Lifetime Characteristics of Nanocomposite Enameled Wire Under Surge Voltage Application

Key Words: nanofiller, enameled wire, repetitive surges, partial discharge (PD), time to breakdown

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V-N characteristics exhibited longer times to breakdown for nanocomposite enameled wires and the PD resistance increased with increasing nanofiller concentration.

Introduction

With the growing market of inverter-fed motors in industrial applications, the rated capacity, and hence the rated voltage, are going to increase. Inverter-fed motors are characterized by adjustable speed drives using power electronics devices such as IGBT (insulated gate bipolar transistor), so that the magnet wires of inverter-fed motors are exposed to repetitive surge voltages with short rise-times of several tens or hundreds of nanoseconds, referred to as inverter surges. The inverter surge voltages give rise to novel and critical problems for the electrical insulation design and reliability even for low-voltage motor windings [1]–[3].

The inverter surge voltages may cause PD with an increase in the operating voltage in inverter-fed motors. Therefore, PD characteristics of magnet wires become crucial to determine the electrical insulation reliability and breakdown lifetime of inverter-fed motors. One technical countermeasure to improve the electrical insulation performance of inverter-fed motors is to increase the breakdown lifetime of magnet wires, even under PD exposure, i.e., the development of PD-resistant enameled wires.

PD-resistant enameled wires filled with inorganic materials (e.g., metal oxides based on Si, Ti, Al, Cr, or Zr) have been developed to have longer breakdown lifetimes than those of conventional enameled wires. Microcomposites such as SiO_2, TiO_2, Al_2O_3 [4] and mica-based wires [5] contributed to the PD-resistant enameled wires. Recently, nanocomposites such as fumed silica [6], layered silicate [7], TiO_2 [8] are expected to be used for PD-resistant enameled wires as one of the potentially wide applications of nanotechnology [9]. The lifetime characteristics of nanocomposite enameled wires have been experimentally confirmed [10], [11]. However, their physical mechanisms of longer breakdown lifetime have not yet been clarified, especially under surge-voltage application.

From the above background, we have been investigating the PD inception, propagation, and breakdown (BD) characteristics of nanocomposite and conventional enameled wires under surge-voltage application [7], [12], [13]. In this article, we focus on the BD lifetime characteristics of nanocomposite enameled wires under repetitive surge-voltage application. First, we measured the relationship between the surge-breakdown voltage, V, and the total number of PD generated, N, (V-N characteristics) under surge-voltage application, and verified the longer BD lifetime of nanocomposite enameled wires as a function of nanofiller content. Second, we investigated the time transition of the remaining thickness of enameled layers from the viewpoint of the V-N characteristics, and we discussed the mechanisms of longer BD lifetime for the nanocomposite enameled wires.

Experimental Setup

Figure 1 shows the experimental setup for the measurement of V-N characteristics of the twisted-pair samples. The inverter surge-generation circuit consists of direct current (DC) high voltage

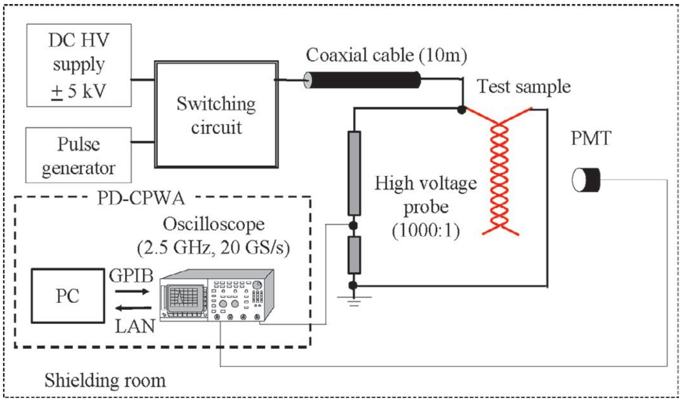

Figure 1. Experimental setup.

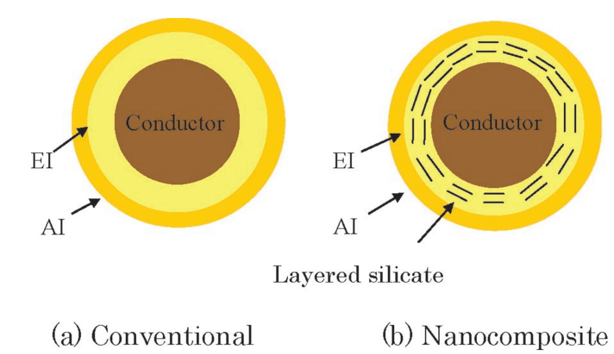

Figure 3. Cross section of test samples.

supply, high-voltage semiconductor switch, pulse generator, and coaxial cable. This circuit can generate damped oscillating surge voltages with different surge parameters such as polarity, peak value, rise-time, repetition rate, and pulse width. In this article, the polarity of the applied surge voltage was unipolar, the peak value, V, was 2 kV_{peak} – 4 kV_{peak}, the rise-time, t_r, was 120 ns, the repetition rate, f, was 10,000 pps, and the pulse width was 10 μs, respectively. In order to discuss the time transition of the remaining thickness of the enameled layers, more simplified point contact samples as shown in Figure 2(b) were used, where V was set at 1.5 times the PD inception voltage (PDIV) and f was 5000 pps.

Nanocomposite enameled wires were composed of an inner polyesterimide (EI) layer with layered silicate nanocomposite and the outer polyamideimide (AI) layer, as shown in Figure 3, the preparation of which is given in [11]. The nanofiller concentration, X, was 0 wt% – 5 wt%, the thickness of the enamel coating was 15 μm for the EI layer, 5 μm for the AI layer, and 20 μm in total.

PD signals were detected by PD light intensity using a photo multiplier tube (PMT). 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 [14]. PD-CPWA is a PD detection/analysis system developed for the purpose of pursuing the transition of PD current pulse waveforms. It was applied to the PD light intensity waveforms by the PMT in this article. After the repetitive surge-voltage application for fixed time duration, the total number of PD generated, N, was evaluated by the PD-CPWA. The surface condition of the point contact samples was analyzed by a scanning electron microscope (SEM) and a digital microscope. The remaining enamel thickness and its time variation were evaluated with a resolution of 1 μm. In addition, the temperature on the enameled wires and its time variation under repetitive surge-voltages were measured by an infrared thermograph. All experiments were done in atmospheric air at room temperature.

Experimental Results and Discussion

A. V-N Characteristics

PD characteristics from PD inception to BD were measured using twisted pair samples under repetitive surge-voltage application. Figure 4 shows typical applied-voltage and PD light-intensity waveforms. Within the experimental conditions in this article, PD always was generated twice per single surge-voltage application, i.e., at each rise-time and fall-time of the surge-voltage waveform, and finally resulted in BD. PD at the fall-time of the surge voltage was attributed to surface charging on the enameled wire caused by PD during the rise-time of the surge voltage [15]. Figure 5 shows the time variations of the PD light intensity and

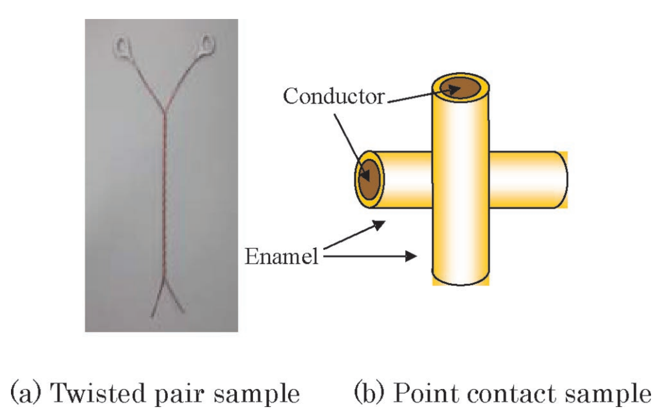

Figure 2. Structure of test samples.

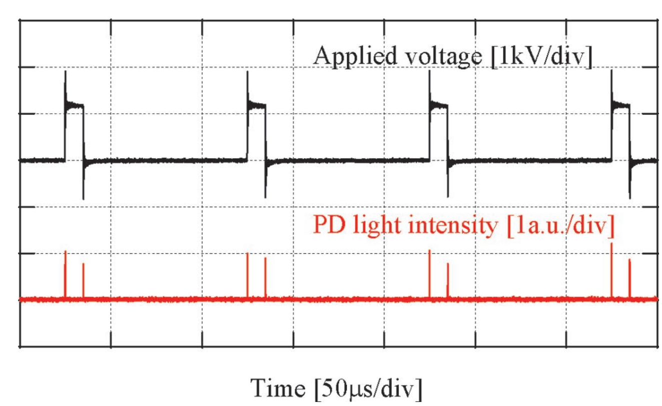

Figure 4. Applied voltage and PD light intensity waveforms. (Twisted pair sample, V=2 kV_{peak}, f=10000 pps).

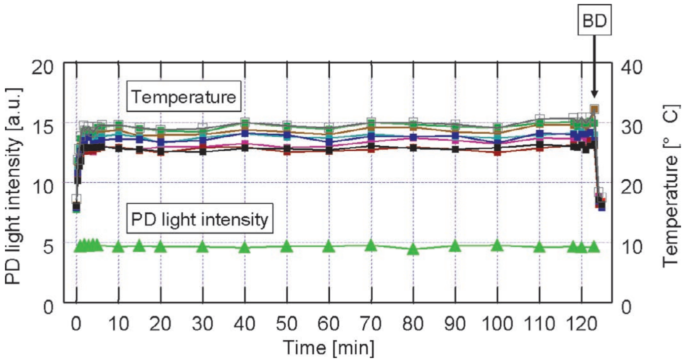

Figure 5. Time variation of PD light intensity and temperatures on a conventional enameled wire from PD inception to BD under the repetitive surge voltage. (Twisted pair sample, V=3 kV$_{peak}$, f=1000 pps).

temperatures at different points on a conventional enameled wire from PD inception to BD under the repetitive-surge voltage, V, of 3 kV$_{peak}$ and repetition rate of 1000 pps. Both PD light intensity and temperature were almost constant from PD inception to BD, which also was confirmed under the other applied surge-voltage conditions and for nanocomposite enameled wires.

Figure 6 shows V-N characteristics under repetitive-surge voltage application, where N is the total number of PD generated and not the total number of surge voltage application. Each plot in Figure 6 corresponds to the result of one test sample, at which the statistical scatter of N on each regression line is small. Figure 6 shows that the total number of PD generated, N, decreased with increasing applied voltage V. The regression lines were expressed by equation (1) [16]:

$$V = K \times N^{-1/n} \tag{1}$$

where K is constant and n is the life exponent. Figure 7 shows N of nanocomposite enameled wires normalized by N of unfilled

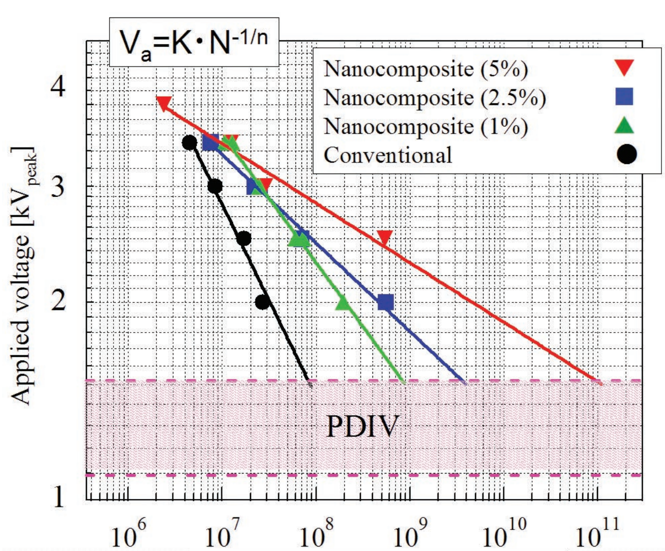

Figure 6. V-N characteristics under repetitive surge voltage application. (Twisted pair sample, f=10000 pps).

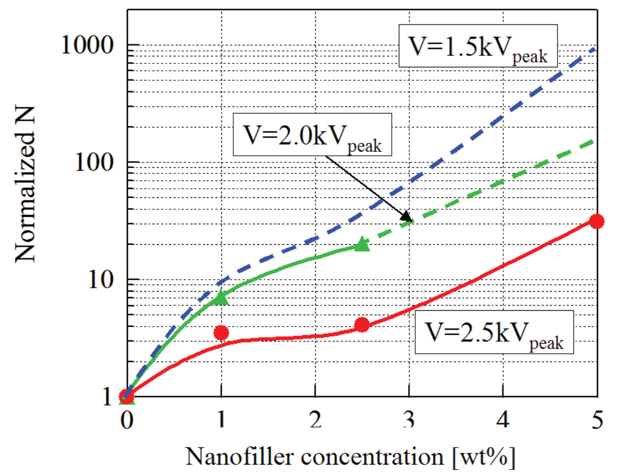

Figure 7. Normalized N as a function of nanofiller concentration. (Twisted pair sample, f=10000 pps).

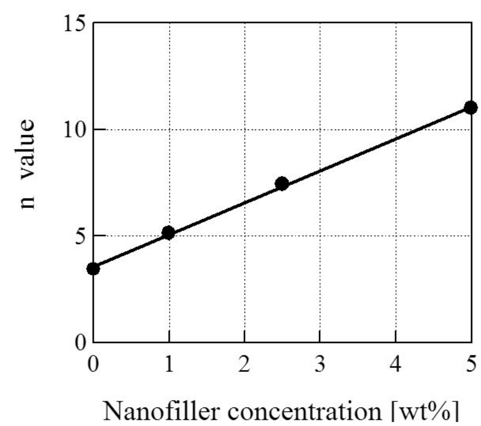

Figure 8. n value as a function of nanofiller concentration. (Twisted pair sample, f=10000 pps).

wires tested under the same conditions as a function of nano-filler concentration, X. The normalized N for 5 wt% was 31 at V = 2.5 kV$_{peak}$ (1.7 PDIV - 2.3 PDIV), and reached as high as 1000 when extrapolated to 1.5 kV$_{peak}$, around the PDIV. Figure 8 shows the value of n as a function of nanofiller concentration. The exponent n increased linearly with increasing nanofiller concentration.

B. Time Variation of Remaining Enamel Thickness

After the repetitive surge-voltage application to point contact samples, the surface condition was analyzed by SEM and digital microscope. Figure 9 shows the SEM images of the cross-section of nanocomposite enameled wires with X = 2.5 wt%, exposed to repetitive 2.9 kV$_{peak}$ surge voltages for 1 hour (N = 36x10[6]). The original thickness (20 µm) of the enamel coating was confirmed, i.e., not deteriorated around the contact point. However, the enameled wire was deteriorated by about 5 µm in depth for about 500 µm along the periphery of the wire on both sides of

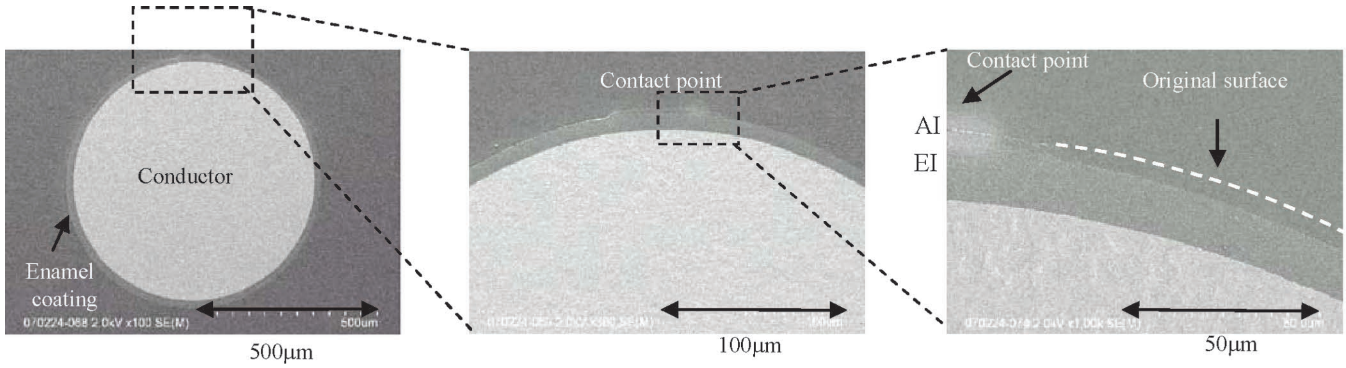

Figure 9. SEM images of nanocomposite enameled wire (X=2.5 wt%) after repetitive surge voltage application with PD. (Point contact sample, V=2.9 kV_{peak} for 1 hour, f=5000 pps, N=36×10^6).

the contact point. The remaining enamel thickness corresponded to the thickness of AI layer in Figure 9, whereas the EI layer with nanocomposites was not deteriorated.

Figure 10 shows the surface condition of nanocomposite enameled wire (X = 1 wt%), observed by the digital microscope after repetitive surge-voltage application with PD for 0.5 hours (N = 18x10^6). The lower image in Figure 10 gives the longitudinal profile of the remaining enamel thickness along the red line in the upper picture. The maximum remaining thickness was 11.0 μm, which means deterioration of the EI layer. The deterioration profile of the nanocomposite enameled wire was relatively wide and flat, compared with that of conventional enameled wire shown in Figure 11 with a similar maximum remaining thickness.

Figure 12 shows the variation of the remaining thickness for nanocomposite (X = 1 wt%) and conventional enameled wires at V = 1.5 PDIV. The remaining enamel thickness was defined as the maximum value in longitudinal profile of each sample after a fixed time duration of repetitive surge-voltage application. In the case of conventional enameled wires, the remaining thickness decreased linearly with the increase in total number of PD generated, N, and the enamel thickness was eventually bridged, i.e. BD. On the other hand, in the case of nanocomposite enameled wires, the remaining enamel thickness decreased gradually in the first stage of deterioration, reached a plateau at about 13 μm, and decreased again finally resulting in BD. In other words, due to the plateau stage of deterioration, the time to BD of nanocomposite enameled wire was about five times longer than that of a conventional one in Figure 12. Figure 13 shows the applied surge voltage dependence of the deterioration process for nanocomposite (X = 5 wt%), enameled wires. The plateau level became deeper with increasing applied surge voltage.

The plateau in deterioration process could be attributed to the contribution of nanofiller in the EI layer, i.e., the resistance to repetitive PD events. The resistance to deterioration in depth could have brought about the expansion of deterioration in the

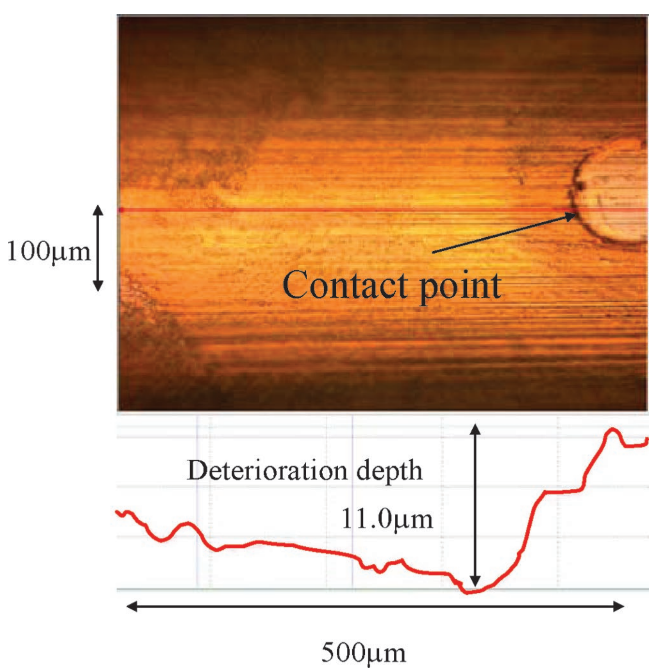

Figure 10. Surface condition of nanocomposite enameled wire (X=1 wt%) after surge voltage application with PD. (Point contact sample, V= 2.9 kV_{peak}, for 0.5 hours, f=5000 pps, N=18×10^6).

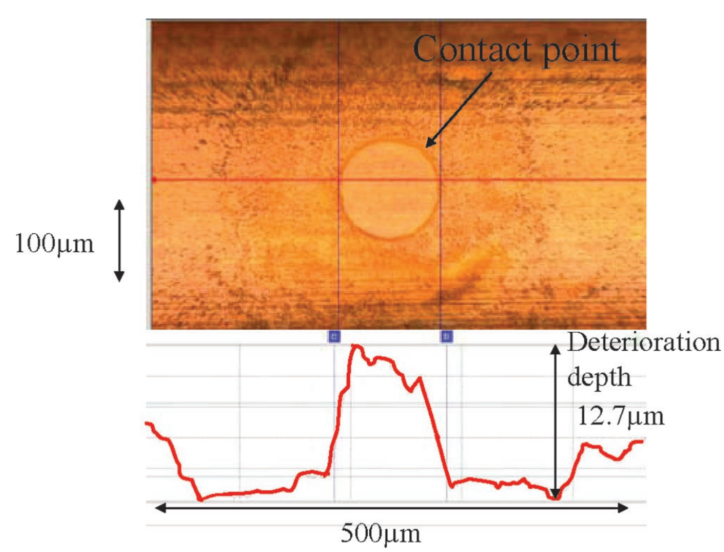

Figure 11. Surface condition of conventional enameled wire after surge voltage application with PD. (Point contact sample, V= 3.4 kV_{peak}, for 0.22 hours, f=5000 pps, N=7.9×10^6).

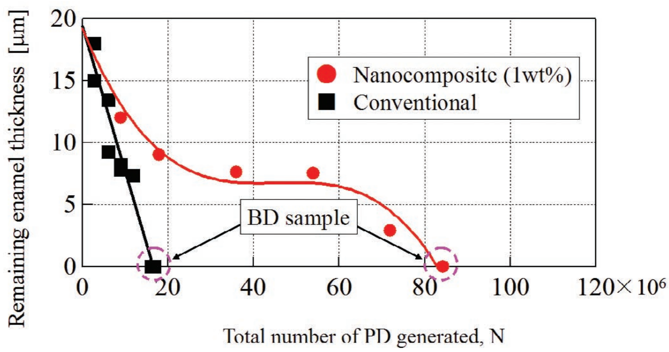

Figure 12. Remaining enamel thickness as a function of total number of PD generated, N. (Point contact sample, f=5000 pps).

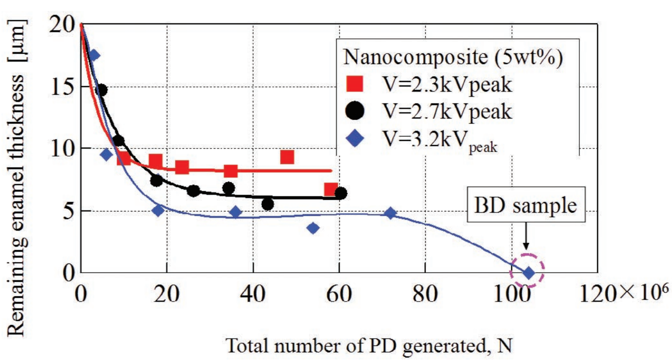

Figure 13. Applied surge voltage dependence of deterioration process for nanocomposite enameled wires. (Point contact sample, f=5000 pps).

peripheral and longitudinal directions of nanocomposite enameled wires, as was shown in Figures 9 and 10.

Conclusions

We obtained and quantitatively evaluated V-N characteristics and the time variation of remaining thickness of nanocomposite enameled wires under repetitive surge-voltage application. The main results can be summarized as follows:

- V-N characteristics exhibited longer times to breakdown for nanocomposite enameled wires, and the PD resistance increased with the increasing nanofiller concentration.
- In the case of conventional enameled wires, the remaining enamel thickness decreased linearly with the time of voltage application, i.e., with increasing total number of PD generated, N, and the enamel thickness was eventually bridged, i.e., BD.
- In the case of nanocomposite enameled wires, the remaining thickness reached a plateau after a gradual deterioration in the first stage, which could contribute to the longer time to BD compared to that of conventional enameled wires.
- The resistance to deterioration in depth could have brought about the expansion of deterioration in the peripheral and longitudinal directions of nanocomposite enameled wires.

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