Online Health Monitoring of Motor Insulation

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Abstract

The motor insulation quality/health assessment is an important aspect during manufacturing as well as operation of electrical motors. Today there are several offline insulation quality assessment techniques available such as surge test, DC high-pot test, Megger tests, step voltage test, continuous ramp test, partial discharge (PD) test, capacitance & dissipation factor test etc. However, there is only one online insulation quality test popularly available based on partial discharge analysis. This technique has a great potential to detect insulation degradation in high voltage equipment such as motors, generators, transformers, cables etc. Although partial discharge analysis has a potential detect degraded conditions of insulation in motors above 6.6kV such as tracking, cracking, porosity, delamination, contamination etc., it comes with a challenge to clearly discriminate between PD patterns generated by good and bad conditions of insulation and thus demands for extensive human interpretation.

The other industry accepted standard test to assess health condition of ground-wall insulation of industrial motors is the capacitance and dissipation factor (C&DF) bridge test. This test is performed on the motors offline only. So far, it was not possible to conduct this test online on large motors due to the great difficulty in online measurement of very small motor insulation leakage currents (few mA) in the presence of large motor line currents (hundreds of amps). The line currents would produce enormous noise to mask the tiny magnetic field produced by the insulation leakage currents.

Now a new online technique for monitoring the insulation condition of AC motor stator winding is proposed. A recently invented novel sensor, named as high sensitivity differential current transformer (HSCT), is presented in this paper that enabled online measurement of stator insulation leakage current of large industrial motor for the first time in the world. Thus HSCT also enabled to conduct the industry accepted capacitance and dissipation factor test on large industrial motors for the first time in the world. Such an online test adds a new

dimension to state-of-the-art online condition monitoring and greatly benefits the motor users to assess the insulation condition since no motor outage is required.

Introduction

Several types of faults develop in industrial motors during operation such as stator turn-to-turn insulation failure, stator ground-wall insulation failure, bearing defects, broken bar faults, eccentricity conditions, shaft misalignments, motor foundation looseness etc. Such faults can result in forced outage of critical industrial motors leading to increased repair and downtime cost, lost production and safety issues to the motor users. So far, several techniques have been developed to detect different types of faults in operating motors. However, instead of detecting fault occurrences in operating motors, it would be rather more advantageous to monitor gradual degradation of motor condition and be able to estimate the remaining useful life (RUL) of the motor. It is well established [1] that in low and medium motors (up to 4kV) bearing defects are ~50% of the total failures whereas in high voltage motors more than 50% of faults are related to stator winding insulation as shown in Fig. 1 and Fig. 2 respectively. Thus online monitoring the health condition of stator insulation is of paramount importance in order to safeguard these motors. Today, there are several offline tests available to determine the health condition of stator insulation such as surge test, DC high-pot test, Megger tests, step voltage test, continuous ramp test, partial discharge (PD) test, capacitance & dissipation factor test etc. based on measurement of insulation power factor, tip-up, resistance, polarization index, partial discharge, capacitance (C) and dissipation factor (DF) of insulation [2-4]. These tests would need outage of motor from service which is not desirable. Instead, it is ideal to be able to assess the gradual degradation of stator insulation online i.e., while the machine is operating. To increase the availability of the machine and to reduce the chances of forced outages, several periodic offline as well as online insulation test methods have been developed over many years [5-7]. Online stator insulation health monitoring helps to schedule planned outages of motors as well as to prevent catastrophic failure of motors. Partial discharge activity has been one of the most important and traditional indications of insulation degradation. Partial discharge monitoring requires installation of specialized equipment, and the interpretation is somewhat subjective. Further, partial discharge phenomenon is more pronounced and easier to detect in high voltage motors.

The capacitance (C) and dissipation factor (DF) of motor insulation can be a simple and good indication of motor insulation health. In an earlier effort, a novel online scheme using an off the shelf current transformer was successfully demonstrated to monitor the health of stator ground-wall insulation by performing measurement of capacitance and dissipation factor of small motors in the range of few kW [8]. However, when this scheme was implemented on a 15000hp large industrial motor, it was identified that the load current of the motor heavily influenced online measurement of C and DF. The large motor load currents (hundreds of amps) generate large magnetic fields that can very well mask the tiny magnetic field created by insulation leakage currents (few mA). This makes online leakage current measurement extremely inaccurate.

In the present work, an attempt is made to develop a novel high sensitivity sensor that enabled online measurement of insulation leakage current and hence C and DF of large motors up to 100,000 HP without being influenced by the load currents of the motor. This work includes a detailed finite element modeling of large motor terminal box rated for 7.5 kV applications that helps to understand various sources of noise that would impede online measurement of stator insulation leakage current. This analysis subsequently led to the invention of the novel high sensitivity differential current transformer (HSCT). This is *the first sensor in the world* that is successfully tested in the field at three separate industrial sites. The principle of operation and the development stages of HSCT along with its lab and field validation are presented in the subsequent sections of this paper.

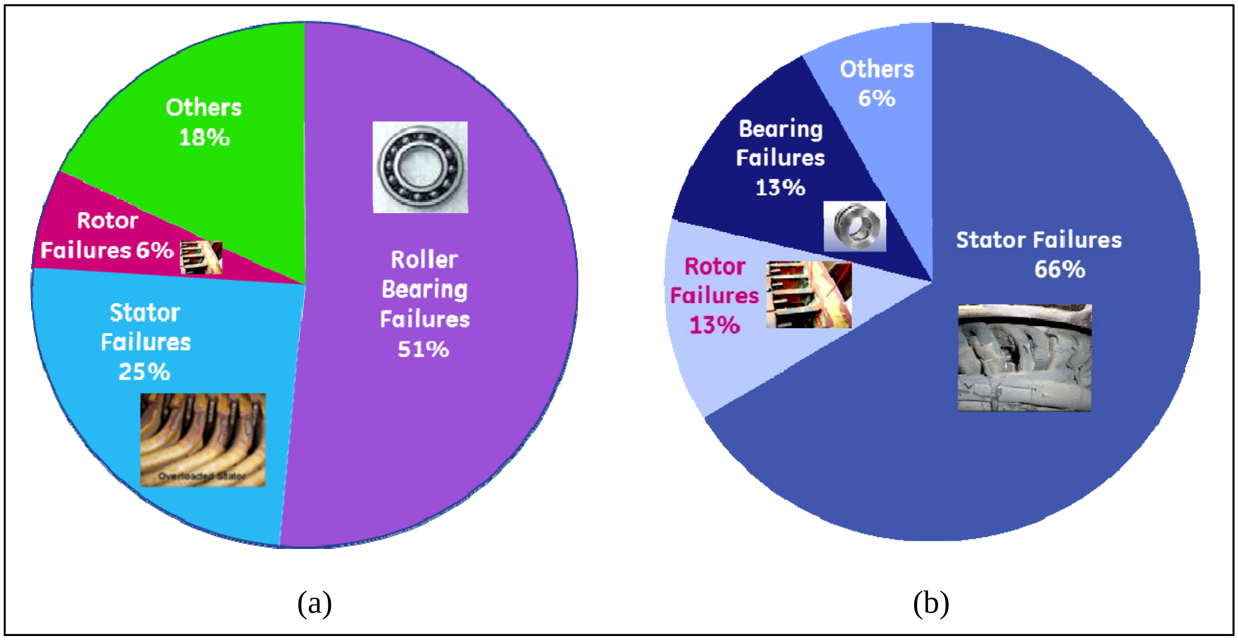

Figure 1. Failure pareto of motors (a) up to 4kV rating and (b) above 4kV rating [1].

Figure 2. Stator winding failure on a 12,000HP, 13.8kV AC industrial motor.

State-of-the-art Solution – Partial Discharge Analyzers

The partial Discharge (PD) is the partial conduction of electricity that occurs in insulation systems due to high voltage stress. This occurs as very high frequency pulses ranging from few tens of kHz to several hundreds of MHz. The PD activity in an electrical motor occurs under good condition of insulation as well. The magnitude and/or the pattern of PD is expected to change under degraded conditions of motor insulation such as tracking, cracking, porosity, delamination, contamination etc. The partial discharge in an electrical motor can be measured using PD couplers such as capacitive couplers, inductive couplers (radio frequency current transformers) or antennas. The partial discharge analyzers can be used online to monitor health of motor insulation. A typical connection of PD couplers on a 3-phase electrical motor for online monitoring is shown in Figure 3. It has three PD couplers, one per each phase. Also the three phase voltages are measured to form reference for PD signals. A simulated PD plot w.r.t. phase voltage is shown in Figure 4. The advantages of PD analysis is its capability to identify localized degradation of motor insulation while is comes with a great disadvantage of very involved human interpretation to come up with a clear diagnosis. In many cases it leads to some level of confusion in separating PD that is coming out of normal conditions than that of a degraded motor insulation. However, this technology has been adopted for a long time since it has been only technique available to monitor motor insulation health *online*.

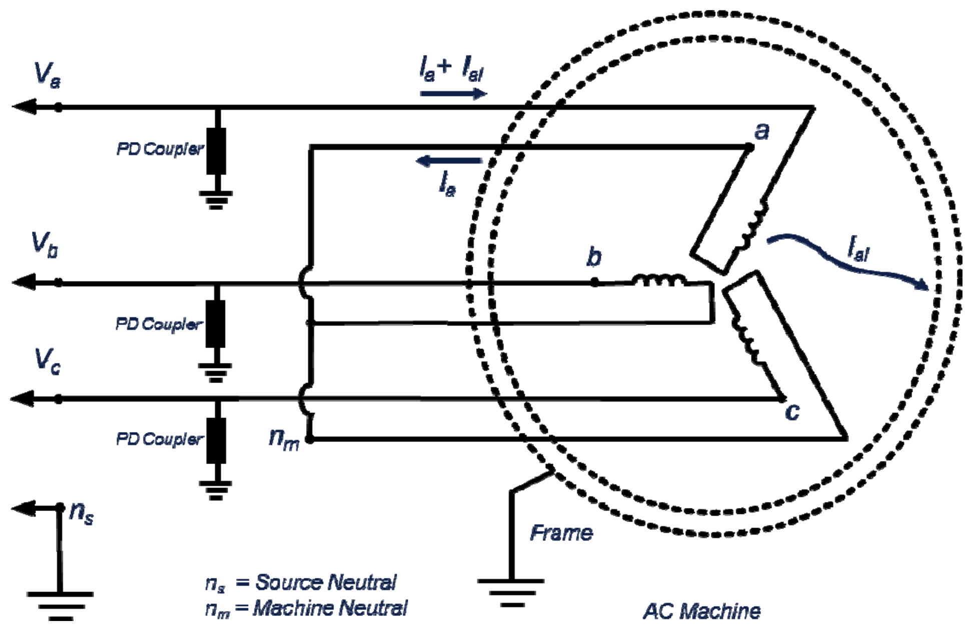

Figure 3. Online insulation monitoring scheme based on partial discharge measurement.

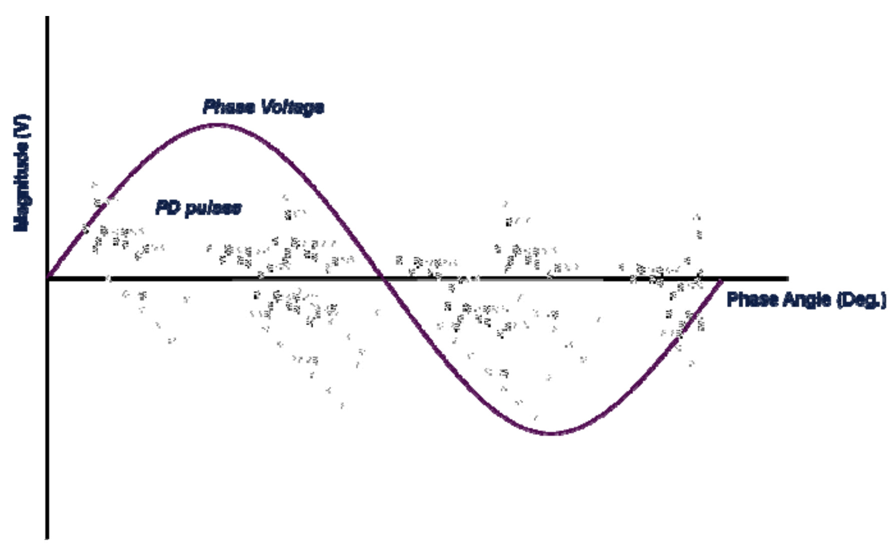

Figure 4. Partial discharge with respect to phase voltage.

Proposed Solution – HSCT/MSIM

So far, offline C & DF test is one of the most popular tests to assess the health condition of stator insulation of ac motors. A novel scheme was proposed [8] that enabled online monitoring of insulation health condition and its degradation in a continuous manner [8], which is a major breakthrough in the area of motor insulation monitoring.

While the motor is running, the stator insulation leakage current (I_{al}) flowing from the winding to ground is equal to the difference between the currents in the line and neutral leads of a stator phase winding. A differential current transformer, which encircles both line and neutral leads of a stator phase winding, measures the insulation leakage current of that phase, as shown in Fig. 5. The measured leakage current, I_{al}, consists of capacitive (I_C) and resistive (I_R) components, which are plotted with respect to the phase to ground voltage (V_{ag}) as shown in Fig. 6. Using measured insulation leakage current during a motor's operation, the key health indicators of ground-wall insulation such as capacitance (C_{eq}) & dissipation factor (DF), can be derived as

$$C_{eq}=2\times I_C / (\omega V),$$

$$DF=I_R / I_C\times 100\%.$$

The online C & DF measurement of small motors was successfully demonstrated on a 15hp motor [9]. The motor insulation leakage current (i_{al}) and the phase to ground voltage (v_{ag}) are accurately measured online, as shown in Fig. 7-(a). However, these measurements were extremely load-dependent and inaccurate when this scheme was implemented on a 15000hp large motor. The *estimated* I_{leak} and δ are constant w.r.t the load current (I_{rms}), as shown in black color, while *measured quantities* varied w.r.t the load current (I_{rms}), as shown in blue (phase-A), green (phase-B) and red (phase-C) colors, as shown in Fig. 7-(b). Thus, it was nearly impossible to implement this scheme on large motors.

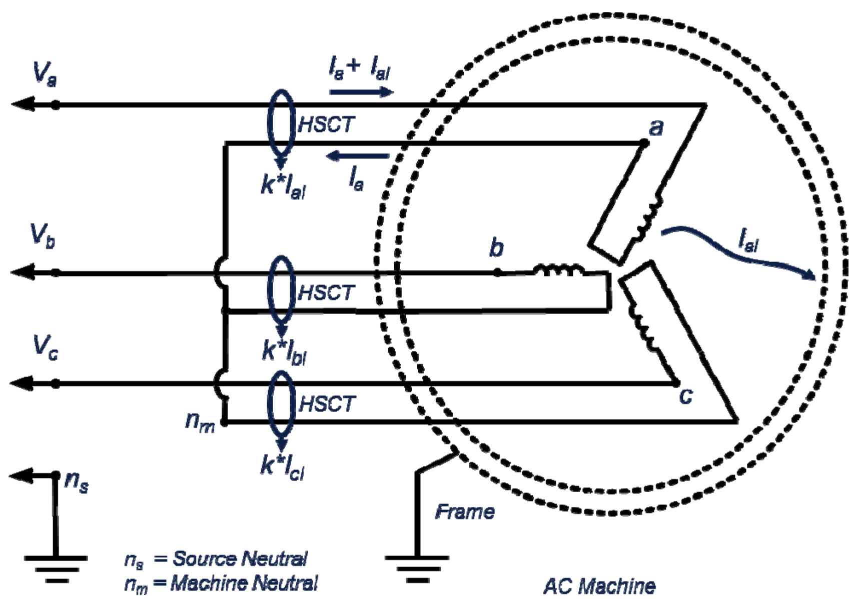

Figure 5. Online insulation monitoring scheme based on leakage current measurement.

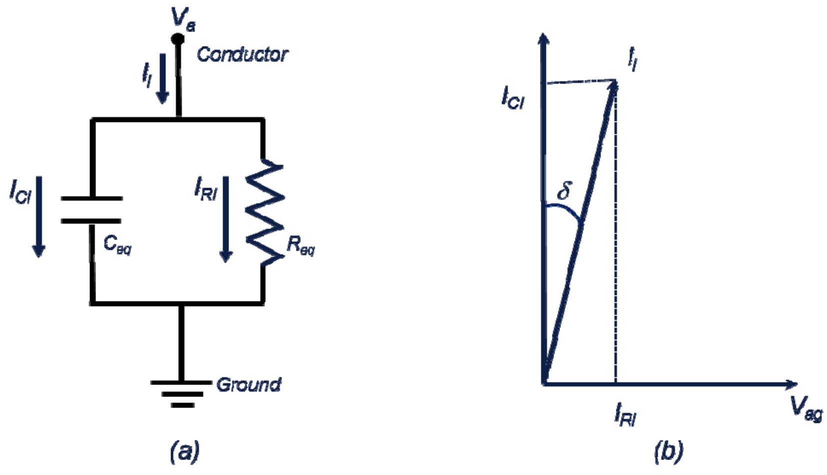

Figure 6. (a) Equivalent circuit of insulation system, (b) Phasor diagram of insulation leakage current.

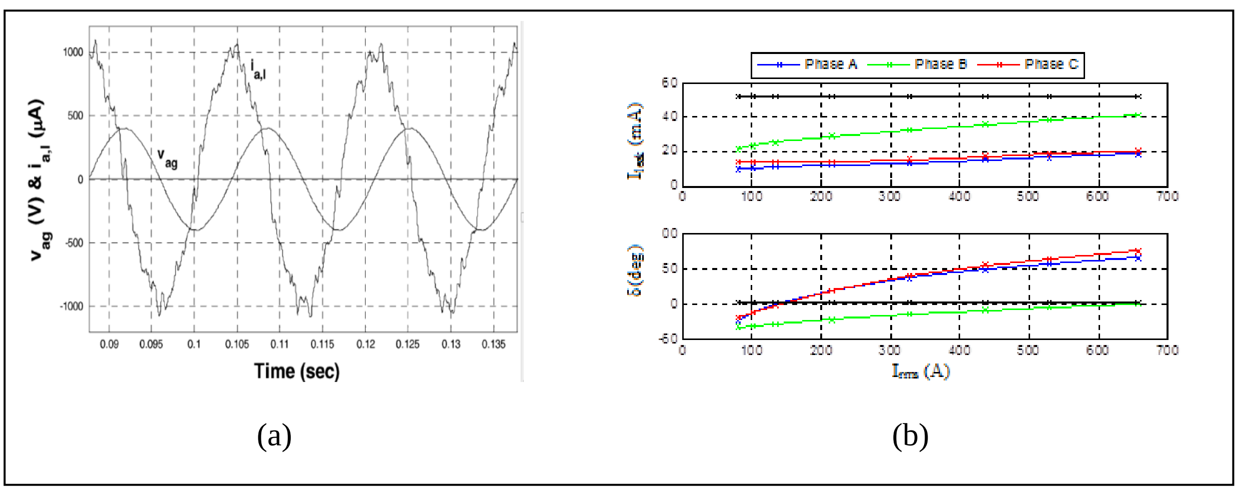

Figure 7. (a) Insulation leakage current measured on a 480V, 15hp induction motor and (b) influence of load current on online measurement of leakage current on a 12kV, 15000hp motor.

Field Installations and Evaluation of Proposed Solution – HSCT/MSIM

The HSCTs are installed in two 4160V, 3-phase induction motor as shown in Fig. 8. Insulation leakage currents on three phases are accurately measured online and insulation capacitance and dissipation factor are computed. The capacitance and dissipation factors of this motor are measured offline using a commercial capacitance bridge. Both online and offline readings match fairly accurately as shown in table-I.

Further, several accelerated aging tests have been conducted on motor insulation using severe thermal and contaminated conditions on low and medium voltage motors while they are monitored using HSCTs [9-10]. As an example, during a contamination aging test [10], salt water was sprayed (with the help of special nozzles implanted on the end-bell) on the end-winding of a 4160V induction motor while the motor was running. The three-phase insulation leakage currents and the loss angles of the stator insulation, measured by HSCTs, showed mostly increasing trend during the aging process as shown in Fig. 10-(a) [10]. The magnitudes of the leakage current and the loss angle increased significantly in the last 50-60 seconds just before the motor failure. The pre-cursor shown in Fig. 10-(b) can be effectively used to indicate near end of life for motor insulation. Such indication can avoid severe damage to motor components in the case of insulation failure. After this dramatic increase of leakage current magnitudes, the motor failed with loud arcing noise and smoke coming out of the motor. The end-winding of the motor after the failure is shown in Figure 9-(b). The black spots observed are due to failure of the end-winding insulation.

For a comparison purpose, partial discharge activities are also monitored during motor operation. PD analysis is complementary to C & DF analysis. The PD results with motor under healthy condition before spray test are shown in Fig. 11-(a), while the PD results just before motor failure are shown in Fig. 11-(b). In Fig. 11-(a), it can be observed that there are less PD pulses with lower amplitudes, as expected for a healthy motor at a relative low voltage.

In comparison, Fig. 11-(b) shows the PD activities measured just before the motor failure, aligned in time. It can be observed that the PD activities are significantly increased in both pulse numbers and amplitude, due to insulation degradation. In addition, it shows significant PD activities between phase B and phase C, since they happened at the same time with opposite polarity. This observation agrees with the leakage current measurement shown in Figure 10.

(a) (b)

Figure 8. Installation of HSCTs (a) in a 4160V, 3000 HP induction motor terminal box (b) in a 4160V, 3000 HP induction motor terminal box.

(a) (b)

Figure 9. A 4160V motor insulation (a) newly rewound (b) after the motor insulation failed during the accelerated aging test.

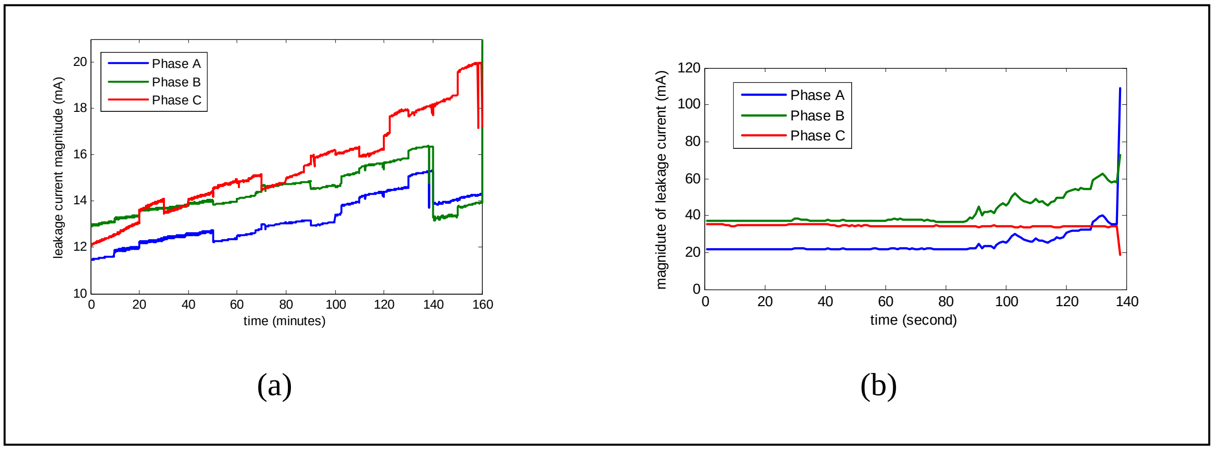

Figure 10. Magnitude of insulation leakage current (a) during the accelerated insulation aging test (b) just before the motor failed at the end of the accelerated aging test.

Table I. Comparison of C & DF from offline and online measurements

Motor Insulation Health indicator	Measurements on Motor	
	Bridge Test (Offline)	***HSCT (Online)***
Capacitance (nF)	28.4	29.4
Dissipation Factor (%)	1.12	1.31

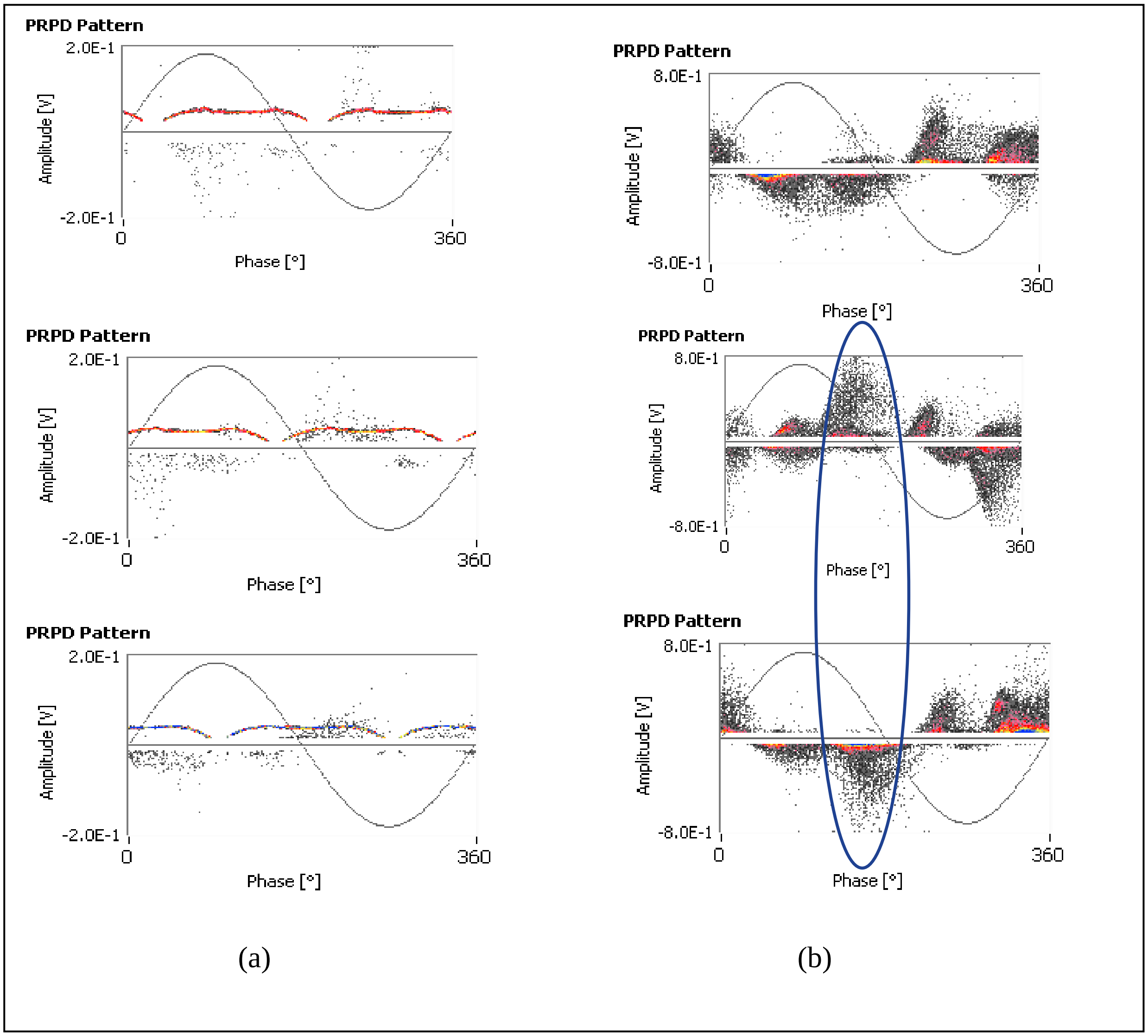

Figure 11. Partial discharge activity (a) before the accelerated insulation aging test (b) just before the motor failed at the end of the accelerated aging test.

Benefits

Following are the benefits of monitoring motor insulation with HSCT/MSIM:

- Provides online version of industry accepted insulation QA test, measurement of capacitance and dissipation factor of motor ground wall insulation
- Monitors motor insulation health online
- Provides early warning of imminent insulation failures
- Decreases overall repair and downtime cost in the event of a motor failure.

A brief comparison of HSCT/MSIM with partial discharge analyzers is provided below in Table II.

Table II. Comparison of HSCT/MSIM with PDA

Feature	PD Analyzers	HSCT/MSIM
Ease of recognition	Very complex pattern analysis	Direct measurements, Simple measurements
Algorithm usage	Very high	Low
Physical measurements	Partial discharge, phase voltages	Phase insulation leakage currents, Phase voltages, Stator temperature
Frequency of signals Measured	100kHz-100MHz	50Hz/60Hz
Applicable voltage range	Above 6.6kV	Any Voltage range. Current solution for up to 7.5kV motors
Cost	$10k-$25k	$15k-$50k
Reliability	Too much dependence on interpretation – Less reliable	Very little interpretation – More reliable
Monitoring system	Standalone	3500
Monitoring system allows other parameters	No	Yes. Multiple
Other parameters monitored for comparison	No	Yes
Fault Location	Phase identification, Slot section vs. end winding	Phase identification, Can be extended to slot Vs. end winding based on data availability

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