Partial Discharge Characteristics of Inverter-Fed Motor Coil Samples Under AC and Surge Voltage Conditions[1]

Key Words: Motors, twisted pairs, partial discharges, inception voltage, periodic surge voltages, AC voltage.

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Introduction

Because conventional inverter-fed motors for electric vehicles and hybrid vehicles operate under low-voltage stresses [1]–[4], their electrical insulation performance has not been critical for their basic design. However, the operating voltage of inverter-fed motors is being increased for higher performance, e.g., high power output and compactness, which requires a rational electrical insulation design. Especially, inverter-fed motors utilize power electronic devices, such as IGBTs with high-speed switching ability [3], and are then exposed to transient surge voltage stresses with steep wave fronts as shown in Figure 1. The surge voltage generation is attributed to the difference in surge impedances of the inverter ($Z_{inverter}$), cable (Z_{cable}), and motor (Z_{motor}). Z_{motor} for a 20- to 50-kW motor is of the order of kΩ, as can be seen in Figure 2 [5], whereas Z_{cable} is of the order of 10 to 30 Ω, and $Z_{inverter}$ is generally very low and ~ 0 Ω, i.e., $Z_{motor} >> Z_{cable} > Z_{inverter}$. Such a surge voltage stress can cause partial discharges in the motor insulation system and can deteriorate the electrical insulation, leading to breakdown.

From this background, in this article, we have investigated the partial discharge (PD) inception characteristics of a twisted pair as a simplified inverter-fed motor-coil sample. We discuss the difference in the PD inception characteristics of a twisted pair under 60-Hz voltage and surge voltages with a steep wave front.

> *The PDIV under surge voltages was 1.6 to 1.8 and 2.3 to 2.7 times higher than those under AC voltage application for the used and virgin samples, respectively.*

Experimental Set-Up

Figure 3 shows the experimental set-up for the measurement of the PD characteristics of the twisted pair. The twisted pair consists of two enamel-coated wires with the following specifications: conductor diameter: 0.845 mm, coating thickness: 0.03 mm, twisted pitch: 7 mm, and total length: 130 mm. The enamel coating has two layers: an inner layer (thickness, 0.023 mm; dielectric constant, 3.8) and an outer layer (thickness, 0.007 mm; dielectric constant, 4.2). One of the wires was grounded, and high-voltage AC or surges were applied to the other wire. The frequency of the AC voltage was 60 Hz, and the surge voltage had a rise time of 20 ns, a duration of 1 μs for a single shot, and a repetitive shot frequency of 6 or 60 pps.

The PD inception voltage (PDIV) was detected by PD light intensity under both AC and surge voltage applications. The PD light intensity signal was observed using a photo multiplier tube (PMT). The PD light emission images were taken by a still cam-

[1]This article is based on a paper presented at the 2003 CEIDP.

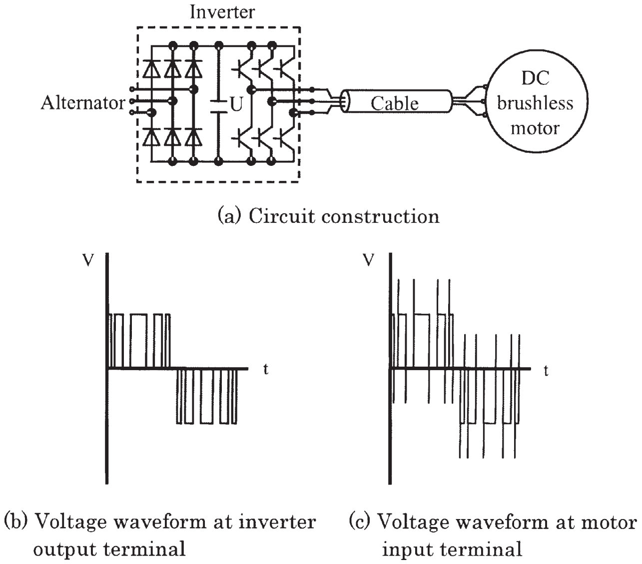

Figure 1. Inverter-fed motor system.

era through an image intensifier (II) with an exposure time of 5 sec. We also measured the PD current pulses under AC voltage application through a high-frequency current transformer (1 GHz); CT1 for the twisted pair, and CT2 for the coupling capacitor.

PD Characteristics Under AC Voltage Application

We measured the PD characteristics of two twisted pairs under AC voltage application; Sample A was a used sample, and Sample B was a virgin one. We found that $PDIV_A$ was 816 Vpk for Sample A, where Vpk is the peak voltage, and $PDIV_B$ was 780 Vpk for Sample B, using the PMT.

Figure 4 shows the applied voltage, PD light intensity, and PD current pulses of Sample A at PDIV (816 Vpk). A PD light intensity signal with a steep-pulse waveform and PD current pulses with a polarity reversal between CT1 (twisted pair) and CT2 (coupling capacitor) were detected simultaneously, which verified the PD generation in the twisted-pair sample.

Figure 5 shows the PD light emission images at a) an applied voltage (Va) of 900 Vpk and b) 2000 Vpk, respectively. The PD light emission was first observed at 900 Vpk and became more intense as the applied voltage was increased. The optical PDIV measurement showed about a 5% higher PDIV than that measured by the current transformers. Figure 6 shows an enlarged image of the PD light emission in the wedge-shaped gap space.

PD Characteristics Under Surge Voltage Condition

Figure 7 shows the applied surge voltage and light intensity waveforms of Sample A for a) a Va of 1000 Vpk (No PD), b) 1350 Vpk (PDIV), and c) 2000 Vpk, respectively, at a pulse repetition rate of 60 pps. A PD light intensity signal was detected during the transients of the applied surge voltage in Figures 7 (b and c). Figure 8 shows the details of the PD generation in Figure 7(c). In Figure 8, we can see clearly the time delay of the PD inception caused by the very steep wave front of the applied surge voltage.

Figure 9 shows the PD light emission images of Sample A under 60-pps surge voltage application for applied voltage magnitudes of a) 1400 and b) 2000 Vpk, respectively. The first PD light emission was observed at 1400 Vpk at both ends of the

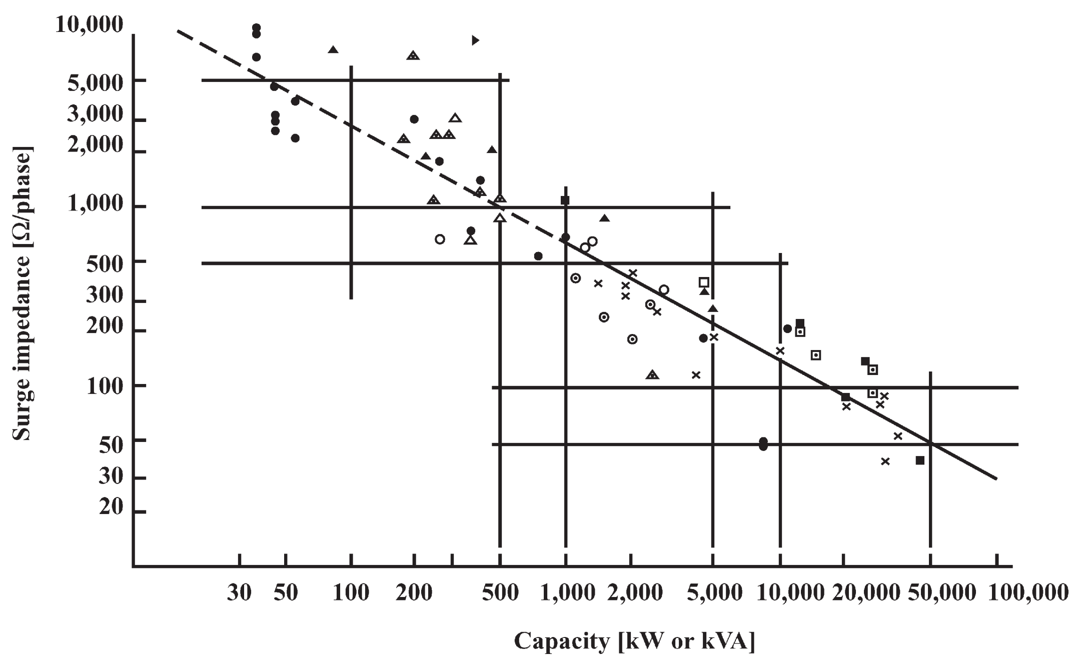

Figure 2. Surge impedance of rotating machines [5].

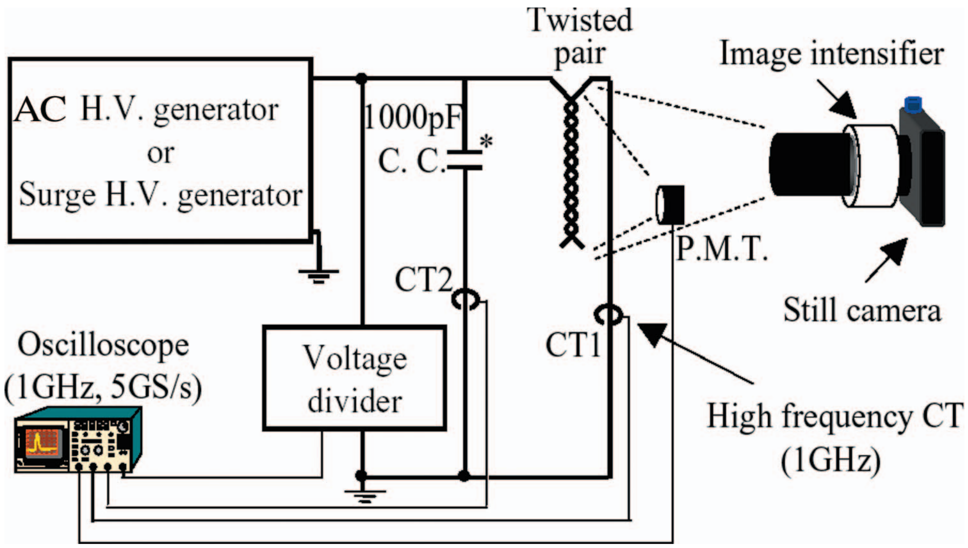

*Figure 3. Experimental set-up. *C.C. (coupling capacitor) is only for AC.*

twisted pair and became more intense with increasing Va, spreading over the whole length of the twisted pair.

Discussion on PDIV Mechanism

We calculated the theoretical value of the AC PDIV of the twisted pair using the finite element method of electric field calculation and Paschen's law for air. Figure 10 shows the equipotential lines for a cross-section of the twisted-pair sample. The gap length d between the two conductors was defined as shown in Figure 10. Figure 11 shows the electric field distribution along the surface of the twisted pair sample as a function of the gap length d for values of Va of 500, 800, and 1500 Vpk, respectively. The calculated breakdown strength in air according to Paschen's law [6]–[7] is also shown in Figure 11. The electric

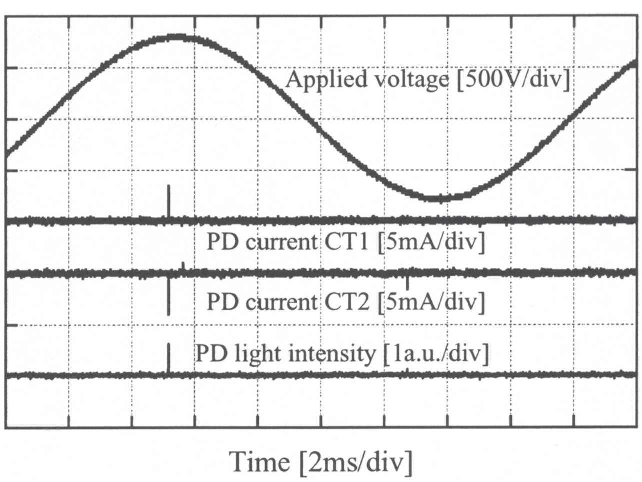

Figure 4. Applied voltage, PD light intensity, and PD current pulse waveforms under AC voltage application. (Sample A, Va is 816 Vpk).

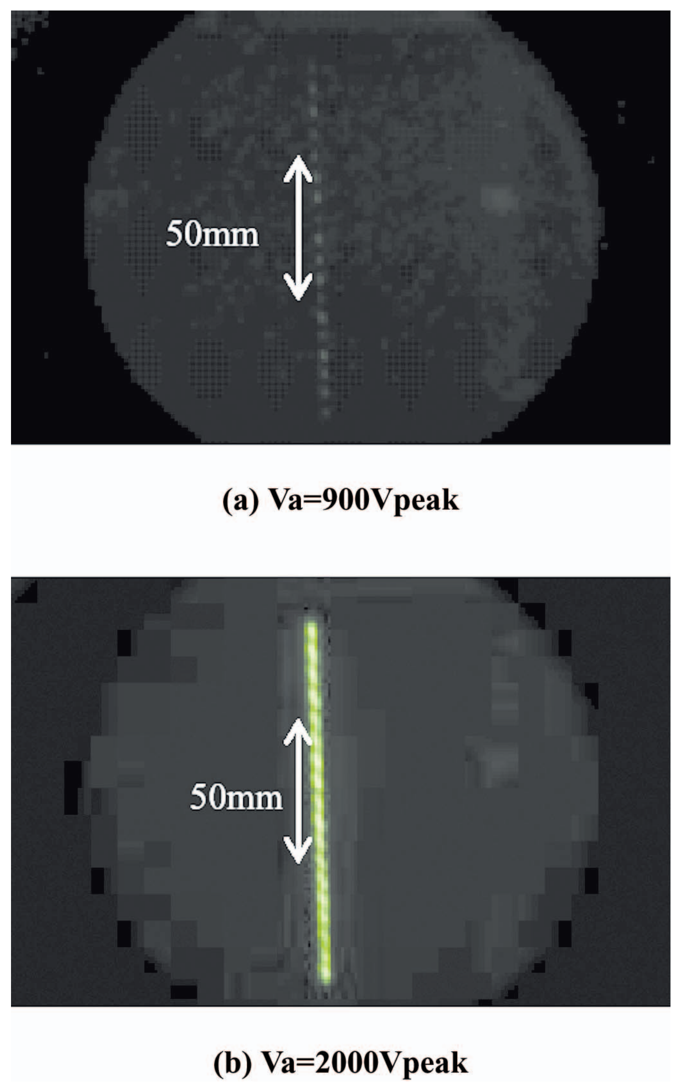

Figure 5. PD light emission images for AC voltage (Sample A).

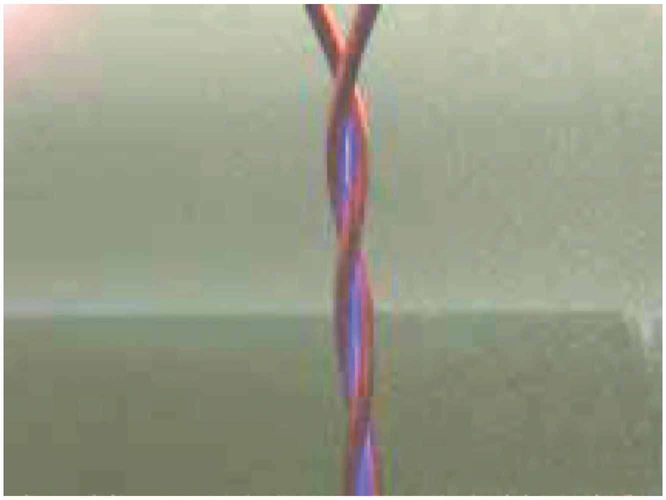

Figure 6. PD light emission image of twisted pair sample (enlarged image).

field distribution along the surface makes first contact with the Paschen curve when d is 0.03 mm and Va is 800 Vpk, which corresponds to the theoretical PDIV under AC voltage application and agrees well with the measured PDIV of 816 Vpk.

The comparison of the PDIV between AC and surge voltage conditions is shown in Figure 12, where the average value and the standard deviation are plotted for both cases. For the AC voltage, the PDIV is almost the same for Samples A and B. On the other hand, for the surge voltages, the PDIV for 60-pps repetition was lower than those for 6 pps and the single shot. This result suggested that the insulation performance of the twisted-pair sample would be more deteriorated under a higher repetition rate of surge voltages. The average value of the PDIV for surge voltages divided by the PDIV for AC voltage is 1.6 to 1.8 for Sample A and 2.3 to 2.7 for Sample B. The higher PDIV for surge voltages than that for AC voltage may be attributed to the lack of an initiatory electron in the localized higher electric field region of the twisted pair sample. In the case of the surge voltage application, the lack of an initial electron would be significant because of the short time voltage application (~100 ns) 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.

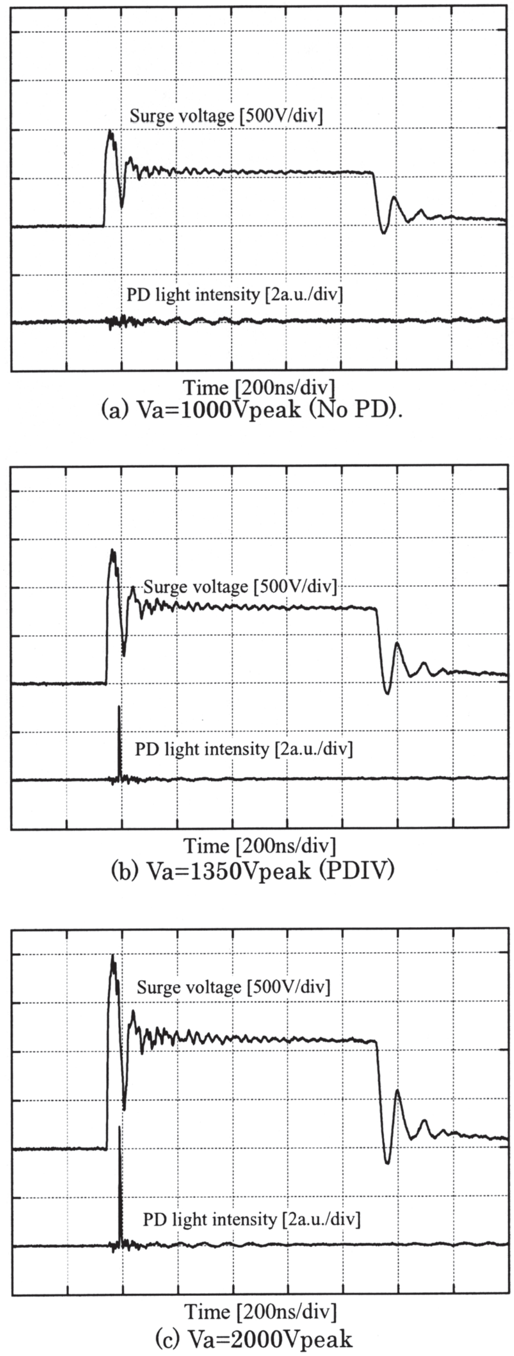

Figure 7. Applied voltage and PD light intensity waveforms under surge voltage condition. (Surge wave front: 20 ns; Sample A, 60 pps).

Conclusions

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

- The PDIV under AC voltage was measured and verified to agree well with the theoretical value using electric-field analysis and Paschen's law.
- The PDIV under surge voltage was measured for different repetition rates; the PDIV for 60-pps repetition was lower than those for 6 pps and for the single shot, which suggested that the electrical insulation performance would be influenced by the repetition rate of voltage surges.
- The PDIV under surge voltages was 1.6 to 1.8 times and 2.3 to 2.7 times higher than those under AC voltage application for the used and virgin samples, respectively. This might be attributed to the lack of an initial electron in the localized high electric field region. The obtained impulse ratio would be highly influenced by the applied surge voltage wave front and the time duration.

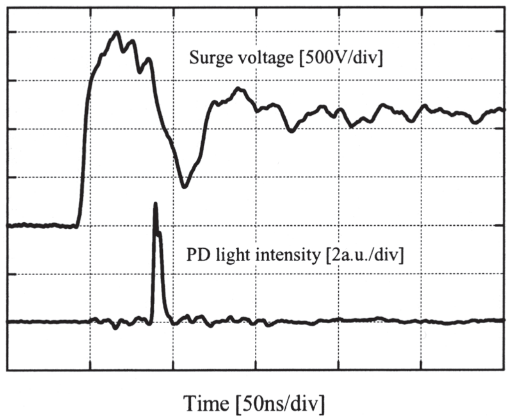

Figure 8. Details of applied voltage and PD light intensity waveforms under surge voltage condition. (Surge wave front: 20 ns; Sample A, 60 pps; 2000 Vpk).

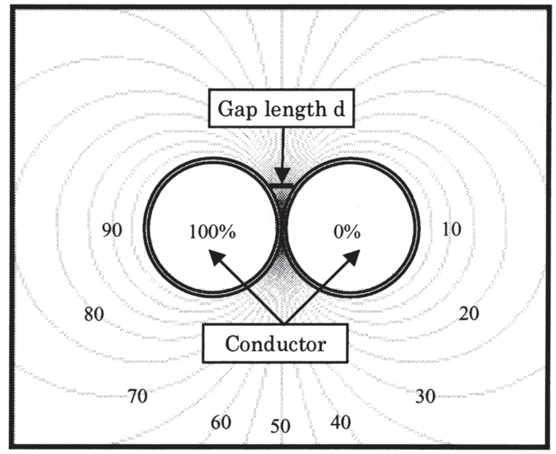

Figure 10. Equi-potential lines of twisted pair sample.

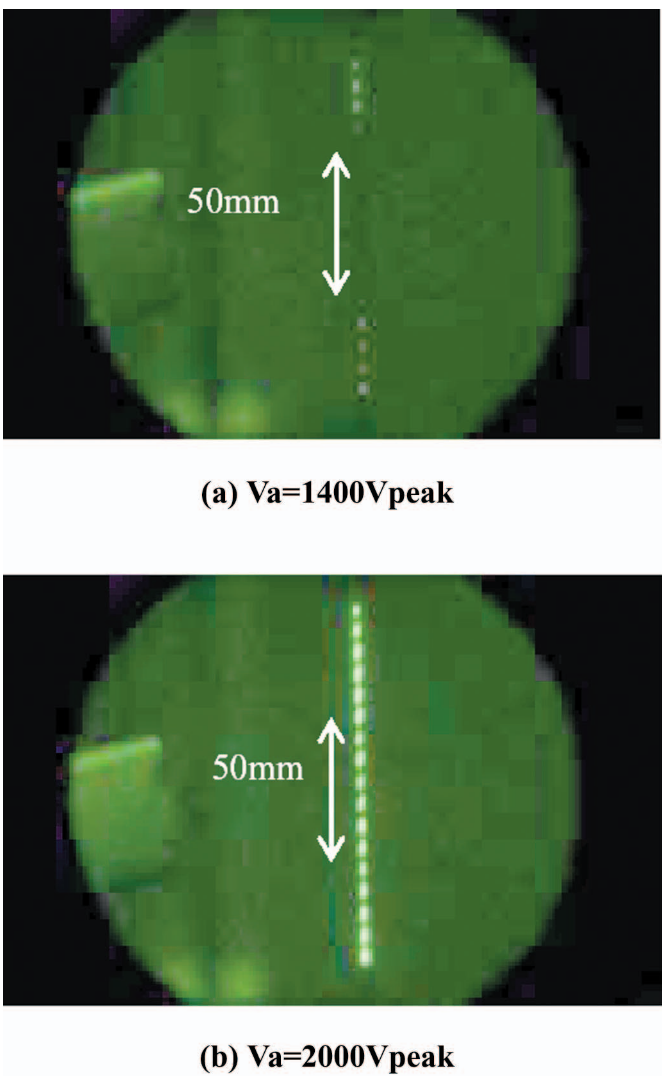

Figure 9. PD light emission images under surge voltage condition. (Surge wave front: 20 ns; Sample A, 60 pps).

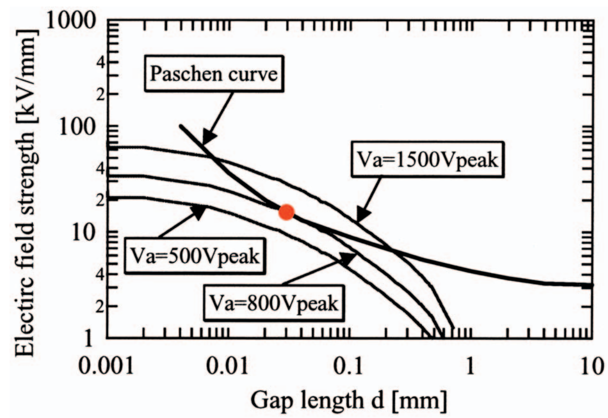

Figure 11. Electric field strength as a function of gap length.

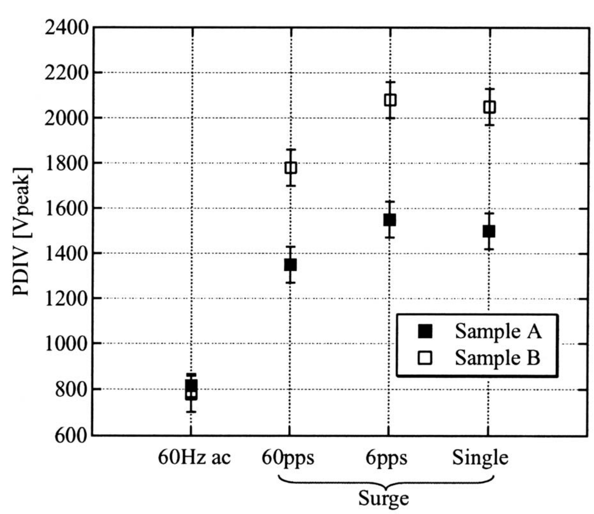

Figure 12. PDIV under AC and surge voltage conditions. (Surge wave front: 20 ns).

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