Impulse Testing as a Predictive Maintenance Tool

E. Wiedenbrug SM IEEE, G. Frey M IEEE, J. Wilson, M IEEE
Baker Instrument Company
engr@bakerinst.com

Abstract:

Impulse testing is an integral part of predictive maintenance of electrical motors. Through the following questions the influence that extensive impulse testing has on a motor is investigated. Can impulse testing damage healthy or deteriorated insulation? Can DC Resistance, Inductance, Megger or HiPot tests diagnose weak turn-to-turn insulation? After failing an impulse test, are motor with weak insulation able to operate? Are motors with a turn-turn short capable of continued operation? This was accomplished by putting a low voltage motor through extensive testing rigors, until inducing a failure. Following the failure, additional testing investigated the possible deteriorating effects on turn-turn insulation due to impulse testing beyond the motor's dielectric breakdown. NOTE: This paper was edited from the original version of the IEEE paper published in 2003.

I. Introduction

Unplanned downtime of industrial processes is very expensive, frequently with costs exceeding tens of thousands of dollars per hour. It is crucial to utilize scheduled plant downtime, during planned maintenance periods, for identifying equipment likely to fail. Identification of weak motors, and their replacement or repair during a planned outage, is more cost effective than the associated costs of unscheduled plant downtime and rushed repairs.

A. Insulation Failure Mechanisms

According to IEEE and EPRI [1-2] studies, insulation faults are associated with 26-36% of motor failures. D.E. Crawford's investigations on failure mechanisms of motors concluded: "the great majority of failures seemed to be associated with wire" [3]. "This results in low power intermittent arcing which causes erosion of the conductor until enough power is drawn to weld them. Once welding has occurred, high induced currents in the shorted loops lead to rapid stator failure". He states: "the ultimate motor failure on a motor returned from the field may not indicate what initiated the failure". In short, most of the stator failures start as turn-turn failures, rapidly developing into catastrophic copper-ground or phase-phase faults.

Internal currents are induced in the motor as soon as an insulation failure reaches a turn-turn short. "These currents have the order of twice the blocked rotor current". Tallam, Habetler and Harley [4] state that "If left undetected, turn faults can propagate, leading to phase-ground or phase-phase faults." The blocked rotor currents are upwards of 6-10 times rated current. The heating energy is proportional to I^2R, which leads to the expected 14,000% – 40,000% of rated wattage deteriorating the insulation in the faulted turns. A basic rule of thumb is, for every additional 10°C the winding deteriorates at twice the rate. Excessive heating by turn-turn shorts is the reason why faulty motors will almost always fail in a matter of minutes if not seconds.

B. Fundamentals of insulation testing:

The most common field tests for ensuring insulation integrity are:

DC coil resistance (IEEE Std 118) [7]

Stator inductance (no standard)

Insulation resistance, (IEEE Std 43) [8]

HiPot (IEEE Std 95) [9]

Polarization index (PI) (IEEE Std 43) [8]

Impulse test (IEEE Std 522, IEC 34-15, NEMA MG1) [4, 10, 11]

II. FUNDAMENTALS OF IMPULSE TESTING

Impulse testing is based on sending a voltage impulse with a steep voltage front (high dV/dt) to the tested coil in the motor. This voltage impulse is generated by quickly discharging a capacitor into the windings of the motor. This steep fronted voltage sets up a nonlinear voltage distribution in the coil similar to the ones observed in PWM drives [12-14]. This nonlinear voltage distribution creates a turn-turn voltage difference. By ramping the amplitude of subsequent voltage pulses sent to the motor, the voltage introduced between turns of the same winding is also ramped. The energy from the capacitor that was discharged onto the windings sets up a dampened oscillation between the motor's inductance L, the capacitor C, and the system's resistance, R. This oscillation has an internal frequency f according to [10] of:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{1}$$

Any weak turn-turn insulation within the motor will have a low failure voltage. While the introduced turn-turn voltage is below failure voltage level, there will be no current flowing through the weak insulation. Discharge current will flow through the insulation as soon as the introduced turn-turn voltage exceeds the breakdown level. This discharge represents a current path that is in parallel to the shorted windings of the coil, and has the effect of reducing the winding's effective inductance.

Changes in the effective inductance of the motor that occurs during the internal discharge increases the frequency of this oscillation.

Impulse testing equipment monitors the voltage trace at the coil terminals or the terminal leads to the motor. This determines the increase in frequency. This frequency increase is easiest viewed by a 'shift to the left' of the impulse waveform as shown in Figure 1.

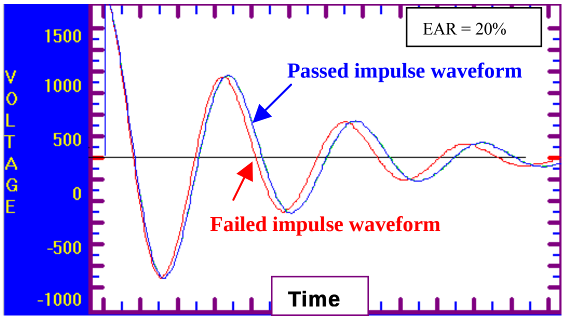

Figure 1: Passed and Failed Impulse Waveforms

This shift to the left can be very slight. For that reason it is advisable to utilize a numeric method of observation which allows an accurate, repeatable and unbiased assessment. One such method is the Error to Area Ratio (EAR). The EAR is defined as:

$$EAR_{1-2} = \frac{\sum_i abs\left(F_i^{(1)} - F_i^{(2)}\right)}{\sum_j abs\left(F_j^{(1)}\right)} \tag{2}$$

where $F^{(1,2)}$ are the two waveforms; and i, j are summation of the samples of the digitized waveforms. Identical waveforms will have an EAR of 0%, while very similar waveforms will have EAR of few percent. In a production environment, phase-phase comparison of impulse waveforms is commonly performed before the motor is assembled. This allows for identifying weak turn-turn insulation, as well as reversed coils or different numbers of turns per phase. In PM applications, subsequent pulses of the same winding are compared during the ramping of the pulse voltage. This has the advantage that the rotor position does not influence the test, while still investigating turn-turn insulation. An EAR of 5%, for example, is very difficult to discern on the display, yet can be the symptom of a failed winding.

Impulse testing and some of the insulation deterioration mechanisms are similar. Therefore it is of interest to investigate whether impulse testing, as commonly performed in Predictive Maintenance (PM), could deteriorate insulation condition.

III. Test Protocol

The study test protocol was designed to answer the questions asked by exposing one motor to the rigors of testing. The first test motor is a new factory 5hp 6 pole 460V connected dual voltage Hemco Global HE EPACT Compliant motor with a rated current of 7.7A, rated speed of 1170rpm and a 215T frame. This motor was chosen because it was the least expensive new motor with these ratings. The hope was that the least expensive motor gave a lower average in insulation quality. In order to have a baseline reading of all tests, the motor was tested prior to starting the study.

Table 1: Testing New Motor

DC Resistance	Phase 1-2: 1.88 Phase 2-3: 1.78 Phase 3-1: 1.88
Insulation Resistance	20 GΩ
HiPot	Pass
Impulse	1-2% >=2kV

The first question, whether impulse testing damages healthy windings, was investigated by exposing the motor to 3 million impulses at the suggested 2kV voltage level. To perform a normal test, modern impulse testers ramp each phase of a 460V winding with approximately 80 impulses of voltage levels increasing from 0V to 2kV. A very intensive PM program will test each motor up to twice a year for turn-turn insulation quality. This frequency of testing would expose a motor to a total of 3 million pulses (one million per phase) only after the motor was in operation for over 6,200 years.

DC resistance per phase, insulation resistance, HiPot and Impulse test including EAR were recorded prior to each set of 3 million impulses. The PI test was not performed because IEEE 43 suggests no useful PI information will be obtained by testing such small motors.

Table 2: Results from Suggested Test Voltage Level

	Results
DC Resistance	Phase1-2: 1.88 Phase2-3: 1.78 Phase 3-1: 1.88
Insulation Resistance	20.4 G Ω
HiPot	Pass
Impulse	Pulse-Pulse EAR: 1-2% <= 2kV

To allow for possible misuse of the impulse tester when checking a motor's turn-turn insulation, we tested the motor, again for 3 million impulses at both, 3kV and 4kV. This represent 150% and 200% over suggested test voltage. The same results were seen after this testing was done.

Table 3: 150% - 200% Testing Voltage

DC Resistance	Phase 1-2: 1.88 Phase 2-3: 1.78 Phase 3-1: 1.88
Insulation Resistance	20 GΩ
HiPot	Pass
Impulse	1-2% >=4kV

Since the question whether impulse testing deteriorates already damaged insulation needed evaluation too, we manufactured a weakness within the insulation. This was achieved by repeating the 3 million impulses at successive 1kV increased levels, until failure occurred.

This failure took place at a 7kV level, or 350% over the recommended test voltage. After failure, subsequent impulse tests showed the punctured insulation to have a breakdown voltage of 1700V. Again, we recorded DC resistance, Insulation Resistance, HiPot values and EAR.

Table 4: Results of Testing After Applied Weakness

	Results
DC Resistance	Phase 1-2: 1.88 Phase 2-3: 1.78 Phase 3-1: 1.88
Insulation Resistance	20.4 GΩ
HiPot	Pass
Impulse	20% > 1.7kV

In order to investigate whether impulse testing further damages already damaged insulation, an additional 20 million impulses were performed on the failed phase at voltage levels above failing voltage level. The attempt here was to further deteriorate the motor and try to induce a lower failure voltage level. After concluding this additional testing, DC resistance, insulation resistance, HiPot and EAR were recorded.

To assess whether a motor that has failed the impulse test is still capable of running, we performed repeated starts on this motor. During this process we monitored voltage spikes on phase *A* (the failed phase) which happened during the closing and the opening of the breaker process. A Tektronix TDS360 Oscilloscope captured the traces utilizing a Tektronix P6015A High Voltage Probe. Steady state operation was recorded with Fluke 77 multimeters and clamp-on probes.

The motor withstood 42 starts and stops, running under normal operation after each one of these starts. On the 43rd start the motor started to sound louder, like an overloaded transformer. Within 40 seconds data was taken on the stator currents. Motor operation was stopped due to the amount of smoke released by the motor, and the fire hazard. The currents prior to the turn-turn short were balanced, 7.2A per phase. The stator currents during the 40 seconds of operation with the turn-turn short were: Phase *A* = 11.9A; Phase *B* = 8.3A; Phase *C* = 7.2A.

After finishing these tests, we measured once more the DC resistance, insulation resistance, HiPot and EARs.

Table 5: After Short Turn

DC Resistance	Phase 1-2: 1.85 Phase 2-3: 1.78 Phase 3-1: 1.78
Insulation Resistance	20 GΩ
HiPot	Pass
Impulse	25% any voltage

IV. Results

The testing is divided into four segments:

Prior to test: The motor is in mint condition

Prior to impulse failure: The motor has withstood over 20 million impulses ranging from 100% rated testing voltage to 300% rated testing voltage without breaking down.

Prior to shorted failure: The motor has been exposed to additional 20 million impulses above the 1700V breakdown voltage.

After shorted turn-turn: The motor has started, ran and stopped 42 times without noticeable deterioration, and additionally started a 43rd time with a shorted turn-turn fault. It ran less than 40 seconds in this condition, during which it released smoke, and was stopped due to fire hazard.

Table 6: Complete Results

	Baseline	2kV Test Voltage	3-4kV Test Voltage	Introduced Weakness	Post 43 Starts & Stops
DC Resistance					
Phase 1-2	1.88	1.88	1.88	1.88	1.85
Phase 2-3	1.78	1.78	1.78	1.78	1.78
Phase 3-1	1.88	1.88	1.88	1.88	1.78
Insulation Resistance	20.4 GΩ	20.4 GΩ	20.4 GΩ	20.4 GΩ	20 GΩ
HiPot	Pass	Pass	Pass	Pass	Pass
Impulse (Pulse-Pulse EAR)	1-2% <=2kV	1-2% <=4kV	1-2%<=2kV	20% >1.7kV	25% any Voltage

A. DC Resistance Values:

All resistance values remained constant per phase until the shorted turn-turn failure occurred. The stator resistance showed no difference from the impulse testing, neither before nor after the insulation was broken down. The DC resistance test is a low voltage test that checks the copper of the stator windings. It does not offer predictive maintenance value for turn-turn insulation.

B. Insulation Resistance:

Insulation resistance values of the winding at the different stages of testing were obtained with 500V DC test voltage.

The copper-ground insulation resistance remained constant throughout the test until the shorted turn-turn condition was established, and parts of the windings were heated up beyond the release of smoke. Until the shorted turn-turn currents caused excessive heat, the Insulation Resistance offered no sign that pointed to possible winding deterioration. After cooling down, the copper-ground resistance dropped by 400 MΩ.

C. HiPot:

The HiPot test passed at every instance. After completion of all other testing, the HiPot failure voltage level was found to be 3040V. This relatively low voltage level can best be explained by the damage of the copper-ground insulation that the excessive heat caused during the turn-turn insulation.

D. Impulse Testing:

The impulse test shows a consistent low EAR value for winding in good condition. Once the winding shows poor turn-turn condition, the value jumped up significantly, yet the motor was still operational.

2kV is the common voltage level for PM testing of 460V motors. Table V shows the number of pulses and their associated voltage level withstood by the motor previous to failure:

Table 2: Voltage Level, % Rating, # of Pulses, Cumulative Years of Intensive PM Testing

Voltage Level	% rated	Impulses	Cumulative years
2,000V	100%	3,276,000	6,825
3,000V	150%	3,536,000	14,191
4,000V	200%	4,536,000	23,642
5,000V	250%	3,546,000	31,029
6,000V	300%	5,175,000	41,810

The healthy motor's winding saw a minimum of over 3 million impulses at each of the five voltage levels. The total number of impulses adds to more than 20 million. Normally, a 480V motor sees 80 impulses per phase per test using the computerized ramp rate. Testing a motor twice a year leads to a total of 480 impulses between 0V and 2kV. In order for a normal motor to see 20 million impulses due to testing, it would need to operate an equivalent of over 41,000 years with a consistent aggressive maintenance schedule. In addition to this very unreasonable number of pulses that the tested motor saw, their average size was of two to three times recommended amplitude.

This absolutely unrealistic rough testing performed on the motor did not cause any noticeable deterioration on the winding until the voltage level of the test was elevated to 7kV, or 350% rated testing voltage level.

The EAR remained constantly low during all the previous testing, between 1% and 2%.

The impulse wave shape and the EAR changed only after the insulation broke down. The breakdown lowered the passing voltage level to 1,700V. Any voltage above that caused the EAR to be 20%; while any voltage below this kept the winding from discharging turn-turn with an EAR of 1%.

The additional 20 million impulses that were sent to the motor above the new 1700V breakdown voltage level, did not change the breakdown inception. The breakdown voltage level remained at 1700V even after 20 million discharges. It was not possible to alter the discharge inception voltage by forcing an unrealistic large amount of discharges in the weakened insulation.

E. Start and Stop stress test:

D.E. Crawford [3] verified the hypothesis of wire-wire motion during startup by using high-speed filming. Weak insulation needs less stress to failure than healthy insulation. B.K. Gupta et al [15] monitored surge transients in power systems. They conclude that opening of breakers, but also their closing, cause voltage surges in the system.

In order to further stress the motor, it was subject to multiple starts and stops. Monitoring of phase *A* voltage with a scope and triggering for surges delivered a number of events where the motor was exposed to transient voltage spikes induced by the operation of the breaker. Compared to startup of a motor, an impulse tester's energy delivered to the winding is very limited and controlled. It does not suffice to set the windings in motion and have them rub against each other. The rubbing of the windings against each other can cause a turn-turn short, and the potentially available energy feeding into the fault is limited only by the over-current protection of the motor. Catastrophic failures are a natural consequence.

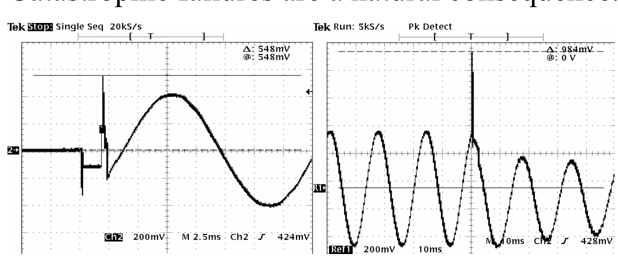

Figure 3-4: Startup and turnoff voltage surge.

Figures 3 and 4 show voltage surges that were captured during starting and stopping of the motor. The stresses introduced into the winding during startup and stopping process were twofold: rubbing of wires against each other, and voltage surges coming from the power system. These stresses were the cause of the shorted turn-turn.

V. Conclusions

Very extensive impulse testing of a 5hp, followed by multiple starts and stops under normal line conditions and high load and excessive startup testing of a 1hp motor lead to the following conclusions:

Exaggerated amounts of impulse testing performed on rated impulse testing levels did not break down healthy insulation of the motor. Increasing the voltage levels to 150%, 200%, and even 250% and 300% while exposing the motor to excessive pulses, did not break down the insulation.

Weakened insulation, tested at voltage levels above breakdown showed no additional signs of deterioration, even after extreme repetitions of discharges in the weak insulation.

The weakened insulation could not be detected neither by DC resistance readings, nor by Insulation Resistance (Megger), nor by HiPot measurements. The only reliable test showing the weakness of the insulation prior to a turn-turn short was the impulse test.

The motor with the weak insulation was very capable to run steady state. It also withstood multiple starts and stops. One of these starts caused the motor to have a turn-turn short.

The motor smoked within a minute of having a turn-turn short and running under a normal load condition, confirming the very rapid development of a catastrophic failure to the motor once the turn-turn fault occurred.

DC resistance were capable of finding the fault only after it had occurred. Finding a shorted turn-turn fault has little, if any value from a predictive standpoint, since the motor typically fails within few minutes if not only seconds of the short, as confirmed in the test series.

VI. References

[1] "Report of Large Motor Reliability Survey of Industrial and Commercial Installations", Parts I and II, Motor Reliability Working Group, IEEE IAS Transactions Vol IA-21, No. 4, pp. 863, 1985.

[2] "Improved Motors for Utility Applications", EPRI EL-4286, Vol. 1&2, pp 1763, 1982.

[3] D.E. Crawford, "A Mechanism of Motor Failures", IEEE 1975.

[4] "Impulse Voltage Withstand Levels of Rotating a.c. Machines with Form-Wound Stator Coils", IEC 34-15, 1995.

[5] J.A. Oliver, "Electric Motor Predictive and Preventive Maintenance Guide", EPRI NP-7502s, 1992.

[6] N.K. Ghai, "Design and Application Considerations for Motors in Steep-Fronted Surge Environments", IEEE IAS Transactions, Vol. 33, No. 1, 1997, pp 177.

[7] "IEEE Standard Test Code for Resistance Measurement", IEEE Std 118-1978.

[8] "IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery", IEEE Std 43-2000.

[9] "IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage", ANSI/IEEE Std 95-1977.

[10] "IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines", IEEE Standards Board, IEEE Std 522-1992.

[11]NEMA, "Motors and Generators", NEMA Standards Publication No. MG1-1998.

[12] M. Melfi, J. Sung, S. Bell, G. Skibinski, "Effect of Surge Voltage Risetime on the Insulation of Low Voltage Machines Fed by PWM Converters", IEEE IAS Conference, 1997, pp. 5_7.

[13]Y. Tang, "Analysis of Steep-Fronted Voltage Distribution and Turn Insulation Failure in Inverter Fed AC Motor", IEEE IAS Conference, 1997, pp. 11_6.

[14] H.A. Toliyat, G. Suresh, A. Abur, "Simulation of Voltage Stress on Inverter Fed Induction Motor Winding Supplied through Feeder Cable", IEEE IAS Conference, 1997, pp. 3_7.

[15]B.K. Gupta, B.A. Lloyd, G.C. Stone, S.R. Campbell, D.K. Sharma, N.E. Nilsson, "Turn Insulation Capability of Large AC Motors. Part 1 – Surge Monitoring", IEEE Transactions on Energy Conversion, Vol. EC-2, No. 4, December 1987.

[16]G.C. Stone, S.R. Campbell, "Development of an On-line Monitor to Measure Motor Voltage Surges", IEEE EEIC Chicago, 1997, pp 397.

[17]NEMA MG 10-1994, "Energy Management Guide for Selection and Use of Polyphase Motors", National Electrical Manufacturers Association, 1994.