

# EXAMPLES OF STATOR WINDING PARTIAL DISCHARGE DUE TO INVERTER DRIVES

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**Abstract:** Random wound stator windings in motors have failed when exposed to the fast-risetime voltage surges coming from inverters. Measurements on motors show that these surges can create partial discharges and these discharges eventually destroy the turn-to-turn and/or phase-to-phase insulation, resulting in premature motor failure. Since the risetime of the voltage surges is in the same order of magnitude as the risetime of the PD pulses themselves, it is very difficult to separate the PD from the surges. Thus there has been little characterization of the PD caused by IFDs. Using a new device that can separate the PD from the surges, preliminary measurements of discharge inception voltage from several different motors, as well on twisted pairs of magnet wire were made. The DIVs under surge voltage are significantly higher than those made with 60 Hz voltage. As expected, the PD magnitude increases dramatically with applied surge voltage. PD pulses occur during a small percentage of the surges.

## INTRODUCTION

Researchers have understood for over 70 years that fast risetime voltage surges from circuit breaker closing can lead to electrical breakdown of the turn insulation in motor stator windings [1]. If the turn insulation is of insufficient thickness, or has aged in service, the insulation punctures when a short risetime voltage surge occurs. Punctured turn insulation allows a very high circulating current to flow in the affected copper turn, rapidly melting the copper conductors, and consequent burning/melting of the slot liner insulation, leading to a stator winding ground fault [2,3].

Rapid advances in power electronic components in the past decade have lead to a new source of voltage surges. Inverter-fed drives (IFDs) of the pulse-width modulated (PWM) type and using insulated gate bipolar junction transistors (IGBTs) can create tens of thousands of fast risetime voltage surges per second. There is anecdotal evidence that the huge number of voltage surges from IFDs can lead to gradual deterioration and eventual failure of the turn insulation both in low voltage (less than 1000 V) and medium voltage (2.3 to 4.16 kV) motors [4-6]. Surges over 3 pu (1 pu is the rated peak line-to-ground voltage) with

risetimes as short as 50 ns have been measured [6,8,9]. The motors most at risk are those that experience the highest magnitude surges and/or surges with the fastest risetime, since the fast risetime causes most of the voltage to be dropped across the first few turns in the winding [2,3].

With the high inter-turn voltage across adjacent turns of magnet wire, and given the relatively small diameter of the magnet wire, it seems that partial discharge can sometimes originate in the air space between two adjacent turns [5-7]. Since the thin magnet wire insulation is primarily made from organic materials, if sufficient PD activity occurs, the insulation is deteriorated.

This paper presents some preliminary measurements to characterize the PD pulse currents during fast risetime voltage surges. The measurements were done both on-line and off-line.

## MEASURING SYSTEM

PD measurement methods in an insulation system exposed to power frequency voltage are well established. Usually a high voltage capacitor filters the 50/60 Hz voltage and the high frequency PD signals are passed to an oscilloscope or other recording apparatus virtually unattenuated. However, these conventional methods to measure the pulse current associated with each partial discharge cannot be used with voltage surges because the PD pulse has much the same frequency content as the surge. Thus the standard high pass filter characteristics of a PD detection capacitor will apply several hundreds of volts to the PD measurement electronics during each surge, destroying the electronics. Since conventional PD detectors cannot be easily used with surges, most researchers have used the 60 Hz PD characteristics as an analog for PD behavior under fast risetime surges, or have been satisfied with extremely low-resolution recording of the PD under surges.

A specialized PD measuring system was developed which can record the PD pulses during a surge, without harming

the electronics. The new device, called XTrac, can be used either off-line (voltage source from a fast risetime surge tester) or on-line where a PWM IFD creates the surges. Further details on the new device are in reference [8]. An HP54542 digital oscilloscope was used to record the PD signals from the new detector.

## PD PULSE CHARACTERISTICS

The new PD measurement system was used to collect preliminary data on the nature of PD caused by fast risetime surges on both random wound motors and on twisted pairs of magnet wire.

Figure 1 shows the oscilloscope waveform of a PD pulse in an operating motor driven by an IFD. The PD pulse was extracted from a surge, using the specialized PD measuring system. Clearly, PD can occur in motors driven by IFDs. It seems that most surges do not produce PD. However, if sufficient numbers of surges are applied, PD will occasionally result. The PD is the fast transient, with the initial peak lasting less than 10 ns. The wave response just before the PD in Trace 1 is relatively slow, and is what remains of the voltage surge. The surge is attenuated over 60 db.

A single PD pulse recorded in an off-line test using a modern Baker Model D1200 surge tester is shown in Figure 2. The surge tester, which uses an IGBT as a switching device, has a surge risetime of 100 ns, at the motor terminals. The high frequency output from the new

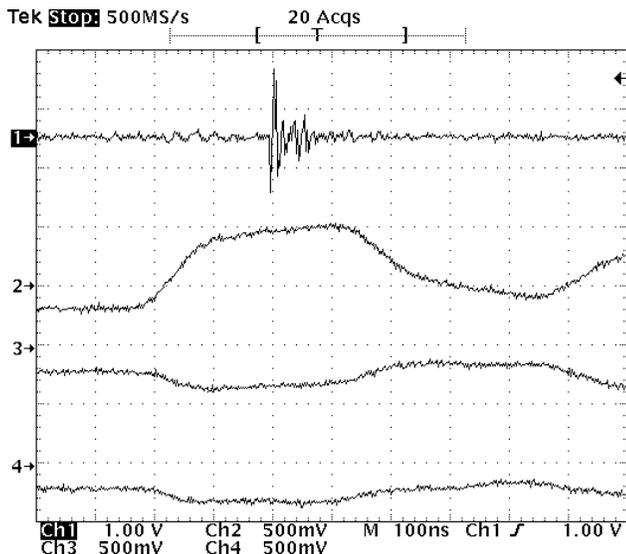


Figure 1 – PD pulse collected at the motor using a 600V IFD operating at 60 Hz. Channel 1 is PD from Phase A. Channel 2 is a A Phase Transient (divided by 2000). Channel 3 is B Phase Transient (divided by 2000). Channel 4 is C Phase Transient (divided by 2000).

detector indicates that the PD is oscillatory (an artifact of the measurement system), and has a risetime of about 5 ns. As with the IFD, there is still some of the residual surge that comes through the device, but it has a lower frequency content, i.e. it is easily distinguishable from the PD pulse. The surge voltage has been reduced by over 66 db. At the PD inception voltage, PD rarely occurs on every surge (Figure 3). As is to be expected, as the surge voltage is further increased above the DIV, a higher and higher percentage of the surges experience PD. Also, some of the PD starts occurring at lower voltages on the wavefront. In some cases, the PD was seen to occur on subsequent rings of the surge.

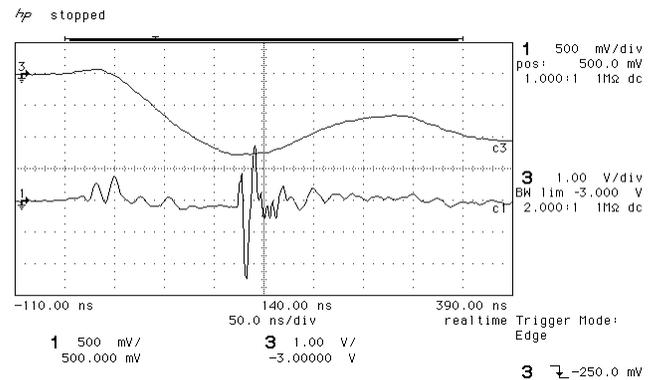


Figure 2 - PD (lower trace) recorded during a single surge (upper trace) from a surge tester.

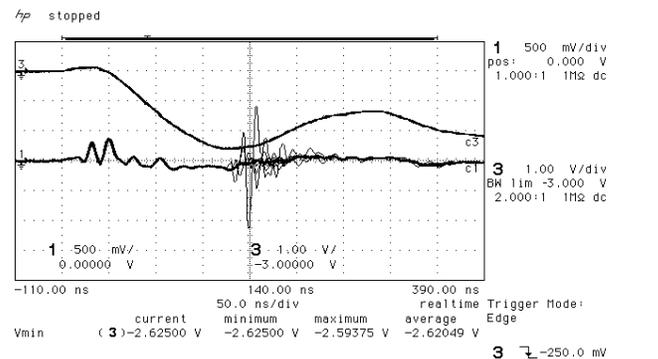


Figure 3 - 'Infinite persistence' recording of multiple PD pulses (trace 1) occurring at the peak of the surge voltage on the same motor as in Figure 4. Since the PD pulses appear as a light trace compared to the bold surge (and the surge transient recorded on the PD signal output) it is clear that most surges do not produce a PD pulse.

## INCEPTION AND EXTINCTION VOLTAGES

The PD inception voltages were measured on twisted pair magnet wires, as well as three commercial motors. Table 1 shows the DIV on 4 different twisted pair magnet wire samples when subjected both to 60 Hz and 100 ns risetime voltage surges. The magnet wire was all of the same diameter (18 AWG), with two samples conventional quad build, and 2 samples quad build with a corona resistant filler. The surge voltage is the peak-recorded voltage. The 60 Hz voltage is the rms voltage. It is evident that the rms (or even the zero to peak) DIV for 60 Hz is substantially lower than the DIV under a voltage surge. This is not surprising. Note that the DIVs in Table 1 were measured with the new PD device, which produces a PD signal that is about 12 times higher than a conventional capacitive detector. After the PD measurements, it was confirmed that the pairs of magnet wires were not shorted.

Three commercial motors were also measured for the DIV and DEV under surge voltage. The DIV/DEV under 60 Hz was not measured, since this would have involved phase-to-ground, rather than turn-to-turn insulation. The motors ranged from 1 HP to 20 HP. All were rated 440V, 3 phase. Table 2 shows that the lowest DEV was 1.6 kV. For this motor, PD would only occur if the applied surge voltage is greater than 4.4 pu, which is unlikely [9]. Thus, none of these motors are likely to fail in-service due to PD. The PD magnitude at inception is also listed in Table 2.

## PD VERSUS SURGE VOLTAGE

Measurements were made on a 1 HP motor to determine how the PD magnitude is affected by surge voltage. The measurements were made at atmospheric pressure and 22°C. As shown in Figure 4, around the inception voltage, the PD magnitude increased dramatically. Similar to what occurs under 60 Hz voltage, eventually the PD magnitude saturates. Since the PD magnitude increases over 10 times in a narrow voltage range just above inception, this makes PD inception measurements relatively easy, and precise.

Table 1 - DIV for twisted pair magnet wire samples

Voltage Type	1A	2A	1CR	2CR
Surge (peak V)	2000	2200	2400	2200
60 Hz (V rms)	660	640	740	700

Table 2 - Inception and extinction voltages of Motors

Rating	Phase	DIV (kV)	DEV (kV)	PD Magnitude (mV)
1 HP	T1	1.9	1.7	600
	T2	2.3	2.1	300
	T3	2.3	2.2	400
10 HP	T1	2.4	2.2	600
	T2	2.2	1.8	50
	T3	2.3	2.1	150
20 HP	T1	2.4	2.3	50
	T2	2.4	2.1	400
	T3	1.8	1.6	300

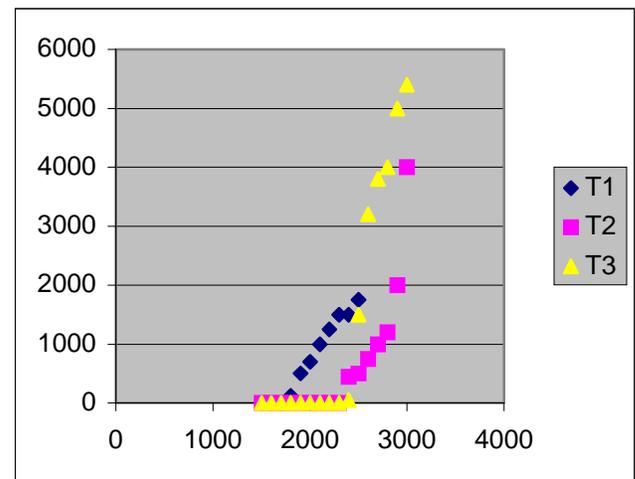


Figure 4 - PD magnitude as a function of applied surge voltage (100 ns risetime). The vertical scale is the PD magnitude from the new detector, in mV. The surge voltage (V) is the horizontal scale.

## CONCLUSIONS

1. Premature failure of stator windings in low voltage motors have been observed due to partial discharges created between turns. The root cause of the PD is the high interturn voltage that can occur due to the fast risetime, high magnitude surges produced by some types of IFDs.
2. Measurement of the PD during surges is difficult with conventional PD detectors, since the frequency content of the surge is close to the frequency content of the PD pulse currents.

3. A new PD detection device that can extract the PD pulses from fast risetime surges has been developed.
4. The PD inception voltage from several conventional motors has been measured. The DIV of these particular motors is higher than the normally expected peak surges from IFDs. The DIV can be readily determined since the PD magnitude is a strong function of applied voltage.
5. The DIV under surge voltage (100 ns risetime) is substantially higher than the PD occurring during 60 Hz AC.
6. Further work is needed to determine the effect of humidity, temperature and insulation aging on PD magnitude. However, with this new tool, users can objectively measure PD characteristics under realistic voltage conditions [10].

## ACKNOWLEDGMENTS

The authors would like to thank Mr. Dave Schump of Baker Instruments for providing a fast risetime surge generator. We are also indebted for advice from Dr. G. Gao of Teco Westinghouse Motors.

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