A Novel Technique to Detect AC Machine Turn Insulation Failure Subjected to Steep Front Impulse Waveform

Ayman El-Hag, Ahmed Gaouda, Shesha Jayaram and Saeed Ul-Haq

***Abstract*-- The stator insulation breakdown is a major cause of rotating machine failures. Ground insulation faults are easily detected by classical systems based on leakage current measurements. Also, the stator insulation failure mechanism is now well-known, as it often begins with a local turn-to-turn breakdown. One of the main causes of turn-to-turn insulation failure is due to steep front impulse voltages. Such steep front impulses can be produced due to the operation of vacuum circuit breaker. However the turn-to-turn insulation degradations are more difficult to detect. This paper proposes a new procedure for monitoring the status of the turn-to-turn insulation using the signature of the line to ground leakage current. The winding of 4 kV induction machine stator winding was subjected to turn-to-turn and turn-to-ground steep front impulse voltages with rise time of 100 ns. It has been found that the turn-to-ground current is very sensitive to turn-to-turn insulation damage and can be used to assess the insulation integrity of AC machines.**

***Keywords*: turn-turn insulation, turn-ground insulation, impulse test.**

I. Introduction

UNPLANNED downtime of industrial processes due to failure of rotating ac machine can be very expensive. The costs frequently exceed tens of thousands of dollars per hour. For example, in an off-shore oil plant, the downtime losses caused by such failures can be as high as $25,000/hour. The stator winding of an ac machine is subject to stresses induced by a variety of factors, which include thermal overload, mechanical vibrations, and voltage spikes caused by adjustable-speed drives (ASDs). It is very important to monitor the status of turn-to-turn insulation of rotating machines, when exposed to steep front voltage pulses. Most of the stator failures start as turn-turn failures, and then rapidly develop into catastrophic copper-ground or phase-phase faults [1]. Stator insulation failures involve about one third of the total number of ac machines outages in industrial environment [2]. About 80% of all electrical failures in the stator originate from a weak turn-to-turn insulation [3].

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It has been reported that classical tests like insulation resistance, polarization index and HiPot tests can't detect turn-to-turn insulation damage [4]. Different off-line and on-line methods have been developed to monitor the status of the motor turn-turn insulation system. PD measured on-line or off-line is widely used to detect turn-to-turn insulation damage for relatively large motors [5]. Recently, a new method based on the indirect measurement of the turn-to-turn capacitance of stator windings was proposed [6].

Surge testing during preventive maintenance is considered one of the most important off-line tests, which is based on applying a voltage impulse with a steep voltage front to the tested coil in the motor. This steep voltage front sets up a nonlinear voltage distribution which creates a turn-turn voltage difference. As soon as the introduced turn-turn voltage exceeds the breakdown level, current will flow through the insulation in the form of a discharge. This discharge is a parallel current path to the shorted windings of the coil, effectively reducing the winding's inductance. The authors of [4] found that error-to-area ratio (EAR) is a good indication of turn-to-turn failure during impulse test. The impulse test shows a consistently low EAR value for the winding in good health. Poor turn-turn insulation prior to turn-turn fault was found with the 20% EAR [4].

In this paper a new technique to detect turn-turn insulation failure in medium voltage ac machine coils is proposed. The proposed technique can be used off-line during preventive maintenance of rotating machines.

II. Materials and methods

The experimental setup is shown in Figure 1. It consists of a 600 kV/30 kJ, six stage impulse generator connected to a 4 kV coil. Each stage can be charged up to 100 kV. The voltage waveform is measured using a mixed divider and the current waveform is measured using a high frequency current transformer (HFCT). Both the measured voltage and current waveforms are connected to a digital oscilloscope with a 2GS/s sampling rate and a 200 MHz bandwidth.

The winding of a 4 kV form wound coil was subjected to steep front impulse voltages with rise time between 100-200 ns. Tests were done by applying voltages were applied to both turn-turn and turn-ground; and the leakage current was recorded. The turn-turn test was conducted as a destructive test to gradually damage the turn-turn insulation. On the other hand, the turn-ground test was conducted to observe the change in the leakage current in both the time and frequency domain due to the turn-turn insulation damage.

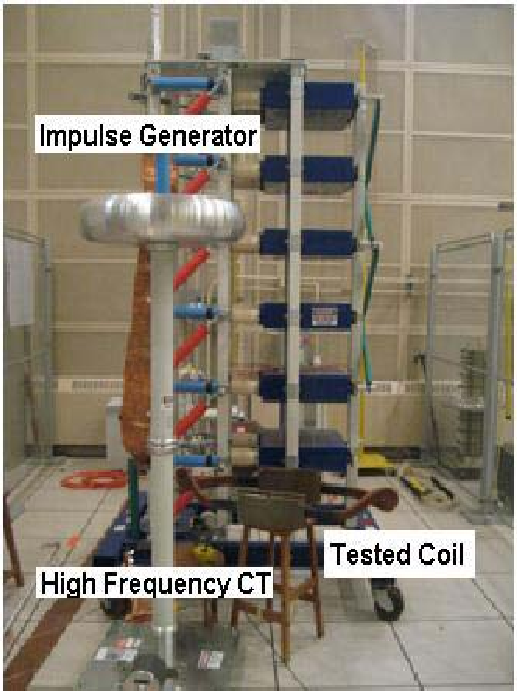


Fig. 1. Experimental setup.

III. RESULTS AND DISCUSSION

1. Turn to ground test on a healthy coil:

During turn to ground test, a 4 kV impulse is applied on the coil sample. The applied impulse magnitude is increased gradually from 6.0 kV to 12 kV in 1.0 kV step. The voltage and the current waveforms are captured at a sampling interval of 2.0 nanoseconds. The data size is 2500 samples that represent a window of 5 μs.

Figure 2 shows the applied impulse voltage during turn to ground test. Figures 2-a and 2-b present the voltage levels of 6 kV and 10 kV peaks of the applied impulses. With increased impulse peak voltages applied, a similar pattern of the voltage impulses are captured. Except for the peak, no other changes with respect to pulse shapes are observed.

Similarly, the current signals are captured during impulse test as depicted in Figure 3. For all applied pulses, high oscillation components with non-stationary features superimposed on the oscillating current waveform is detected during the steep front period. This non-stationary oscillation is changed to a more stationary pattern during the impulse decay interval. Similar to that of a voltage waveform, no changes in the signals pattern was detected, with current waveforms. Only magnitude change due to changes in the applied impulse magnitude was noticed.

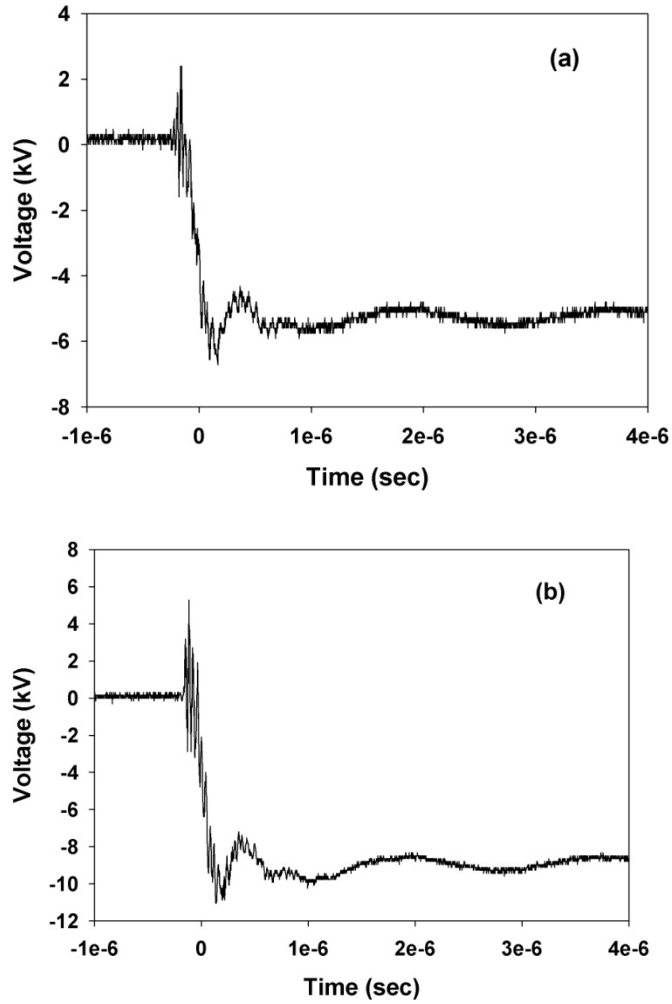


Fig. 2. Measured line-to-ground applied impulses at two different voltage levels, (a) at 6 kV and (b) at 10 kV.

2. Turn to turn test for motor insulation degradation:

In order to degrade the quality of insulation between turns, the 4.0 kV voltage level coil is placed under intensive turn-to-turn impulse test. The applied impulse is increased gradually from 12 kV and voltage waveforms are captured. Figure 4 shows the applied impulse voltage during turn-to-turn test for different voltage levels. It is evident from Figure 4 that there is no change in the voltage waveform and hence no fault is expected.

At 42 kV applied impulse, the voltage and the current show different waveforms that might represent a fault in the coil. Further to the changes in the voltage waveforms, the voltage impulse is collapsed, Figure 5.

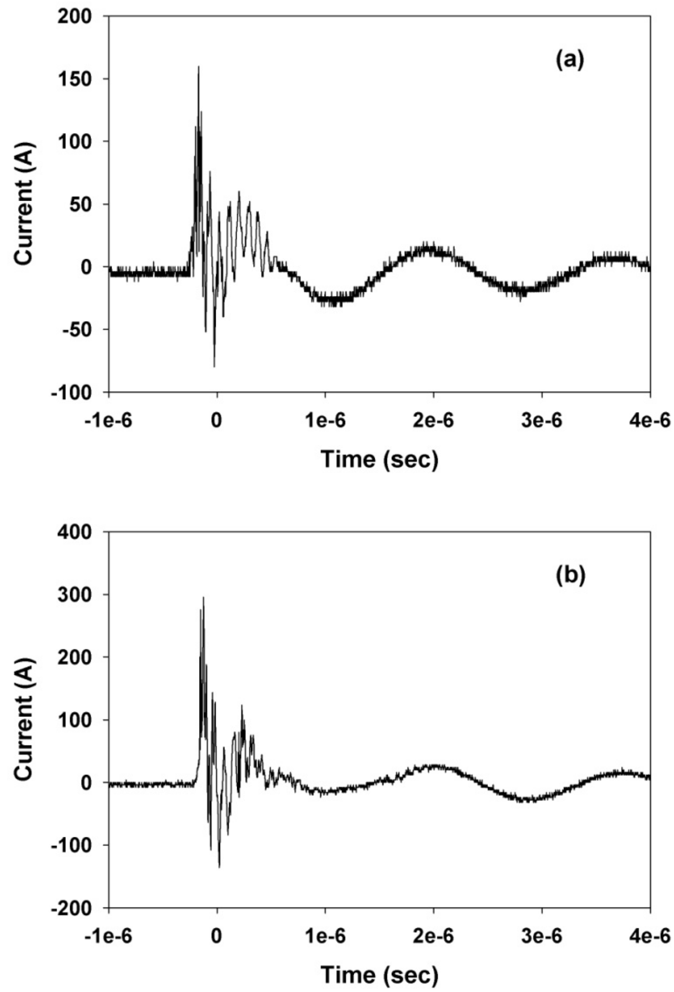


Fig. 3. Measured line-to-ground leakage currents at two different voltage levels (a) at 6 kV and (b) at 10 kV.

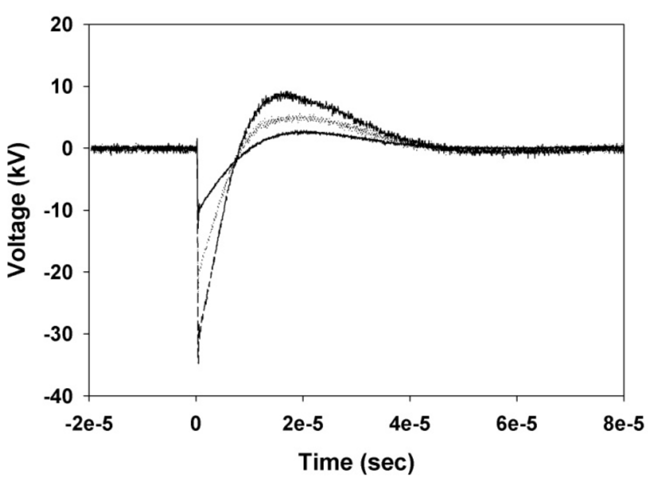


Fig. 4. Measured line-to-line applied impulses at three different voltage levels.

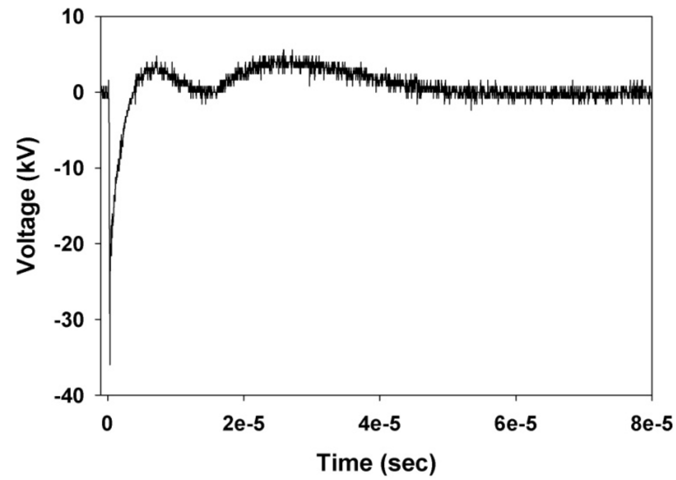


Fig. 5. Measured line-to-line voltage waveform for a failed coil.

3. Turn to ground test on a faulty coil:

Turn to ground impulse test is repeated on the degraded 4.0 kV coil sample. Similar to the previous turn to ground test (before fault), the applied impulse magnitude is increased gradually from 6.0 kV, to 12 kV; and voltage and the current waveforms are captured at the same sampling rate and data size.

The captured current signals show similar pattern for different applied voltage impulses. The current signals at both 6.0 kV and 10 kV applied impulses are shown in Figure 6. Comparing the leakage current waveforms before fault (Figure 3) and after fault (Figure 6) at the same two voltage levels, the following observations have been made:

a) The peaks of all current signals after fault are smaller than those before faults. No change was observed on the voltage magnitude. For example, the voltage waveform at 10 kV is shown in Figure 7 and it is very close the voltage waveform before the fault (Figure 2-b). So, such drop in the current magnitude could be attributed to an increase in the coil impedance.

b) The intensity of the oscillation components superimposed on the current signal during the impulse voltage rise time is reduced after the fault. On the contrary, no change on the oscillation during the fall time was observed.

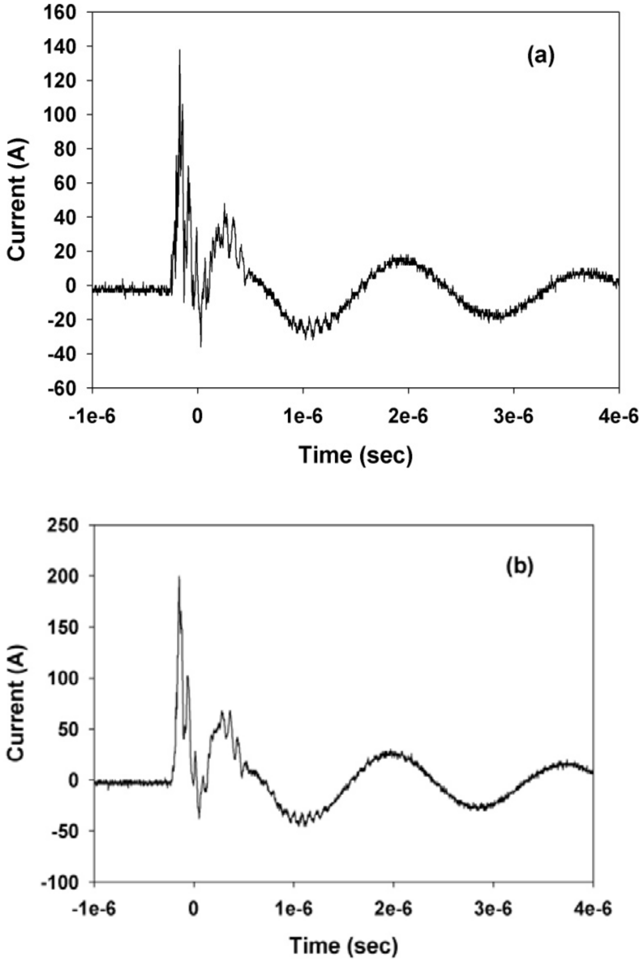


Fig. 6. Measured line-to-ground leakage currents at two different voltage levels for faulty coil. (a) at 6 kV and (b) at 10 kV.

To further analyze the current signal, the fast Fourier transform (FFT) is implemented on the signals before and after turn-to-turn insulation failure. The frequency components of the current signals (before and after fault) localized within the frequency band up to 18MHz. A zoomed version of the frequency components localized within 0-8 MHz range and 7.5-18 MHz range are shown in Figure 8. The FFT are extracted for the current signals at both 6 and 10 kV before and after turn-to-turn insulation failure.

It was noticed that at 2-3 MHz frequency-band no significant changes are detected before and after fault as the applied impulse test voltage is increasing. However, before fault, FFT shows large frequency component localized at 10-12MHz frequency band. After fault, this frequency component is weakened and spread over a wider frequency band of 11.5-14.5MHz.

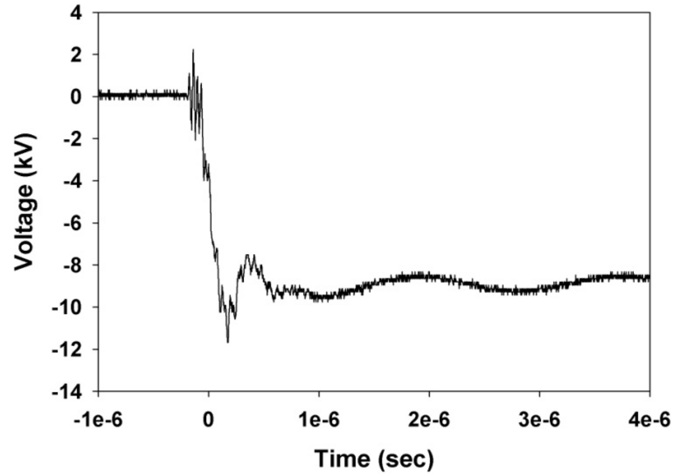
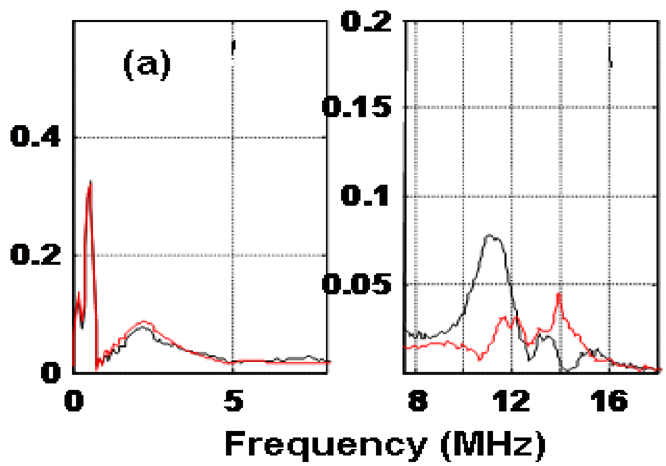
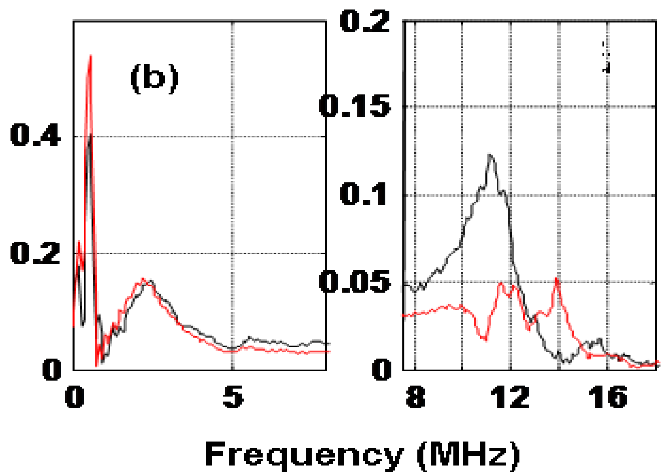


Fig. 7. Measured line-to-ground applied impulses at 10 kV after turn-to-turn failure.



(a)



(b)

Fig. 8. FFT of the measured line-to-ground leakage currents at two different voltage levels before and after turn-turn failure. (a) at 6 kV and (b) at 10 kV.

To confirm the failure of the coil, the voltage was reapplied till physical damage in the coil was noticed as shown in Figure 9.

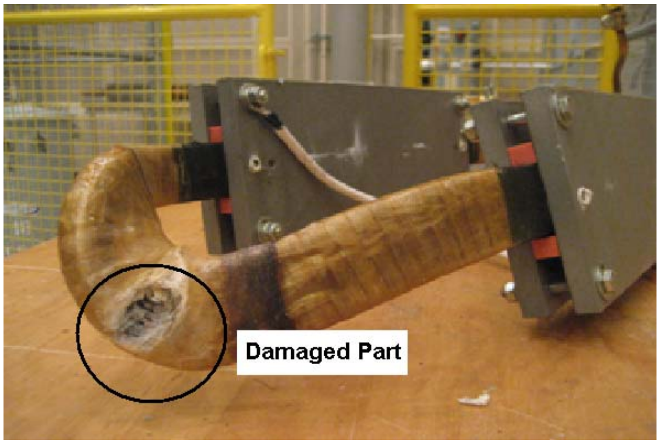


Fig. 9. 4kV coil damaged due to turn-turn failure.

The leakage current was re-measured after the physical damage was noticed in the coil, Figure 10. Distinct difference in the current signature was noticed compared to the previously measured leakage currents, before and after the faults, Figures 3 and 6 respectively. The disappearance in the current damping is an indication of the internal short circuit of the coil due to the complete turn-turn failure.

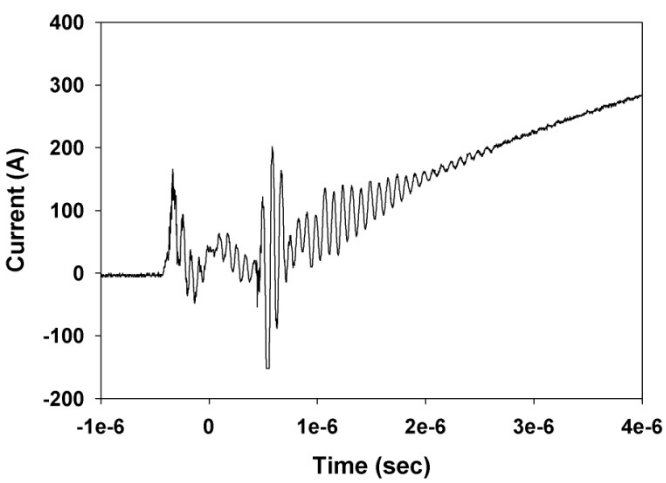


Fig. 10. Measured line-to-ground leakage currents at 8 kV.

The changes in the signature of the line-to-ground current can further be investigated to design an automated monitoring tool to detect the early stages of turn-to-turn failures. The large sets of laboratory data collected from HV labs show promising features to propose a more reliable line-to-ground current based warning system for early detection of turn-to-turn insulation failure.

IV. Conclusions

The leakage current measured during line-to-ground impulse test has been used to detect the turn-to-turn machine insulation failure. It was noticed that significant reduction in the high frequency oscillation of the leakage current has occurred after the turn-to-turn insulation failure. Such reduction in the oscillation was also observed in the frequency content of the leakage current. Such technique could be used to detect turn-to-turn insulation damage during preventive maintenance of ac machines.

V. Acknowledgment

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VI. References

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