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Modern High Voltage Testing, with comparison to vintage High Voltage Testing, Vs impedance based circuit analysis/measurement (i.e. low voltage "testing")

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I. Introduction

Since the early 1980's new technologies have been developed that perform high voltage evaluation of your electrical rotating machinery. Prior to this development, high voltage test equipment was primarily manually controlled, and thus subject to miss-application by untrained or uncertified personnel. Through necessity high voltage equipment vendors needed to warn users of the potential for incorrectly performed testing. As technology developed and improved, the already small risk to rotating machinery became minimized even further. As marketing forces became aware of the technological advances, it became necessary to discuss why the critical difference between pre-1980's equipment, modern equipment, and impedance based circuit analysis (low voltage testing) exists.

This paper discusses the differences between manually controlled high voltage testing, modern microprocessor controller high voltage test techniques and impedance based circuit analysis. For de-energized circuit analysis, modern high voltage testing is used to detect: incipient cable faults, winding faults, both to earth and turn to turn, winding contamination and partial discharge's between turns and to earth. This is done with low energy, high voltage impulses, microprocessor controlled with instantaneous fault detection.

II. Modern High Voltage Technology

Modern techniques of high voltage testing are designed and standardized to evaluate the electrical health of an entire electric motor system. This includes the ability to test from the motor control center, the feeder cable run, the windings and the rotor or armature of the AC or DC rotating machine. This means the tests are capable of detecting and locating incipient: cable faults, winding faults, insulation to ground faults, motor contamination and other problems such as leaking check valves located in the driven load.

The advances in high voltage testing since the 1980's have been many. Modern high voltage testers use modern high speed electronic evaluation of changes to resistance, leakage current, leakage current versus time, voltage, step-voltage, Dielectric-absorption, frequency response, wave shape, C.I.V. and more to detect faults at or under the levels of energy exposed to the motor during operation. The microprocessor controlled instantaneous trips allow winding condition to be evaluated without compromising dielectric integrity. The addition of field developed PASS/FAIL test criteria makes the testing extremely repeatable. One of the major advances is in solid-state high voltage power supplies, replacing the heavy step up transformer. This results in a large improvement to the portability of the equipment. Every test is digitized and compared to the previously applied pulse. If any weakness is detected the test is instantaneously stopped, preserving dielectric. The level of weakness is stored for future reference, in the memory bank.

Ten's of thousands of critical motors, in actual applications, continue to be evaluated, yearly, at over 5000 industrial locations around the world. As opposed to studies where a few dozen motors are currently being evaluated, this data has already provided meaningful trending results. These

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trends correspond to field studies of rotating machine failure rates. The time required for motor failure has already been known for many years, with a study performed jointly by Baker Instrument Company and Owens Corning during the 1980's.

Fig 1: Modern High Voltage Test Instrument

"Studies have shown that many motor failures begin as turn-to-turn shorts within a single winding. These turn-to-turn shorts then create hot spots which in turn degenerate the insulation in adjacent turns until the entire winding fails. The mechanism of this type of failure may take three to six months, or more, depending upon the operating parameters of the motor".[1]

The following statement, made in 1985 was certainly predictive!

"Improvements in surge test equipment will include automatic test evaluation and interruption to obviate operator interpretation and the risk of damage. Development work is under way to demonstrate the feasibility of computer control of such a device".[1]

III. Vintage 1980's high voltage technology

[1] Schump, David, President, Baker Instrument Company, "An introduction to the testing of insulation systems in electrical apparatus" 1986 International Coil Winding association refereed paper.

Back in those days, there was no way for an operator of a 1980's style tester to guarantee motor dielectric after a fault was detected. Fortunately - technology has changed since then. A 1980 vintage tester was completely manually controlled, and simply incapable of providing an instantaneous trip. In other words, the operator was ENTIRELY responsible, both to perform the test to the correct voltages and then interpret the results. He simply could not release the switch fast enough to react, even if he cared to!

The 1980's vintage technology surge comparison tester was (and is still) used as a Q.C. tool to detect and diagnose many winding faults. For example: incorrect winding connection, turn to turn insulation integrity, phase to phase insulation integrity, incorrect turns count, backwards coil groups. The better 1980's vintage surge tester's manufactured by Baker Instrument Company included a DC HiPot function, which is used to verify the status of the insulation to ground.

The design of the testers of this era was limited by the technology available at the time. For example, the commonly used LCD display of 2003 did not exist in 1983, making the use of phosphor CRT technology for display a prominent design consideration. Since the display technology available in that era was not capable of making a persistent display appear, high frequency surge pulse application was required. In those days, 60 or more surges per second were required simply to refresh the phosphor CRT.

Fig 2: Vintage Surge Tester

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Sometimes described as “High Frequency Surge Testers” they apply 60 surges per second to the winding. The surges are generated by large, heavy step up transformers and variable transformer to manually control the tests. These machines are certainly effective at what they do, by brute force application of high voltage, with no instantaneous fault detection capability, and no current limits. If a coil or motor passes the test, quality is assured. If a coil or motor fails this type of test, due to the lack of instantaneous trips, current limits and need for operator intervention - damage may possibly occur.

A good analogy is operating a motor vehicle. Safe operation requires the avoidance of other vehicles, following speed limits and minor items such as driver intervention to stop at a red light.

Properly performed high voltage testing by trained personnel presents a minimal risk to rotating equipment, just as properly performed operation of a motor vehicle presents minimal risk to driver safety.

IV. Are impedance based circuit analysis/measurements (i.e. low voltage “testing”) predictive?

Webster’s Collegiate Dictionary defines prediction thus:

Main Entry: **pre·dict**
Pronunciation: pri-'dikt
Function: *verb*
Etymology: Latin *praedictus*, past participle of *praedicere*, from *prae*- pre- + *dicere* to say -- more at DICTION
Date: circa 1632
transitive senses **: to declare or indicate in advance**; *especially* **: foretell on the basis of observation, experience, or scientific reason.**

One of the recently made claims in the marketplace is that low voltage impedance based measurements, i.e. “tests” are now miraculously capable of making predictive measurements of high voltage insulators. The marketer claims that this is now available because of sudden, new technological breakthroughs. These measurements are reported to be able to proof any and all rotating machines as fit for continued service.

“Results can be found in motors from fractional to over 10,000 horsepower”.[2]

The marketer discusses his predictive findings about motor insulation life in the form of a refereed paper presented at the EIC/EMCW conference 2003. According to this paper:

“The insulation between conductors is stressed, causing a change to the resistive and capacitive values of the insulation at the fault point. High temperatures and similar reactive faults result in carbonization of the insulation at that point”.[3]

The wording of this statement is very similar to the findings published by Baker Instrument Company nearly 20 years ago![1]

It also reveals the winding must already have a copper-to-copper fault present to generate I2R losses at the fault point, before the impedance measurement can detect it. It is the gross overheating of the shorted turn conductor, due to autotransformer effect that carbonizes the insulation. [11]

[2] Penrose, Howard W, Ph.D. “Applications of motor circuit analysis for predictive maintenance, reliability and quality control” EMCW 2000

[3] Penrose, Howard W, Ph.D. “Estimating motor life using motor circuit analysis predictive measurements”, IEEE EIC refereed paper, EIC/EMCW conference 2003

[1] Schump, David, President, Baker Instrument Company, “An introduction to the testing of insulation systems in electrical apparatus” 1986 International Coil Winding association refereed paper

[11] IEEE Transaction on Industry applications, Vol38, No3 May/June 2002
Habertler, Tallam, Hartley. “Transient Model for Induction Machines With Stator Winding Turn Faults”

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The marketer then reveals that the studies do not include any medium or high voltage apparatus of any type:

"The motors covered by this paper will include low voltage (<600 Vac), standard integral three phase motors, operating an average of 4000 hours per year".[3]

Therefore, how can this technology make a meaningful predictive analysis of medium and high voltage rotating equipment?

V. Is Modern High Voltage Testing Destructive?

A published survey (2001) of utilities routinely performing High Voltage testing was the source of this information:

"Does HiPot testing damage a good winding? This question is raised many times, most often by managers, who have to approve the tests. The answer is a resounding NO. HiPot tests do not introduce any significant degradations in a machine with a good insulation system. Machines that have failed a HiPot test have ALWAYS revealed poor insulation systems upon later examination."[5]

Modern High Voltage test equipment has many built in instantaneous trips, which simply did not exist 20 years ago. As an example, the over-current trip function of modern Baker Instrument Company equipment can be activated with less than 1 micro-amp of leakage current.

The Maintenance Engineering Handbook 6th edition 2002 is even more descriptive:

"The surge test is a method for evaluating turn-to-turn insulation within the coils. THIS IS A NON DESTRUCTIVE TEST which indicates shorts and dissymmetries such as incorrect number of turns in a given coil".[6]

The new P – P Error Area Ratio analysis algorithm can reliably detect the slightest wave shape discrepancies and is capable of tripping the tester off even before turn-to-turn conduction can occur. The P – P EAR analysis looks at the tiny differences in the wave, and is capable of detecting partial discharge activity between insulated conductors.

The Meg-Ohm test is configured with instantaneous trip protection, preventing the continued application of further tests once compromised insulation has been detected. The Dielectric Absorption, Stepped DC, Continuous Ramp, and the HiPot tests are microprocessor controlled, which minimizes the possibility of any test error. If instability exists in the insulation system, the automated test will conclude with a user safety discharge period.

"Direct voltage over-potential testing is generally considered a controlled, NON-DESTRUCTIVE test in that an operator, utilizing a suitable test set can often detect marginal insulation from the behavior of measured current. It is therefore possible, in many cases to detect questionable insulation and plan for replacement without actually breaking it down under test"[7]

When a weak rotating machine has been identified using these techniques, there is a window available where a minor overhaul such as a clean dip and bake, will restore much of the integrity of the insulation system. However, this cost savings opportunity could be lost if the motor is kept in service until insulation to ground failure. When insulation fails to ground, the core components of the motor could be irrevocably damaged, a fact well known to EASA:

[5] Gupta, Stone, Stein, "Use of machine Hipot testing in electric utilities" 0-7803-7180-1 IEEE, 2001

[6] Higgins & Morrow, "Maintenance Engineering Handbook, 6th Edition, 2002"

[7] NFPA70B 1998 18-5.2

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"It may be unwise to repair motors with catastrophic damage since there could be a reduction in efficiency. The customer's operational needs, however, may necessitate the repair even though he is aware that there may be a reduction in efficiency"[8]

The reduction of efficiency will then increase the operational lifetime energy requirement. Without predictive testing methods, it may simply have been a more cost effective choice to replace the motor, though the initial replacement cost (instead of repair) is greater.

VI. Capability comparison of Surge Testing and impedance based circuit analysis/measurements (i.e. low voltage "testing")

Many operators of electric motors are successfully using the technology refined in the last 20 years to improve the reliability of their electric motors, and beyond that, plant productivity. Modern surge testing is used to evaluate the integrity of the turn-to-turn and phase-to-phase insulation, and is proven to give advance warning of impending motor failure. Due to the low energy levels involved, the applied power is not capable of carbonizing motor insulation, or welding copper. Motor life remains, and time is now available for competent repair or replacement of the machine. Since the fault was detected before the insulation to ground was compromised, major repair jobs are now just minor overhauls.

Some misinformation exists about the method that Baker Instrument Company uses to perform the surge test. Baker Instrument Company uses a conducted surge test method, where the surge generator internal to the tester is connected directly to the terminals of the winding. (Therefore, the method detailed in IEEE Std 389-1996 recommended practice for testing electronics transformers and inductors sec. 5.3.2 is not applicable).[9]

All Baker Instrument Company equipment adheres to the guidelines given by IEEE Std 522-1992.[10]

Impedance based circuit analysis/measurements (i.e. low voltage "testing") have successfully evaluated windings that were deliberately sabotaged. A marketer of this type of equipment published data regarding this treatment. The damage consisted of manipulating a single turn fault into a 2.5 horsepower electric motor as described:

"A single turn fault was induced in a 2.5 horsepower electric motor by raising two conductors and scratching the wire. The wires were then placed that the surge would not detect them until an impressed voltage of 1,750 V was reached".[4]
Deliberate sabotage is certainly an effective method of causing premature failures in electric motors. The author did not provide any information about the ability of the surge test to detect the problem before the scratched wires were manipulated.

The measurements obtained with the impedance based circuit analysis/measurement before and after winding manipulation, showed difference percentages of approximately 2%.

"However, surge testing does allow for the detection of turn to turn and coil to coil faults in most electric motors"[4]

When the surge test was used to diagnose insulation integrity in a 5 HP electric motor, the numerical difference percentages obtained against weak insulation was approximately 20%, clearly a much larger

[8] Bonnet, Austin, "THE RESULTS ARE IN: MOTOR REPAIR'S IMPACT ON EFFICIENCY"

[9] IEEE Std 389-1996 Section 5.3.2

[10] IEEE Std 522-1992

[4] Penrose, Howard W, Ph.D. "Applications of motor circuit analysis for predictive maintenance, reliability and quality control" EMCW 2000

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error value. Interestingly enough, this data was obtained at a very similar test voltage, with a Baker Instrument Company test set. This proves the high degree of discrimination obtained with the test.[11]

The fact modern high voltage test equipment provides numerical quantification to the waves, removes the subjectivity of analysis.

Studies of rotating machines in the field reveal that most turn-to-turn stress is located in the end turns of the motor. These fast rise time transients are present in across the line applications due to load switching and atmospheric discharge (Lightning strikes).

They are also present when variable frequency drives are used, due to the improved switching efficiency of modern semiconductors, very fast rise-time voltage spikes are developed across the motor windings. For example:

“Eventually, an ionized electrical path develops which allows electrical stresses (fast rise time spikes) to cross the boundary and short. The tendency is for a few turns to short in the end turns of the motor windings”.[3]

Armed with this important information, we can make the following statements:

A) Motor winding end turns are where most of the electrical stress develops. It is therefore critically important to test the insulation of these end turns with a meaningful voltage stress.
B) Slow rise time transients or low voltage cannot cross this boundary, giving little to no electrical stress at these locations in the winding.

[11] Wiedenbrug, E.; Frey, G; Wilson, J; “Impulse testing as a predictive maintenance tool”, SDEMPED 2003

[3] Penrose, Howard W, Ph.D. “Estimating motor life using motor circuit analysis predictive measurements”, IEEE EIC refereed paper, EIC/EMCW conference 2003

The surge test is the only known method where instantaneous turn-to-turn voltage can be developed across conductors and monitored in a controlled manner. It is commonly accepted that surge testing is most useful for detecting faults in the end turns.

At the EPRI Advanced Electric Motor Predictive Maintenance Project 2003, even a fault deliberately inserted at the midpoint of the winding was directly detected.[12] Impedance based circuit analysis/measurements (i.e. low voltage “testing”) are by their very nature completely incapable of providing any warning of impending insulation failure without pre-existing measurement data.

VII. Conclusions

Modern High Voltage test techniques proof the integrity of insulation in rotating electric machines. Accordingly, they give the end user the highest level of confidence in proving machine reliability for operations. With advances in instantaneous trips and current limited microprocessor controlled tests, risk to insulation integrity and motor life is further minimized. Numerical quantification to surge waveforms removes subjectivity of the analysis.

Surge testing detects faults in most types of windings, with absolutely no limitation to <600 Vac motor application.

Vintage 1980’s style high voltage testing remains a meaningful test, and in the hands of an experienced, trained operator will continue to provide meaningful test results.

Impedance based circuit analysis/measurements (i.e. low voltage “testing”) do not allow any meaningful conclusions to be drawn about the service capability of high voltage insulation. They

[12] EPRI, Advanced Electric Motor Predictive Maintenance Project, EPRI 2003

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appear able to "predict" faults that are deliberately inserted into low voltage <600Vac windings, with a low degree of certainty. Impedance based circuit analysis/measurements appear entirely limited to low voltage applications, and offer no miraculous, newfound, predictive capability.