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Partial Discharge Inception Characteristic and Charge Behavior for Magnet Wire under Repetitive Inverter Surge Voltage Condition

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Abstract: In this paper, we discussed partial discharge (PD) inception characteristics and mechanisms of magnet wires for inverter-fed motor under repetitive surge voltage application. Experimental results revealed the relationship between PD inception voltage (PDIV) and parameters of applied surge voltage waveform. The relationship between PD pulses and repetitive surge voltage pulses was also investigated. PD generation mechanisms were discussed from the view point of charge behavior in the wedge-shaped air gap and on the enamel surface.

INTRODUCTION

Inverter surge voltage is an emerging problem for the reliable operation of inverter-fed motors associated with recent progress in power electronics, which is characterized by the short rise time of ns order and the high repetition rate of kHz order [1]-[3]. Partial discharge (PD) phenomena of magnet wires are decisive for the electrical insulation of inverter-fed motors, however the PD characteristics and their physical mechanisms have not yet been understood.

From the above background, we have been investigating the PD inception, propagation and breakdown characteristics and mechanisms of magnet wire for inverter-fed motors under inverter surge voltage application [4][5]. In this paper, we focused on PD inception characteristics of twisted pair samples under repetitive surge voltage application. Firstly, we measured the relationship between PDIV and applied surge voltage waveform parameters such as repetition rate, pulse width, pulse interval and so on. Secondly, we statistically investigated the relationship between PD pulses and repetitive surge voltage pulses in terms of PD inception timing, and discussed the PD generation mechanisms in consideration of the generation probability of initial electrons in wedge-shaped air gap and the surface charging on enameled wires of the twisted pair samples.

EXPERIMENTAL SETUP

We used twisted pair samples which consists of two enamel coating wires with the outer diameter of 0.893 mm and the coating thickness of class 0.

Figure 1 shows the experimental setup for the measurement of PD characteristics of the test sample. The inverter surge 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; in this paper, the rise time t_r = 120 ns, repetition rate f = 0 (single shot) ~ 10000 pps, cycle t = 100 ~ 1000 μs, pulse width τ = 10 ~ 495 μs, pulse interval τ_0 = 5 ~ 990 μs, Duty ratio D = τ/t= 2 ~ 99 %, and the polarity was unipolar and bipolar. PD signal was detected by photo-multiplier tube (PMT) and PDIV was defined as the peak value of the applied surge voltage when PMT detected PD signal for the first time.

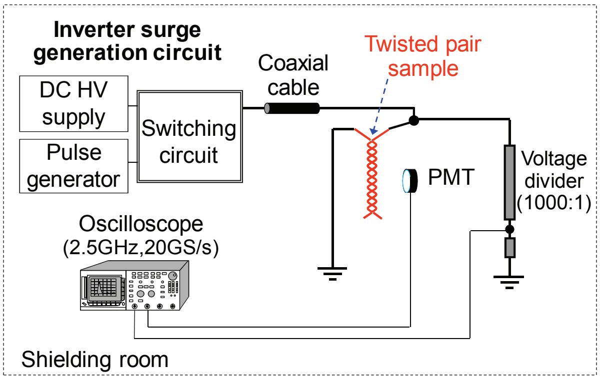


Fig.1. Experimental setup.

EXPERIMENTAL RESULT AND DISCUSSION

PD inception characteristics under different surge parameters

In order to reveal the relationship between PDIV and applied surge voltage waveforms, two experiments were conducted. Firstly, we fixed τ = 10 μs and changed f from 0 to 10000 pps, i.e. pulse interval τ_0 was 90 μs ~ ∞. Table 1 shows the parameters of applied surge voltage waveform and Fig. 2 shows typical applied surge voltage (f = 5000 pps) and PD light intensity waveforms. PD was generated at the rise time and the fall time of surge voltage.

Secondly, PDIV was measured under the fixed t = 500 μs and f = 2000 pps, where τ was changed from 10 to

Table 1. Parameters of applied surge voltage waveforms (τ=10μs fixed).

Repetition rate f	Cycle t	Duty ratio D	Pulse width τ	Pulse interval τ_0	Rise time t_r	Polarity
single			10μs		120ns	negative
1000pps	1000μs	1%		990μs		
2000pps	500μs	2%		490μs		
5000pps	200μs	5%		190μs		
10000pps	100μs	10%		90μs		

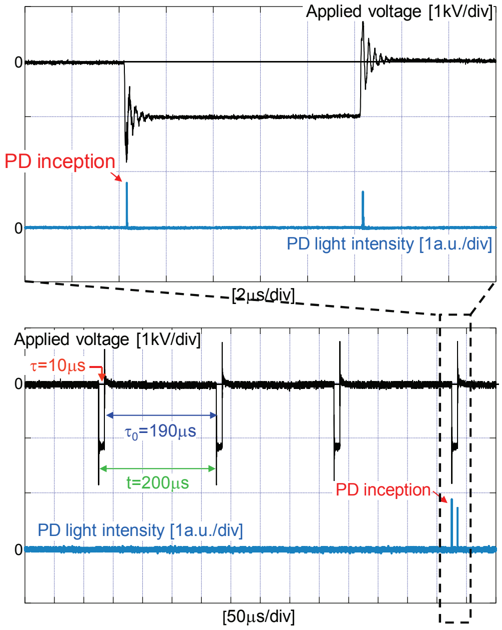
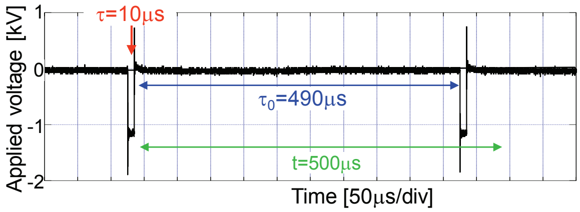


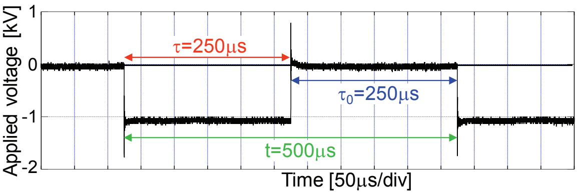
Fig.2. Applied surge voltage and PD intensity waveforms (τ=10μs, f=5000pps, D=5%).

Table 2. Parameters of applied surge voltage waveforms (t=500μs, f=2000pps fixed).

Repetition rate f	Cycle t	Duty ratio D	Pulse width τ	Pulse interval τ_0	Rise time t_r	Polarity
2000pps	500μs	2%	10μs	490μs	120ns	negative
		50%	250μs	250μs		
		99%	495μs	5μs		



(a) τ=10μs (D=2%)



(b) τ=250μs (D=50%)

Fig.3. Applied surge voltage waveforms (t=500μs, f=2000pps).

495 μs, i.e. pulse interval τ_0 was 5 ~ 490 μs. Table 2 shows the parameters of applied surge voltage waveform and Fig. 3 shows examples of the applied voltage waveforms. In both experiments, the polarity of applied surge voltage was negative and unipolar.

Figure 4 shows the relationship between PDIV and τ_0 (PDIV–τ_0 characteristics) from the above two experiments. PDIV under repetitive surge voltage depended mainly on τ_0 and decreased with the decrease in τ_0. PDIV was also depended mutually on τ at $\tau_0 < 300$ μs. The PDIV-τ_0 characteristics were discussed with a charge behavior model in wedge-shaped air gap of the twisted pair sample and the generation probability of an initial electron, as shown in Fig. 5. Here, the first PD was assumed to be generated at nth pulse of the repetitive surge voltage.

(1) Before the peak of (n-1)th pulse
Though the applied voltage is nearly equal to PDIV ($V_a \cong$ PDIV), PD does not occur because of the lack of initial electron in the wedge-shaped air gap.

(2) In the plateau duration of (n-1)th pulse
Since V_a is smaller than PDIV, PD does not occur. At the same time, initial electron sources such as negative ions and electrons can be generated incidentally, or drifted by applied electrical field, in the wedge-shaped air gap.

(3) In the pulse interval between (n-1)th and nth pulses
Most initial electron sources are diffused from the wedge-shaped air gap.

(4) At nth pulse
Because V_a is nearly equal to PDIV at the rise time of nth pulse, PD can be triggered by a residual initial electron source in the wedge-shaped air gap.

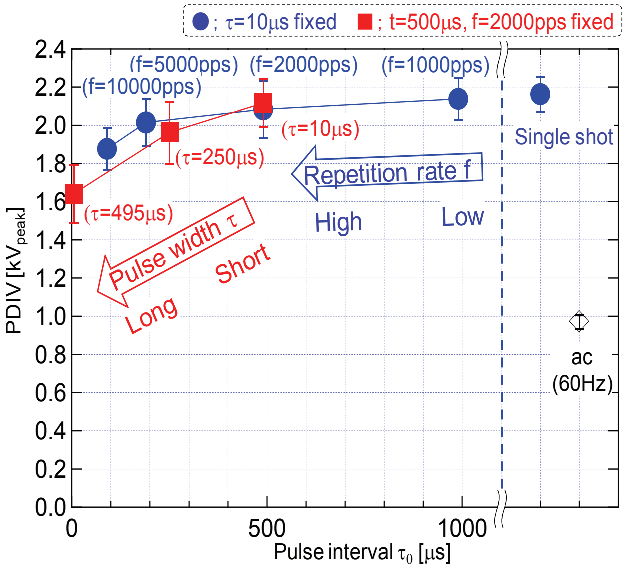


Fig.4. PDIV as a function of pulse interval (PDIV – τ_0 characteristics).

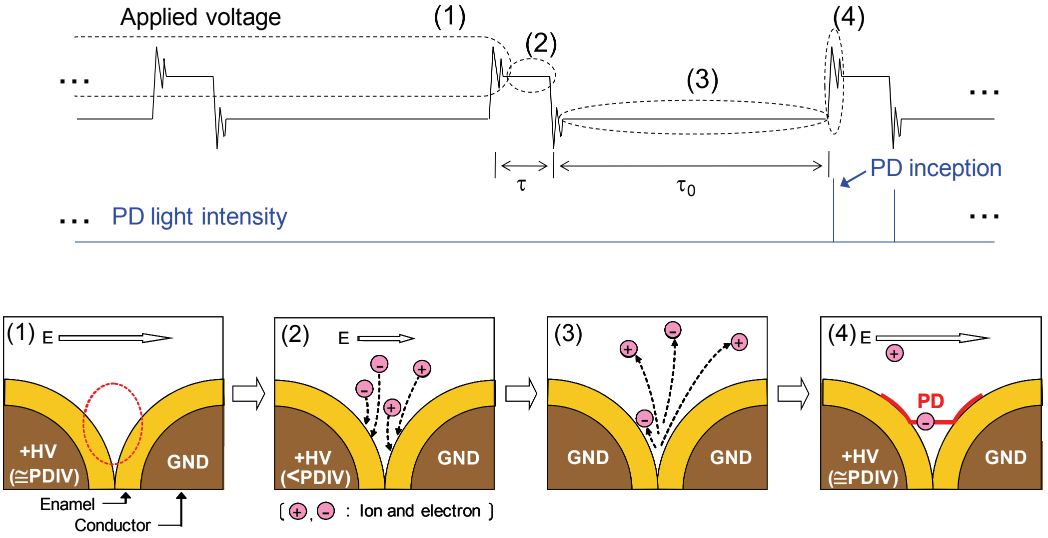


Fig.5. Charge behavior model in wedge-shaped air gap.

According to the above charge behavior model, PDIV would decrease with the decrease in τ_0 because of the shorter diffusion distance of initial electron sources, i.e. the enhancement of existence probability of initial electron sources. On the other hand, PDIV would also decrease at the longer τ, where the generation probability of initial electrons could be high. Therefore, the charge behavior model in Fig. 5 is consistent with the experimental results in Fig. 4.

Relationship between PD pulses and repetitive surge voltage pulses

PD inception characteristics were also investigated under bipolar repetitive surge voltage condition, in order to discuss the charge behavior at the polarity reversal. Figure 6 shows an example of the bipolar repetitive surge voltage and PD generation. The surge voltage has the fixed parameters: t_r = 120 ns, τ = 495 μs, τ_0 = 5 μs, D =99 %, t = 500 μs, f = 2000 pps, and the repetition number of surge voltage is 10 in each polarity. The first PD was generated at the 1st surge pulse after the polarity reversal in Fig. 6.

Figure 7 shows the frequency distribution of PD inception timing. The probability of PD inception at the 1st surge pulse after the polarity reversal was highest (40 %), and those at the subsequent surge pulses were almost equal (5~9 %). This result suggests that PD under bipolar repetitive surge voltage is not always generated at the polarity reversal, but relatively often initiated at the subsequent surge pulses, which supports the PD inception mechanisms depending on the generation probability of initial electrons.

After the PD inception, as was shown in Fig. 6, PD was generated at each polarity reversal. Statistical measurements revealed that the PD generation probability at the 1st polarity reversal after PD inception was 94 %, those at the 2nd and 3rd ones were 56 % and 47 %, respectively. This result can be interpreted by surface charging on the enameled wire caused by the first PD inception.

Figure 8 shows the PD generation mechanism based on surface charging. Firstly, at the applied surge voltage of $V_a \cong$ PDIV, the wedge-shaped air gap is exposed to high electric field (E_a) nearly equal to PD inception electric field (PDIE). Similarly as the PD inception mechanism in Fig. 5, the first PD can occur at a certain

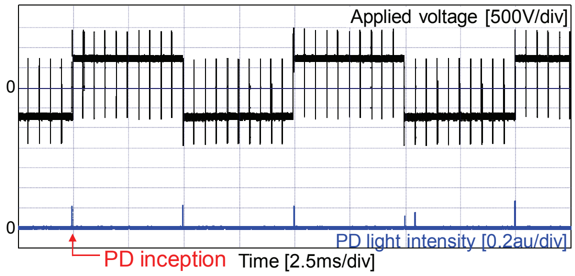


Fig. 6. Bipolar surge voltage and PD light intensity waveforms (t=500μs, D=99%).

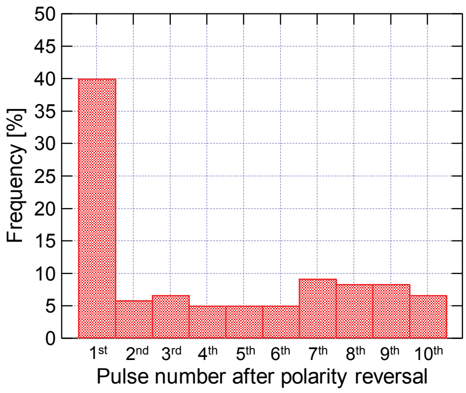


Fig. 7. Frequency distribution of PD inception timing

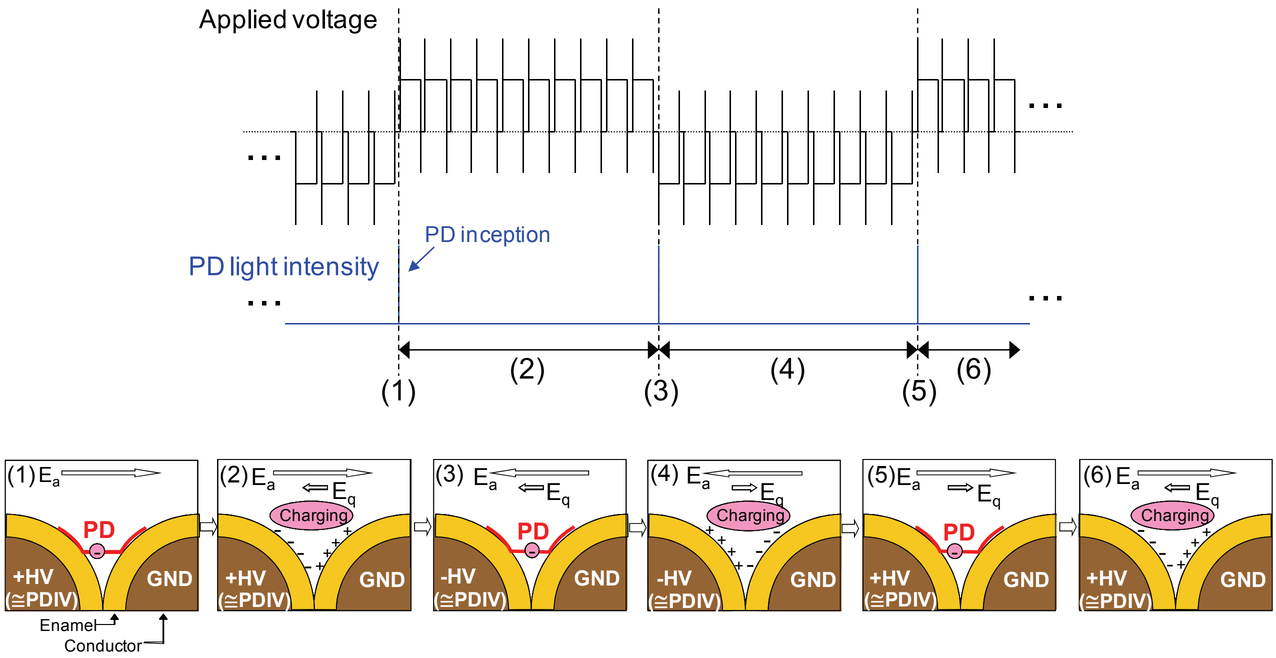


Fig.8. PD generation mechanism in consideration of surface charging

surge pulse where an initial electron was generated, as shown in Fig. 8 (1). The first PD induces the surface charging, as shown in Fig. 8 (2), and the electric field (E_q) due to the surface charging with the opposite polarity to E_a is generated, which reduces the PD generation probability during unipolar repetitive surge voltage. At the polarity reversal in Fig. 8 (3), E_a is emphasized by E_q, leading to the PD generation. Afterwards, PD generation and surface charging are repeated at the polarity reversal, as shown in Fig. 8 (4)~(6).

CONCLUSIONS

PD inception characteristics of magnet wire under repetitive surge pulses were obtained and discussed in terms of charge behavior in wedge-shaped air gap. The main results can be summarized as follows:

(1) PDIV under unipolar repetitive surge voltage depended mainly on τ_0 (pulse interval) and mutually on τ (pulse width) at $\tau_0 < 300$ µs.
(2) PDIV would decrease at the shorter τ_0 and the longer τ, due to the enhancement of existence probability of initial electron sources.
(3) PD under bipolar repetitive surge voltage is not always generated at the polarity reversal, but relatively often initiated at the subsequent surge pulses.
(4) The surface charging on enameled wire caused by the first PD could generate PD at the polarity reversal of applied surge voltage.

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