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Partial Discharge Testing of Random Wound Stators During Short Risetime Voltage Surges

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Abstract: **Modern inverter fed motors often produce short risetime, high magnitude voltage surges that may lead to partial discharge in the random wound stator windings. Detection of PD during such voltage surges can not be done with the usual PD detectors described by ASTM D1868. Instead a detector that can separate PD pulse currents from a short risetime voltage surge is required. This paper describes a PD detector that can measure PD pulses when the applied voltage is a voltage surge with a risetime as short as 100 ns. PD data has been collected from dozens of stators, many of which had known insulation problems. In most cases the PDIV easily met the requirements of a new IEC technical specification that sets the partial discharge inception voltages for random wound stators. Since most of these stators had obvious insulation system deficiencies, it seems that the PDIV levels set by IEC TS 60034-18-41 may be too low.**

I. INTRODUCTION

Variable speed drives of the voltage source, pulse width modulation type have become one of the most popular types of motor drives. Such drives can produce switching voltage surges with a risetime as short as 100 ns, and with thousands of surges per second [1]. There is anecdotal evidence that the large number of voltage surges from such inverter fed drives (IFDs) may lead to the deterioration and eventual failure of the insulation in low voltage (less than 1000 V) motor stator windings [1-4]. Surges over 3000 V and risetimes as short as 100 ns have been measured on motors that are nominally rated up to 690 Vrms (phase to phase) [3].

The stator windings are “random wound” in most motors rated less than 1000 V. This implies that the magnet wire connected to the phase terminals in one phase, may be adjacent to magnet wire in another phase or a magnet wire near the neutral. In addition, for short risetime pulses, the voltage is not uniformly distributed from the phase terminal down to neutral. Instead, most of the voltage is dropped across the turns at the line –end of the winding [2]. As a result, unusually high voltages can occur across adjacent turns of magnet wire; between magnet wires in different phases; and between the magnet wire and the grounded stator slot.

The electrical stresses may be high due to these voltages, the relatively small diameter of the magnet wire and the thinness of the magnet wire insulation. As shown in Figure 1, if there are any air spaces between two adjacent wires and/or ground, the stress may be high enough to initiate partial discharge (PD) [1-3]. Since the magnet wire insulation is primarily made from organic materials, if sufficient PD activity occurs, the insulation deteriorates and eventually fails. Thus it is usually desired that no PD occurs during operation of the motors. IEC TS 60034-18-41 sets the minimum voltages that PD may occur (Table 1).

This paper discusses how the PD can be measured during short risetime voltage surges, and presents some PD data measured on many stators during short risetime surges.

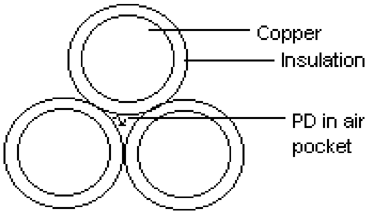

Fig. 1: PD occurring in air space between magnet wires at high stress.

II. MEASURING PD DURING VOLTAGES SURGES

ASTM D1868 and IEC 60270 describe the measurement of PD in an insulation system exposed to power frequency voltage. Such conventional PD detectors usually have a high voltage capacitor to reduce the high AC voltage to the millivolt range, yet pass the PD signals 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 fast risetime 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.

A specialized PD measuring system is needed which can record the PD pulses during a surge. This involves suppressing the surge voltage (up to 3 or 4 kV) to less than a volt, while passing the PD pulse with little or no attenuation. IEC TS61934 was recently issued that addresses this measurement problem. The TS describes a number of measurement methods. All but one are classed as working in the VHF or UHF frequency range, since the PD pulses are

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detected in the hundreds of megahertz range due to the PD pulse risetime of only about 1 ns [5]. Although high order high pass filters have been used to suppress the voltage surge, these do not seem to be effective in suppressing the residual of the voltage surge to about the same magnitude as the PD, when the surge risetime is less than 200 ns or so.

TABLE I
RPDIV MEASURED WITH A SURGE TESTER FOR A 480 V RATED MOTOR STATOR FED FROM A 2 LEVEL INVERTER

Stress Category	Peak V/DC Bus	RPDIV (V_{p-p})		
		Phase to Phase	Phase to Ground	Turn to Turn
Benign	1.1	1853	1297	1297
Moderate	1.5	2527	1769	1769
Severe	2.0	3370	2359	2359
Extreme	2.5	4212	2948	2948

The only devices that seem to have sufficient suppression capability for the risetimes typical of voltage source invertors use either a very small UHF antenna near the winding or a directional electromagnetic coupler. Small UHF antennae seem to be relatively insensitive to PD. However, 10 years of experience has shown that a directional electromagnetic coupler technique has good sensitivity to PD, while adequately suppressing high voltage surges with risetimes as short as 100 ns [6]. An instrument called PDAlert uses the directional electromagnetic coupler approach (Figure 2). The PD output of the instrument is displayed on a digital oscilloscope, as is a divided version of the voltage surge. As with all VHF and UHF PD detectors, the PD magnitudes should **not** be expressed in pC [5], thus the PD magnitude is measured in terms of mV. A sensitivity check is made, using the method described in IEC TS 61934, or by using a twisted pair of magnet wire with a low PDIV.

Figure 3 shows a single PD pulse recorded in an off-line test of a 5 HP motor using a Baker Model D12000 surge tester. The surge tester has a surge risetime of about 100 ns, at the motor terminals. Depending on the load, the risetime with the D12000 is between 100 ns and 400 ns. The Baker D12R and a modern PJ tester have also been shown to produce short risetime outputs into stators. The high magnitude, high frequency output on the lower trace is due to PD. It is oscillatory (an artifact of the measurement system), and has a risetime of about 5 ns. It is evident on the lower trace that there is still some of the residual surge that comes through the instrument. However it has a lower frequency content and linearly increases in magnitude as the surge voltage increases. These characteristics make it easy to distinguish the surge residual from the PD pulse. The surge voltage has been reduced by over 66 db (2000 times).

PD-free is defined in IEC TS 61934 as having a **repetitive** partial discharge inception voltage (RPDIV) higher than a specified voltage, with a surge risetime similar to that which is expected in service. The RPDIV is measured by slowly increasing the voltage from the surge tester, which outputs one surge per second. The surge residual voltage gradually increases from 0. The PD inception voltage (PDIV) is determined when the high frequency PD pulse burst is first noted on the detector output trace on the oscilloscope. However, at this voltage, PD pulses will often not occur on repeat surges. By increasing the voltage (usually by 50 to 300 V), the PD occurs on most of the applied surges, and this is termed the RPDIV (according to IEC TS 61934 the lowest voltage at which a PD occurs during 50% of the surges). After one hour or so of training, factory floor technicians have been able to reliably measure the RPDIV.

The magnitude of the surge residual in Figure 3 depends on the surge risetime that actually is impressed on the stator winding (the shorter the risetime, the higher is the residual). For most of the motors tested to date, the residual had a magnitude between 500 and 1500 mV at the RPDIV. In comparison, the PD magnitude at the RPDIV depends on the effective load capacitance of the winding and the distance the PD pulse has to travel to the PD instrument. For most of the motors tested to date, the PD magnitude was between 300 mV and 1000 mV. The PD magnitude increases dramatically as the surge voltage increases above the RPDIV [7].

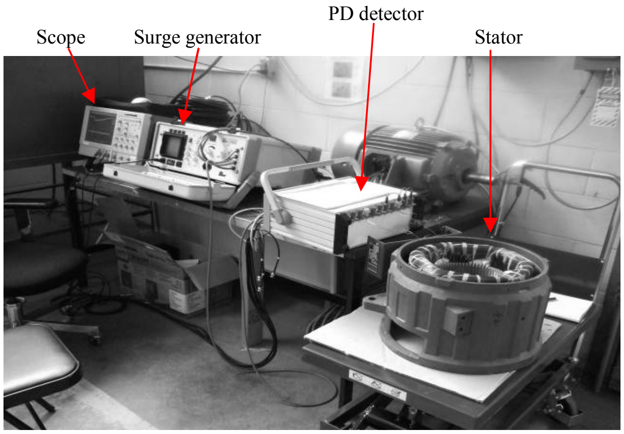

Fig. 2. RPDIV measurement of a small motor stator (right side). The voltage surges come from a Baker D12000.

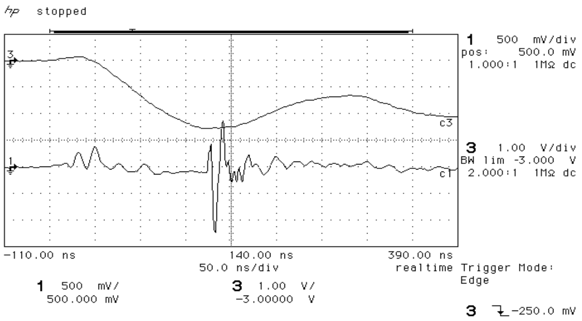

Fig. 3. PD (lower trace) recorded during a single surge (upper trace) from a surge tester applied to a small stator. The time base is 50ns.div. The surge voltage is 1000 V/div while the PD is 1 V/div. The low frequency transient at the beginning of the PD waveform is the residual from the surge. The high frequency oscillation in the middle of the lower trace is the PD.

III. EXPERIMENTAL PD DATA

The RPDIV has now been measured on over 100 stators, and the data formally recorded from 39 machines. Table 2 shows a summary of the RPDIV collected by ourselves using either a D12R or a D12000 surge tester. The test objects were all stator windings, rated from 1 HP to 6400 HP and from 380 V to 690 V. Almost all were random wound stators. Most of the measurements in Table 2 occurred because the motor OEM or the enduser had experienced premature stator winding insulation failures, and PD due to IFD voltage surges was one of the possible failure mechanisms.

The measured surge risetime was from 150 to 400 ns, and the surge pulse width for most stators ranged from 10 to 40 μs, with a slow fall-time. Due to the long width and slow fall, and since the opposite polarity undershoot was always less than 25% of the peak surge magnitude, the RPDIV is measured from 0V to the peak, as suggested in IEC TS 60034-18-41 (Table B.2, Column 6, Note b). This is valid for the turn to turn RPDIV. Example minimum RPDIVs are shown in Table 1. The phase to ground RPDIV may be as much as 25% higher than shown in Table 2.

The second last column shown in Table 2 is the lowest RPDIV measured on all phases and with all possible test connections in 39 stators. The PD may be occurring between turns, between a phase and ground, or in the endwinding between phases. If the RPDIV is indicated with ">", the RPDIV was not measured since the motor owner did not want to exceed the indicated voltage. The measured RPDIVs can be compared the minimum required RPDIV for a "moderate" and "severe" surge environment in columns 4 and 5, as defined in the IEC TS.

TABLE II

MEASURED PHASE TO GROUND AND TURN TO TURN RPDIV COMPARED TO THE MINIMUM REQUIRED RPDIV FOR THE MODERATE AND SEVERE STRESS CATEGORIES.

Rating		**DC Bus**	**Min. Turn or Ground RPDIV (Volts)**		**Measured Min. PDIV**	**Condition**
HP	**Volts**	**Volts**	**Moderate**	**Severe**	**Volts**	
1	440	590	1593	2124	1900	
10	440	590	1593	2124	2200	
20	440	590	1593	2124	1800	
650	440	590	1593	2124	1250	
650	440	590	1593	2124	2080	
1100	690	975	2632	3510	1352	Failed
170	690	975	2632	3510	983	Failed
6400	1287	?			1600	Failed (tr 500 ns)
880	600	850	2295	3060	2200	
300	600	850	2295	3060	2200	Failed
300	600	850	2295	3060	>2500	
300	600	850	2295	3060	>2500	
300	600	850	2295	3060	>2500	
300	600	850	2295	3060	>2500	
880	600	850	2295	3060	1890	Cast, cracks?
950	600	850	2295	3060	1240	No phase insulation
880	600	850	2295	3060	>2600	
950	600	850	2295	3060	>2400	
950	600	850	2295	3060	>2600	
880	600	850	2295	3060	2320	Contaminated
1000	690	975	2632	3510	>2000	
1000	690	975	2632	3510	2600	
1000	690	975	2632	3510	>2000	
17	415	560	1512	2016	2960	
17	415	560	1512	2016	2160	No phase insulation
35	415	560	1512	2016	2640	
35	380	513	1385	1847	2480	
35	380	513	1385	1847	2960	
17	380	513	1385	1847	2240	
17	380	513	1385	1847	2560	
17	380	513	1385	1847	2320	
36	380	513	1385	1847	2720	
17	380	513	1385	1847	1400	Failed
17	380	513	1385	1847	1900	Poor impregnation
17	380	513	1385	1847	1400	Poor impregnation
350	440	590	1593	2124	>2000	Similar motors failed
350	440	590	1593	2124	>2000	Similar motors failed
350	440	590	1593	2124	2700	Similar motors failed
350	440	590	1593	2124	3100	Similar motors failed

Some observations on these results are:

- 4 stators with known problems exceeded the "severe" level, and thus the level set for the severe level seems to be too low for these stators since the "bad" windings still would have passed.
- 9 of the 39 stators with known problems had RPDIVs that exceeded the moderate level. Thus these motors would have passed a moderate severity RPDIV test, even with the known problems. Of course none of the motors were originally qualified to the new IEC TS, since most of the motors predate the TS. Thus we do not know the stress category the motors were designed for.
- The RPDIVs range from 1000 V to 3000 V (for all voltage ratings). For motors of one voltage rating (say 440 V), the RPDIV ranged from 1250 V to 3100 V. Clearly there is a great difference in RPDIVs between stators, and presumably a great difference in design, manufacturing and impregnation.

Data published by GE on 18 motors of the same rating from 6 manufacturers also showed high variability in the RPDIV – ranging from 1600 V to 3200 V [8]. GE also reported that in factory tests on 2088 motors rated 440V, the PD ranged from 2950 V to 3690 V [8]. All of these motors easily passed the RPDIV acceptance requirement for a "severe" insulation environment.

IV. CONCLUSIONS

1. A new IEC technical specification has been issued which sets the minimum PD inception voltages for inverter fed motors, based on the expected severity of the voltage surges at the motor terminals.

2. PD measurement equipment that is capable of separating PD from the relatively large applied voltage surges has been in commercial use for 10 years. This PD detector will separate PD from the surges for surge risetimes as short as 100 ns – which is the risetime of surges that can occur from IFDs. At least two OEMs use the detector routinely on the factory floor to ensure production motors have a suitably high RPDIV.

3. Separating the PD from the various sources (turn, ground and interphasal insulation) is not trivial. In addition to measuring the PD under surges, it is useful to also measure the PD with 50/60 Hz AC voltage applied to the windings. This will help to separate turn to turn PD (which only occurs with surge voltages) from ground and interphasal PD (AC will only excite ground and interphasal PD).

4. Production motor acceptance testing by others shows the RPDIV easily exceeds the IEC TS 60034-18-41 requirements for Type I insulation systems, thus indicating that perhaps the minimum RPDIV levels that have been established are too low. This is further supported by the 39 stators reported here, since some of the motors which had known deficiencies, also passed the current minimum levels.

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