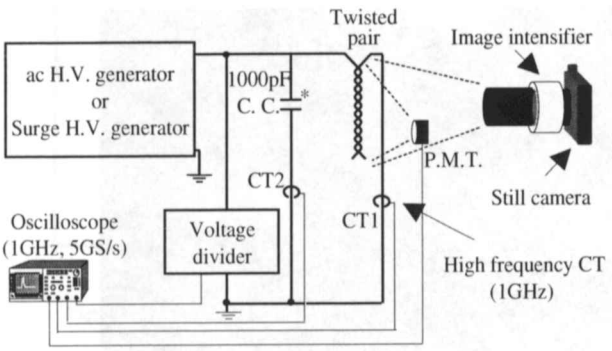

Figure 1: Experimental setup.

[*: C.C. (Coupling capacitor) is only for ac.]

Experimental results

PD characteristics under ac voltage application

We measured the PD characteristics of the twisted pair under ac voltage application. Two twisted pair samples were examined; Sample A was a used sample and Sample B was a virgin sample. We found that $PDIV_A$=816Vpeak in Sample A and $PDIV_B$=780Vpeak in Sample B, by P.M.T. measurement.

Figure 2 shows applied voltage, PD light intensity and PD current pulse of Sample A at

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Va=816Vpeak (PDIV). PD light intensity signal with a steep pulse waveform and PD current with the reversal polarity between CT1 (twisted pair) and CT2 (coupling capacitor) were detected simultaneously, by which the PD generation in the twisted pair sample was verified.

Figure 3 shows the PD light emission images at (a) Applied voltage Va=900Vpeak and (b) Va=2000Vpeak, respectively. PD light emission was observed firstly at Va=900Vpeak, and became stronger with the increase in the applied voltage. Optical PDIV measurement shows about 5% higher PDIV than current value measurement.

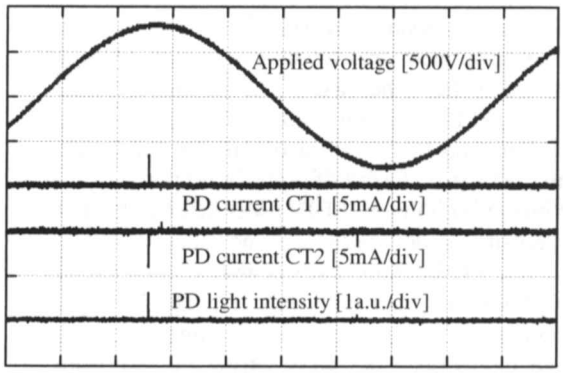
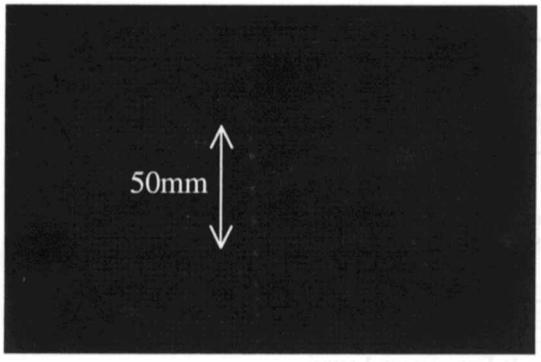
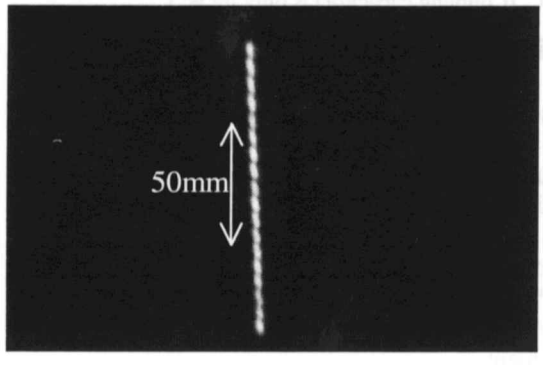


Figure 2: Applied voltage, PD light intensity and PD current pulse waveforms under ac voltage application.
(Sample A, Va=816Vpeak).



(a) Va=900Vpeak

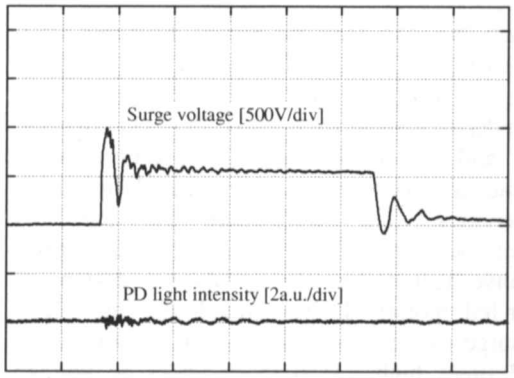


(b) Va=2000Vpeak

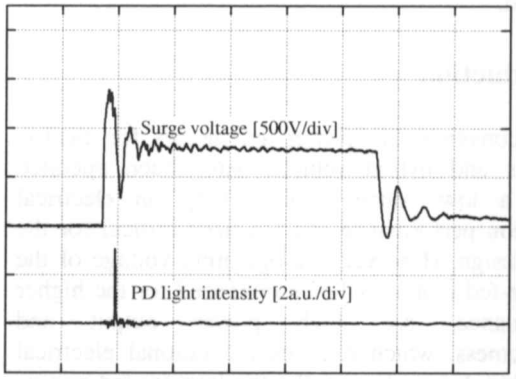
Figure 3: PD light emission images under ac voltage application (Sample A).

PD characteristics under surge voltage condition

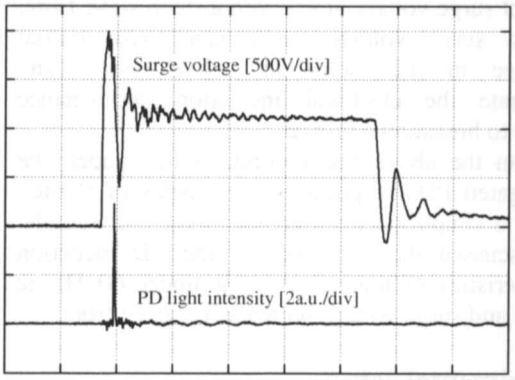
We measured the PD characteristics of the twisted pair



(a) Va=1000Vpeak (No PD).



(b) Va=1350Vpeak (PDIV)



(c) Va=2000Vpeak

Figure 4: Applied voltage and PD light intensity waveforms under surge voltage condition.
(Surge wave front: 20ns, Sample A, 60 pps).

under surge voltage condition. Figure 4 shows the applied surge voltage and light intensity waveforms of Sample A for (a) Va=1000Vpeak (No PD), (b) Va=1350Vpeak (PDIV) and (c) Va=2000Vpeak, respectively, with 60 pps repetition. PD light intensity signal was detected in the transients of the applied surge voltage in Figs. 4 (b) and 4 (c). Figure 5 shows the details of PD generation of Fig. 4 (c). As shown in Fig. 5, we can recognize the time delay of PD inception, because of the applied surge voltage very steep wave front of surge voltage.

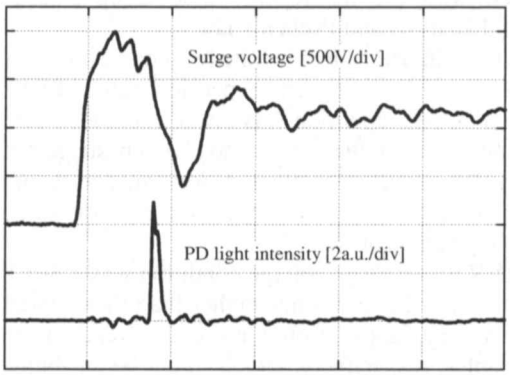
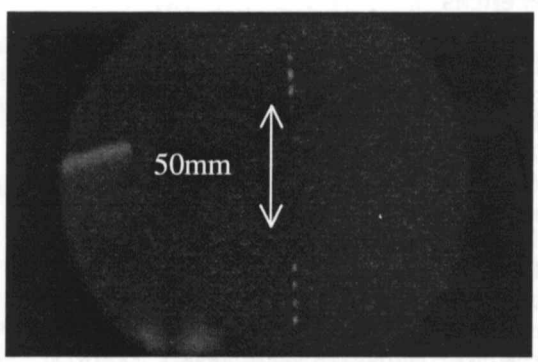
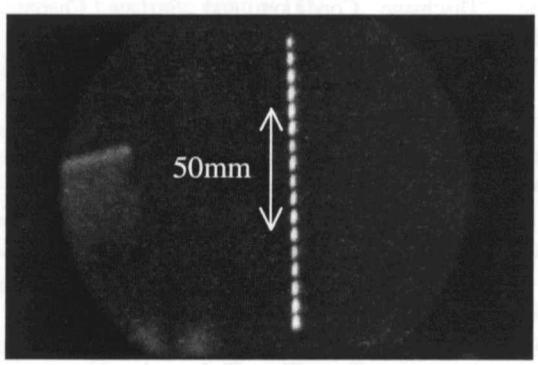


Figure 5: Details of applied voltage and PD light intensity waveforms under surge voltage condition.
(Surge wave front: 20ns, Sample A, 60 pps , Va=2000Vpeak).



(a) Va=1400Vpeak



(b) Va=2000Vpeak

Figure 6: PD light emission images under surge voltage condition (Surge wave front: 20ns, Sample A, 60 pps).

Figure 6 shows the PD light emission images of Sample A under 60 pps surge voltage application for (a) Va=1400Vpeak and (b) Va=2000Vpeak, respectively. The first PD light emission was observed at Va=1400Vpeak at both ends of the twisted pair, and became stronger with the increase in the applied voltage, spreading over the whole length of the twisted pair.

Discussion on PDIV mechanism

We calculated the theoretical value of ac PDIV of the twisted pair, using the finite element method of electric field calculation and Paschen's law in air. Figure 7 shows the equi-potential curve in the cross section of the twisted pair sample. The gap length d between two conductors was defined as shown in

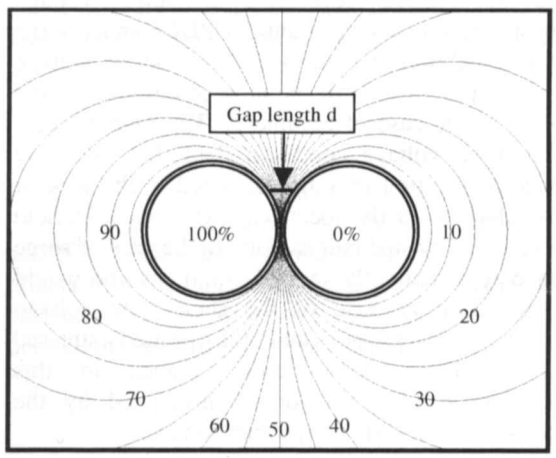


Figure 7: Equi-potential curve of twisted pair sample.

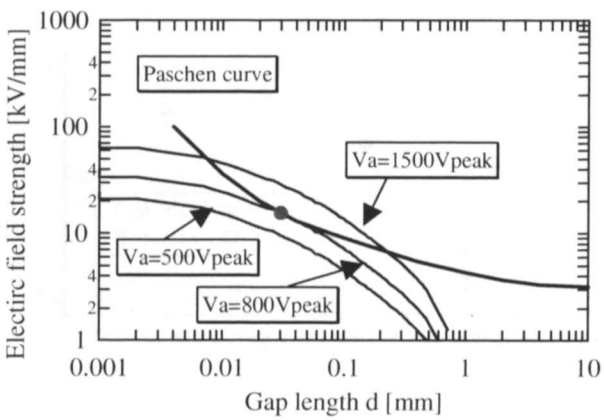


Figure 8: Electric field strength as a function of a gap length.

Fig. 7. Figure 8 shows the electric field distribution along the surface of the twisted pair sample as a function of the gap length d for Va=500Vpeak, 800Vpeak, 1500Vpeak, respectively. Calculated breakdown strength in air according to the Paschen's law [5-6] is also shown in Fig. 8. The electric field distribution along the surface of the twisted pair firstly came in contact with the Paschen curve at d=0.03mm for Va=800Vpeak, which corresponds to the theoretical PDIV under ac voltage application and agrees well with the measured PDIV of 816Vpeak.

The comparison of PDIV between ac and surge voltage conditions is shown in Fig. 9. In the case of ac voltage application, PDIV is almost the same for Samples A and B. On the other hand, in the case of surge voltage condition, PDIV with 60 pps repetition was lower than those with 6 pps and for the single shot. This suggested that the insulation performance of the twisted pair sample would be deteriorated under the higher repetition of surge voltage application. The average value of PDIV under surge voltage condition divided by PDIV under ac voltage application is 1.6~1.8 in the case of Sample A, and 2.3~2.7 in the case of Sample B. The higher PDIV under surge voltage condition than that under ac voltage application may be attributed to the lack of initial electron in the localized higher electric field region of the twisted pair sample. In the case of surge voltage application, the lack of initial electron would be significant because of the short time voltage application (~100nsec) and the limited stressed volume. The impulse ratio obtained in this experiment would be strongly influenced by the surge wave front and voltage duration etc.

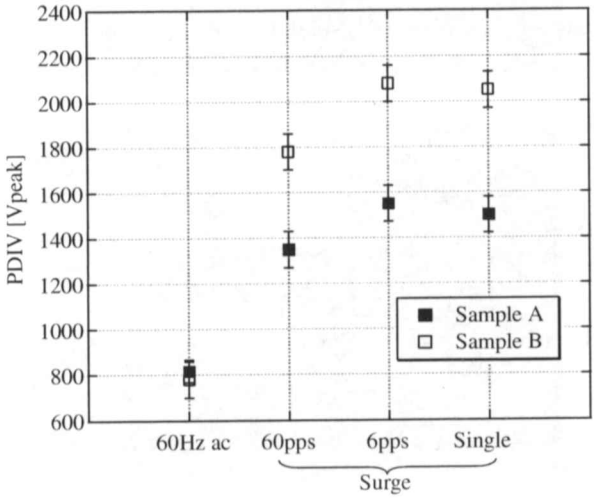


Figure 9: PDIV under ac and surge voltage conditions. (Surge wave front: 20ns).

Conclusions

We investigated the PD characteristics of twisted pair samples for inverter fed-motors coil under ac and surge voltage conditions. The results can be summarized as follows:

(1) PD inception voltage (PDIV) under ac voltage application was measured and verified to agree well with the theoretical value using electric field analysis and Pschen's law.

(2) PDIV under surge voltage condition was measured for different repetition rates; PDIV with 60 pps repetition was lower than those with 6 pps and for the single shot, which suggested that the electrical insulation performance would be influenced by the repetition rate of surge voltage application.

(3) PDIV under surge voltage condition was 1.6~1.8 times and 2.3~2.7 times higher than those under ac voltage application for the used and virgin samples, respectively, which might be attributed to the lack of initial electron in the localized high electric field region. The above obtained impulse ratio would highly be influenced by the applied surge voltage wave front and the time duration.

References

[1] M. Fenger, S. R. Campbell, G. C. Stone: "Some Properties of Partial Discharges Measured During Fast Risetime Voltage Surges", *Insucon 2002,* pp.153-156, 2002

[2] M. Kaufhold, "Failure Mechanism of the Interturn Insulation of Low Voltage Electric Machines Fed by Pulse Controlled Inverter," CEIDP, pp 254-257, 1995

[3] M. Melfi, J. Sung, S. Bell, G. L. Skibinski; "Effect of Surge Voltage Risetime on the Insulation of Low-Voltage Machine Fed by PWM Converters" IEEE Trans on IA, pp.766-775, vol.34, 1998..

[4] K. Kimura, S. Itaya, S. Ushirone, M. Hikita and W. Bito: "Discharge Condition and Surface Charge Distribution under Repetitive Bipolar Impulse", 7th ICPADM, pp.1061-1064, 2003

[5] T. W. Dakin, G. Luxa, G. Oppermann, J. Virgreux, G. Wind and H. WInkelkemper: "Breakdown of Gases in Uniform Fields. Paschen Curves for Nitrogen, Air and Sulfur Hexafluoride", Electra, No. 32, 1974

[6] J. M. Meek and J. D. Craggs: "Electrical Breakdown of Gases", John Wiley & Sons , 1978.

Author address: Hitoshi Okubo, Center for Integrated Research in Science and Engineering, Nagoya University, Furo-Cho, Chikusa-ku, Nagoya, 464-8603, Japan.
E-mail: okubo@nuee.nagoya-u.ac.jp