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Partial Discharge Inception Characteristics Influenced by Stressed Wire Length of Inverter-Fed Motor

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Abstract: Surge voltages with the rise time of several tens or hundreds of nano-second in inverter-fed motor coils may cause partial discharge (PD) and degradation of electrical insulation performance. We investigated the PD characteristics of inverter-fed motor coil samples with different lengths of enamel-coated wire under surge and ac voltage conditions. Experimental results revealed that PD inception voltage (PDIV) decreased with the increase in the wire length, which was evaluated in terms of the stressed wire contact length, i.e. size effect. We proposed a regression line for the size effect on PDIV for the electrical insulation design of inverter-fed motor coils.

Introduction

With the increase in the demand for environmentally-benign hybrid vehicles, the operating voltage of inverter-fed motors is being enhanced for the higher performance and the higher output power. The inverter-fed motors are exposed to transient surge voltages composed of bipolar pulses with the rise time of nano-second order. Such surge voltages may cause partial discharge (PD) in the electrical insulation system of the inverter-fed motor coils and result in the degradation of electrical insulation performance [1][2]. Therefore, rational electrical insulation design and evaluation techniques for the inverter-fed motors are strongly required, which should take account of the PD mechanisms under surge voltage condition [3][4].

From the above viewpoints, we have been investigating the PD characteristics of inverter-fed motor coil samples under surge and ac voltage conditions [5]. In this paper, we measured the PD inception voltages (PDIV) of inverter-fed motor coil samples with different lengths of enamel-coated wire under surge voltage condition. Together with the dependence of PDIV on the repetition rate and polarity reversal of the applied surge voltage, PD inception mechanisms under surge voltage condition were discussed and compared with those under ac voltage condition.

Experimental setup

Test samples used in this experiment are shown in Fig. 1: (a) twisted pair samples and (b) coil samples. Each sample was composed of two enamel-coated copper wires. The conductor diameter is 0.845 mm, the coated thickness is 0.03 mm and the dielectric constant is 3.85. The twisted pitch and length of the twisted pair samples are 7 mm and 130 mm, respectively. In the coil samples, two enamel-coated copper wires were wound in parallel for 1 layer around a PMMA cylinder with the diameter of 50 mm. The turn numbers of the coil samples are 1, 5, 10, 20, 40, 100 and 200, respectively. Figure 2 shows the relationship between the turn number and the wire contact length of the coil samples. The wire contact length of the coil samples is confirmed to be proportional to the turn number.

Figure 3 shows the experimental setup for the measurement of PD characteristics of the test samples. One of the copper wires was grounded, and surge or ac high voltage was applied to the other wire. A capacitor was connected in parallel with the test samples. The capacitance C_0 was complementary to the test sample; the total capacitance C_{Total} of the test sample and the parallel capacitor was 6,000 pF or 10,000 pF. Using the above complementary capacitor, the rise time t_f of the applied surge voltage could be controlled to be within 450 ns to 600 ns (average t_f=520 ns) for C_{Total}=6,000 pF or within 700 ns to 900 ns (average t_f=830 ns) for C_{Total}=10,000 pF. The repetition rate of the surge voltage was within 6 pps to 60 pps. Single shot, positive or negative shot of the surge voltage were also possible. The time width of the single shot was 1 μs. The frequency of ac voltage was 60 Hz.

PDIV of the test samples was measured by the detection of PD light intensity signal using a photo multiplier tube (P.M.T.) under both surge and ac voltage conditions. PD light emission images were also 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 signal under ac voltage condition through high frequency CT (1GHz); CT1 for the test sample and CT2 for the complementary capacitor.

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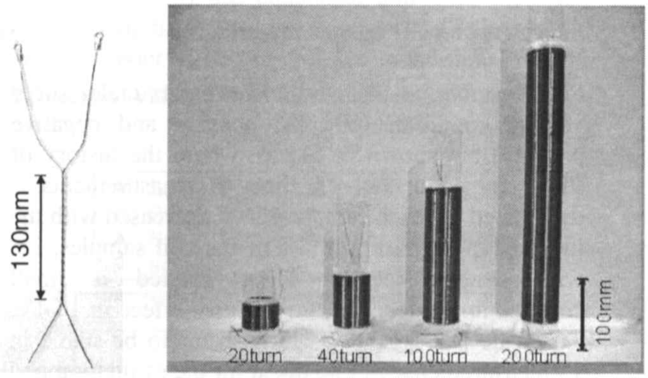


(a) Twisted pair (b) Coil samples

Figure 1: Test samples

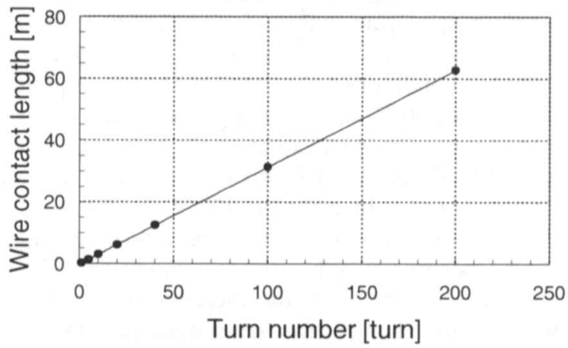


Figure 2: Relationship between turn number and wire contact length of coil samples.

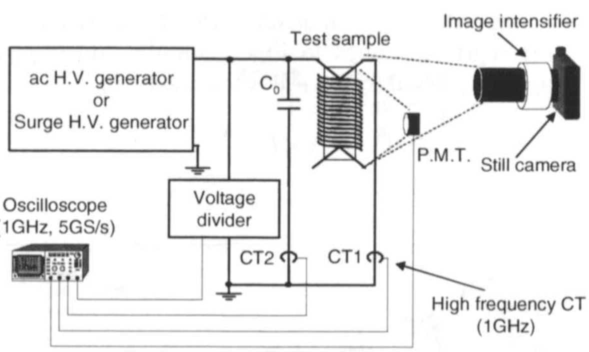
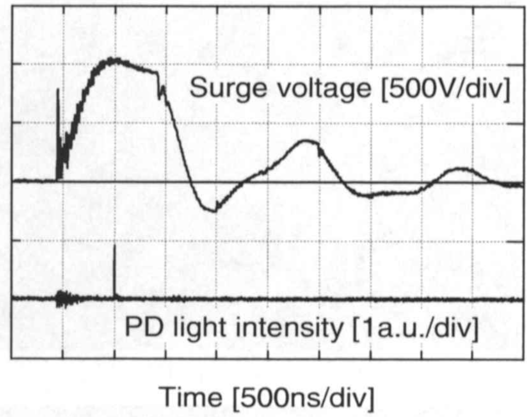


Figure 3: Experimental setup.

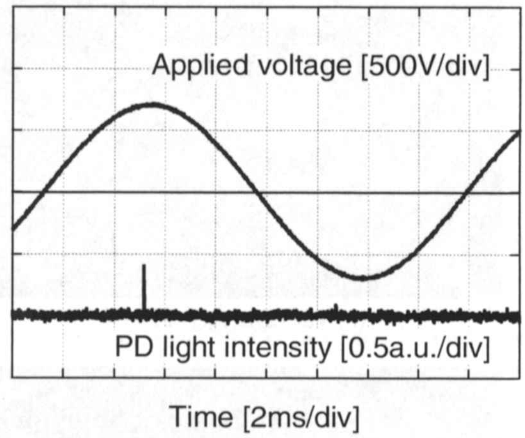
Experimental results

PD inception characteristics

Figure 4 shows typical PD light intensity and applied voltage waveforms at PD inception under (a) surge voltage condition (t_f=520 ns, 60 pps, positive polarity) and (b) ac voltage condition (60Hz), respectively, for the 100 turn coil sample. The surge PDIV was 1078 V_{peak} and the ac PDIV was 716 V_{peak},



(a) Surge voltage (t_f=520 ns, 60 pps, positive polarity)

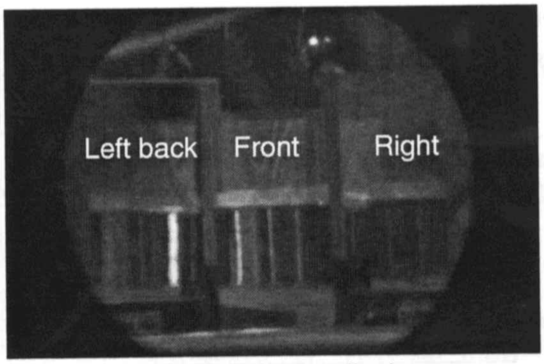


(b) ac voltage (60 Hz)

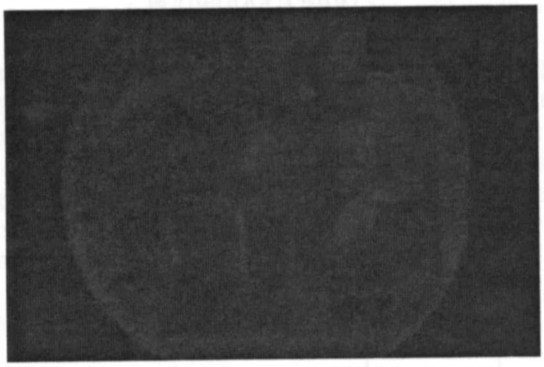
Figure 4: PD light intensity and applied voltage waveforms (100 turn coil sample)

respectively. In both figures, PD signal was detected at around the peak of the applied voltage waveform.

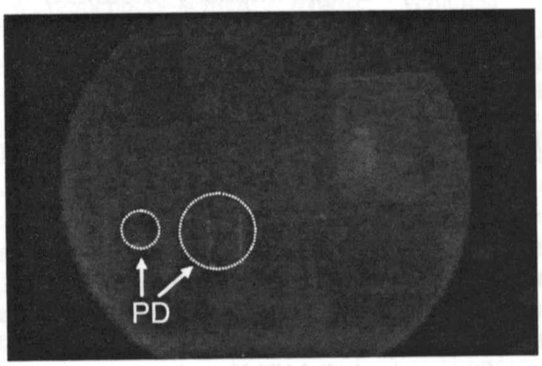
Figure 5 shows typical PD light emission images at the applied voltage Va of (b) 1276 V_{peak} (PDIV), (c) 1300 V_{peak}, and (d) 1400 V_{peak}, respectively, under surge voltage condition (60 pps, t_f=520 ns, positive polarity) for the 20 turn coil sample. Using mirrors at left and right back of the coil sample, as shown in Fig. 5 (a), PD light emission image at any location of the sample could be observed. PD light emission image was not observed at PDIV in Fig. 5 (b), whereas was successfully observed both in front of the sample and at the left back of the sample in Fig. 5 (c) at Va=1300 V_{peak}. With the increase in Va, the PD light emission image became clear and was found to be spread over the whole surface of the coil sample in Fig. 5 (d). Thus, PD phenomena of inverter-fed motor coil samples under surge voltage condition could be verified, located and visualized as a light emission image by the optical PD measurement technique.



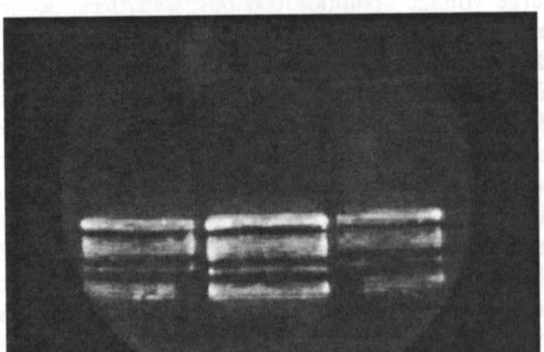
(a) Before voltage application



(b) Va=1276 V_{peak} (PDIV)



(c) Va=1300 V_{peak}



(d) Va=1400 V_{peak}

Figure 5: Surge PD light emission images
(20 turn coil sample, t_f=520 ns, 60 pps, positive polarity)

Size effect on PD inception voltage

PDIV of twisted pair and coil samples under surge voltage condition (60 pps, positive and negative polarity) are shown in Fig. 6, where the history of PDIV for sequential 15 shots of measurements is designated for each sample. PDIV decreased with the increase in the turn number of the coil samples, i.e. wire contact length. There existed a small conditioning effect and no polarity effect in PDIV. Then, the last 5 PDIVs which seems to be stable in 15 measurements will be taken for the evaluation and analysis of PDIV, hereinafter.

Figure 7 shows surge PDIV for (a) t_f=520 ns, (b) t_f=830 ns and ac PDIV as a function of wire contact length. Each figure represents the average value and the standard deviation of PDIV under different voltage conditions. In the case of repetitive positive-negative surge voltage condition, the time interval of surge application was 5 seconds. In each case, PDIV decreased with the increase in the wire contact length. For example, PDIV of 100 turn coil decreased into 85 % of PDIV of 1 turn coil under surge (positive, single) voltage condition. This is attributed to that, with the increase in the stressed wire contact length, the generation probability of initial electrons and/or the weak points on electrical insulation would be increased, which can be regarded as the size effect on PDIV.

In order to quantitatively evaluate the size effect, the regression lines in Fig. 7 for the coil samples were expressed by the following equation:

$$\mathrm{PDIV} = \mathrm{A} \times \ell^{-1/\mathrm{B}}$$

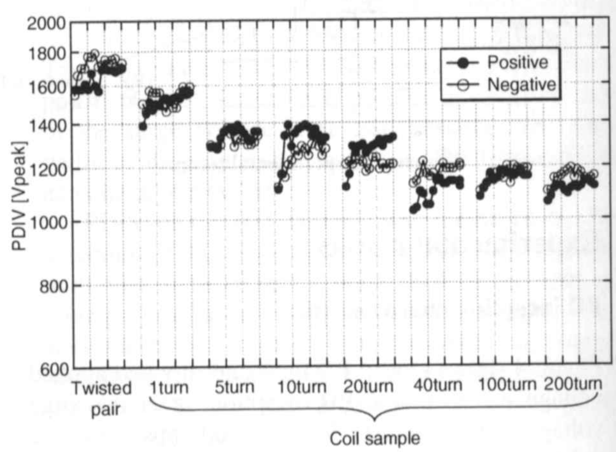
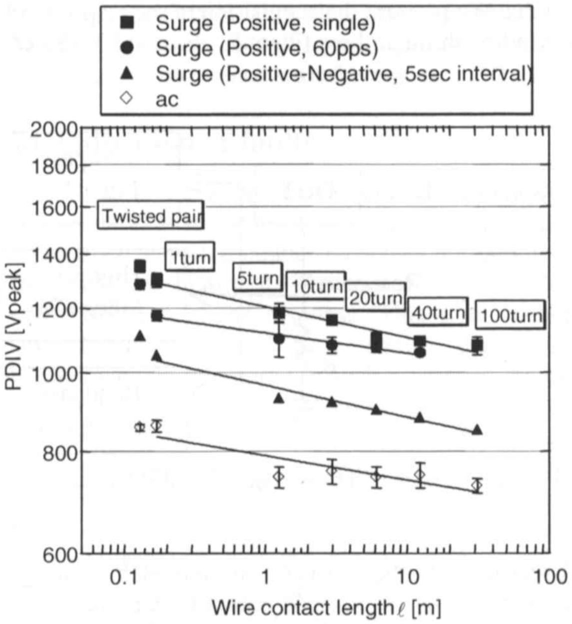
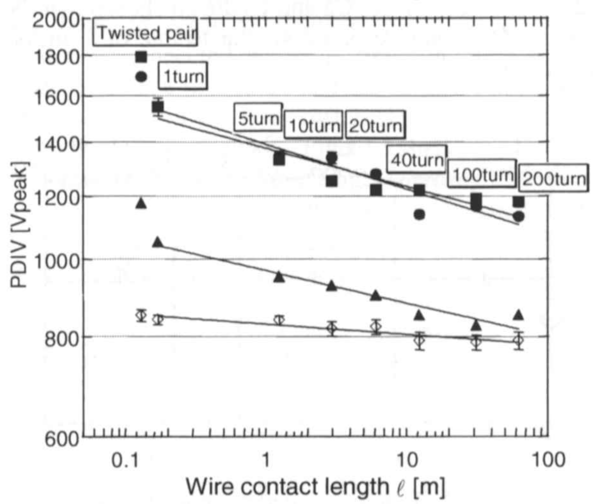


Figure 6: Surge PDIV for different test samples
(t_f=520 ns, 60 pps)

where A and B are constants, and ℓ is the wire contact length. Table 1 summarizes the values of A and B under different voltage conditions. PDIV decreased with the increase in ℓ, repetition rate of



(a) t_f=520 ns (C_{Total}=6,000 pF)



(b) t_f=830 ns (C_{Total}=10,000 pF)

Figure 7: PDIV as a function of wire contact length

Table 1: Constant A and B under different voltage conditions

C_{total}	t_f=520ns		t_f=830ns	
	A	B	A	B
Surge (Positive, single)	1205	26.5	1375	21.0
Surge (Positive, 60pps)	1118	40.5	1392	17.8
Surge (Positive-Negative)	965	25.4	967	24.5
ac	790	33.3	829	77.9

surge voltage application and polarity reversal. The surge PDIV (60 pps) normalized by ac PDIV (60 Hz), referred to as the impulse ratio, was 1.4 to 2.0. The impulse ratio for t_f=830 ns tended to decrease with the increase in ℓ; which means that the generation probability of initial electrons would increase under the longer contact length of stressed wire or the larger volume of wedge-shaped gap between the enamel-coated copper conductor.

In addition, PDIV for t_f=520 ns was lower than that for t_f=830 ns. Thus, PDIV would be influenced not only by the rise time of the applied surge voltage, but also by the other factors on surge voltage waveform such as surge build-up factor. Furthermore, the surge PDIV at the polarity reversal was lower than those for single shot or repetitive shot with an identical polarity. This may suggest the possibility of charge generation at the applied surge voltage lower than PDIV.

Conclusions

PD inception characteristics of twisted pair and coil samples under surge and ac voltage conditions were obtained and quantitatively evaluated. Experimental results revealed that PDIV decreased with the increase in the wire length, which was evaluated in terms of the stressed wire contact length, i.e. size effect. We proposed a regression line for the size effect on PDIV for the electrical insulation design of inverter-fed motor coils.

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