FROM MEASUREMENT RESULT TO CONDITION DIAGNOSTICS OF HIGH VOLTAGE ROTATING MACHINES

Mladen Šašić

Iris Power, 3110 American Drive, Mississauga, Canada
msasic@irispower.com

Keywords: High-voltage, rotating, diagnostics

Abstract

Condition diagnostics of complex systems, such as high voltage rotating machines was never a simple task. Design requirements, use of different materials and demanding operating conditions require multiple off-line tests and on-line monitors to get information on machine condition. However, some tests just provide simple measurement results, without high diagnostic value. The application of different off-line test techniques for diagnostic of stator and rotor insulation and stator core and on-line monitoring tools will be described in this paper.

1 Introduction

Although electrical rotating machines can be divided in two very broad groups, motors and generators, and can be of different design, all will have a rotor and stator. The three main parts of a stator are the stator core and stator winding, consisting of a conductor and insulation (Fig. 1). The stator core of a typical large rotating machine can weigh 200 tonnes, can be 5-7 m long and can have an internal diameter of 1.5 m. It is built from a stack of individual steel sheets or “laminations” each 0.3 to 0.5mm thick and coated on each side with a layer of electrical insulation to prevent current flow between them. The most common cause of core failure occurs when this insulation is damaged on a group of laminations, and an electrical circuit is created; the machine’s rotating magnetic field will then induce a current around the circuit, which can create a “hot spot” within the stator core. Stator winding of high voltage rotating machines is usually made of form wound bars or multi-turn coils installed in stator core slots. The conductors are commonly made of copper and different types of insulation were used in the last 100 years, most based on the application of mica materials in various forms. Two distinctive parts of stator winding are the slot part and endwinding part.

Many failure mechanisms can affect the condition of stator winding insulation, and can be broadly grouped in thermal, electrical, ambient and mechanical causes [1]. The coils and bars are exposed to large mechanical forces at twice of AC operating frequency and much larger forces in the case of machine faults or system disturbances. Several means of mechanical support are utilized to prevent winding movement, both within slots and in the end winding area. Within slots, the wedging system, consisting of the top wedge and sometimes side wedging is usually sufficient to prevent movement of the stator winding. However, in end winding areas, on both sides of the core, this task is more complex since axial movement of the winding due to thermal dilatation must be allowed. Radial and tangential movement of endwinding in normal operation and during the faults should be limited and the use of non-magnetic, usually non-metallic brackets, braces, support rings and spacer blocks is the preferred method.

As a result of such a complex design, many off-line and on-line tests were developed [1, 3, 9, 11] to help in the condition assessment of rotating machines.

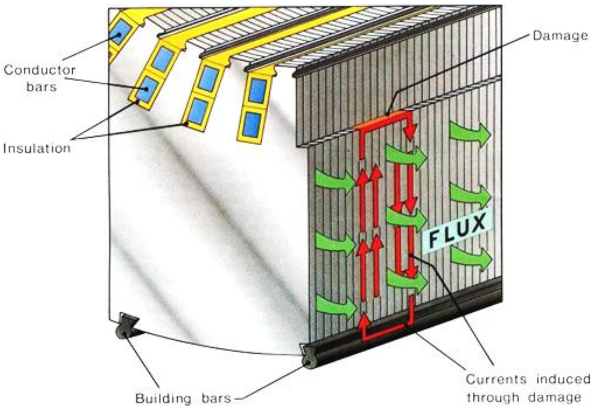

Fig. 1. Stator core cross-section with damaged area

2 HV Machines Off-line Testing

Typically, tests can be divided into off-line [19] and on-line [18], each having some advantages and disadvantages. Off-line testing requires machine shut-down and an external source of energy, while on-line tests generally require installation of a sensor during shut-down, to be used once the machine is back in operation. Off-line electrical stator winding tests can be divided into AC and DC tests. Some of the most common tests and their diagnostic value will be described in this chapter.

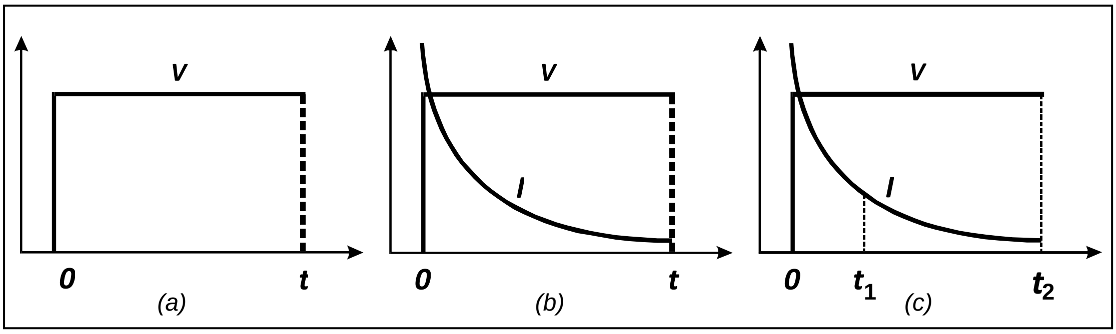

Fig. 2. High Potential, (HIPOT), Insulation Resistance (IR) and Polarization Index (PI) testing

2.1 High Potential Testing

High Potential Test or HIPOT can be performed using AC or DC power supply. The purpose of the test is to detect the major problems in the insulation. The expectation is that if high enough voltage is applied to the stator winding, it will result in insulation breakdown at the location of problem. Although insulation in good condition can survive voltage levels much higher than those recommended for AC or DC HIPOT, this test is destructive in its nature and is of limited diagnostic value. The test can be performed in different ways, as described in IEEE Standard 95-2002 and IEC Standard 60034 for DC and in IEEE Standard C50.10-1990, IEEE Standard 43-2000 for AC power frequency and in IEEE Standard 433 for 0.1 Hz HIPOT testing [2]. Both AC and DC HIPOT tests are not diagnostic tests, since winding either passes or fails the test. There is no indication on the condition of insulation, except pass/fail criteria. HIPOT testing of the stator and rotor windings is similar in its diagnostic value, however it should be noted that rotor HIPOT test levels are much higher, in reference to winding rated DC operating voltage [3].

2.2 Insulation Resistance (IR) and Polarization Index (PI) testing

This test can be applied to stator and rotor windings, and is being used since the introduction of electrical rotating machines. The purpose of the test is to measure resistance between the conductor of rotor or stator winding and the rotor or stator core. Since stator or rotor winding insulation is not perfect, the measured resistance is not going to be infinite, and with a lower measured value, it is more likely that there is a problem present. IR testing is usually done with the application of DC voltage, and the test voltage can be between 500 V and 10000 V. Guidelines on acceptance criteria are given in IEEE 43 Standard, making this test a useful tool in the detection of contaminated or wet windings. A major problem with IR testing is that the measurement result is strongly dependant on temperature (ambient and winding) and therefore cannot be easily compared. Some experiments have indicated that a temperature change of 5 to 20°C can result in a 50 percent reduction in the resistance of modern polyester and epoxy insulations [4]. Given that attempts to correct measurement results at different temperatures to a standard temperature (40 degrees C) are not very reliable, the diagnostic value of this test is also not very big. The PI test can be seen as an improvement over the IR test, because it is relatively insensitive to the effects of temperature change. PI is the ratio of the measured insulation resistances after the application of DC test voltage after ten (t2) and after one minute (t1), see Figure 2 (c). In some cases IR values are measured after 60 and 15 or 10 seconds, or after 5 minutes and 30 seconds. PI test results are highly dependent on ambient humidity and cannot be corrected, making result comparison impossible. Although results of IR and PI tests are numerical values and can be seen as an improvement over HIPOT testing, the diagnostic value of these tests is still limited by ambient condition changes and a lack of agreement on what is an acceptable time ratio for the PI test.

2.3 Time stepped voltage testing

The timed stepped voltage test is an improvement over the previously described direct-voltage tests. This test involves application of the direct high potential in a series of several voltage steps at regular time intervals as shown in Figure 3(a). Current readings are taken at the end of each interval, and the I-V (current versus voltage) data is hand plotted on graph paper. During and after testing, the data is examined for increases in conduction current or other variations versus applied potential—possible indications of stator insulation weakness. And because the maximum test voltage is above the normal operating stress, the test also can serve as a proof test. To minimize dielectric polarization effects, the test voltage may be held at each level long enough to allow the polarization current to decay to a negligible value. Since it is usually not practical to hold the test voltage at each level long enough to make the polarization current negligible and to shorten the time required to obtain the I-V curves of stator insulation, complex volt-time schedules were developed [5]. As illustrated in Figure 3(b), the basic idea of these test schedules is to adjust the voltage, in steps, according to a predetermined, diminishing time schedule so the polarization component of the measured current is proportional to the applied voltage. In effect, the volt-time schedules attempt to linearize the polarization current so that relative changes in the conduction current become more readily discernible. Nevertheless, even with the use of graded time intervals, it may be difficult to detect subtle changes in conduction or ionization. Two persons are generally required to perform timed stepped voltage tests: one to monitor the time intervals and record the measured data, and another to apply the voltage steps and read the current meter. Tests performed in this manner rely on individual judgment and actions to control test time intervals, apply uniform voltage increments, and visually read and average a fluctuating current meter. This "human factor" may result in poor data quality and impact repeatability of the measurements. Such uncertainty decreases confidence in the data and may even lead to misdiagnosis of the insulation condition, minimizing the diagnostic value of this test.

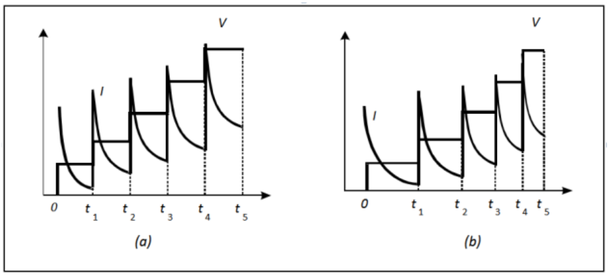

Fig. 3. Time stepped voltage testing, uniform (a) and graded time (b)

2.4 DC Ramp voltage testing

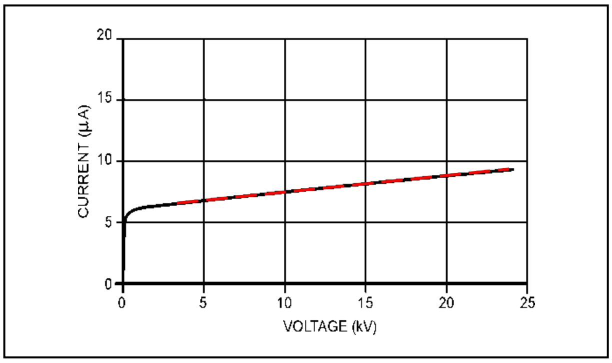

Fig. 4. Typical DC Ramp voltage test from new epoxy mica insulation

A third variation and further improvement over the other direct voltage tests is the test where DC voltage is linearly increased at a constant from zero to maximum test voltage. This represents a major advantage of this test method; as a result of the constant increase in voltage (dV/dt=C, usually one or two kV per minute), the capacitive charging current is constant and with the test result shown graphically, can be ignored, unlike in any other DC test. The total current (sum of capacitive, polarization and leakage currents) is plotted during the test, versus applied voltage and graphical presentation of the test result is very helpful diagnostic tool. In the case of defect free insulation, the measured current is linear with applied voltage and any deviation from the expected linear response can be easily observed. Typical result from a new epoxy-mica insulation system result is shown in Figure 4. IEEE Standard 95-2002 provides general guidelines and some typical DC Ramp test results. Since this test method is the most sensitive way to detect the leakage current instability, it is superior in the detection of problems that cannot be identified by other tests, like incompletely cured epoxy insulation or moisture within insulation.

Figure 5 indicates the DC Ramp test results for all three phases of a 30 MVA, 6.9 kV generator, collected upon installation of a new winding [6]. Only phase B results were acceptable, while a major deviation from the expected linear response is easily visible in phase A and C results. AC and DC HIPOT tests and the PI test did not indicate the presence of problems on phases A and C. After being detected by the DC Ramp test, many other tests failed to identify the location of insulation problem, and winding was sectioned first in parallel sections and then into coils, and DC leakage current measured to locate two faulty coils on phases A and C.

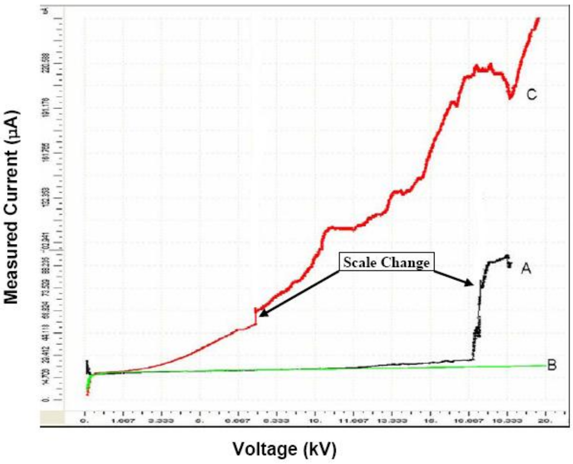

Fig. 5. Unacceptable DC Ramp Test Result, A and C phases

Although potentially destructive, as any other HIPOT test, the DC Ramp test is the most likely to enable the user to avoid failure during the test, and according to United States Bureau of Reclamation experience, the failure rate after 5400 tests was lower than 0.01%, or just four sudden failures, without precursor to a failure. The diagnostic value of this test, compared to other DC and AC HIPOT tests is significant. The comparison of DC Ramp results from the same or different machines is a useful tool in the detection of stator winding problems.

2.5 Stator Core testing

The stator core of a typical large (e.g. 500MW) turbogenerator weighs 200 tonnes, could be 6m long and 2.6m in diameter, and has a bore of 1.3m. It is built from a stack of some 200,000 individual steel sheets or "laminations" each 0.3 to 0.5mm thick and coated on each side with a layer of electrical insulation to prevent current flow between them. If this insulation is damaged on a group of laminations, an electrical circuit can be created and the machine's rotating magnetic field will then induce a current around the circuit, which can create a "hot spot" within the stator core. Traditionally, the only method of testing inter-laminar insulation in stator cores was the High Flux Ring Test (or Loop Test). This requires the rotor to be removed and a massive excitation winding to be installed through the core to generate a circumferential, or "ring" magnetic flux around the core. To provide the required level of flux (typically 80%-100% of rated flux), several loops of high voltage, high current carrying capacity cable need to be connected to a high power source (3-4 MVA for a 500MW generator). Ideally, the core is energised for a few hours to produce measurable tooth tip temperature rises for deep-seated faults located near slot bases. Hot spots are then detected using thermal sensing equipment. The principal disadvantages of the Loop Test are the installation of the winding, the high power requirements, high voltage safety concerns, the difficulty of detecting deep-seated faults and risk of further core damage due to the normal cooling systems being absent. Although the diagnostic value of this test is not low, the difficulties related to excitation requirements, led to the development of low power core test, known as EL CID (Electromagnetic Core Imperfection Detector) [7]. This method also uses a temporary ring flux winding but it is much lighter and requires only a 3kVA supply for a typical 500MW turbo-generator or less than 5kVA for a large hydro generator. The flux level required is only 4% of the rated value so only small currents flow through any damaged areas (typically between the fault and rear building keybars as shown in Figure 1). Heating of the core from such currents is insignificant but EL CID detects the actual currents using a very sensitive electromagnetic technique; faults are readily detected even if they are located deep down in the slots between the teeth. A special pickup coil, known as a Chattock Potentiometer is used to measure the magnetic fields produced in the air by current flowing along the core surface. The voltage induced in the coil is proportional to the line integral of the magnetic field along its length, i.e. to the magnetic potential difference (m.p.d.) between its ends. Since the core fault current circuit has a significant resistance, the fault current is substantially in-phase with the fault voltage and therefore in phase quadrature (shifted for ninety degrees) with the excitation flux. EL CID exploits this phase relationship and virtually eliminates the signal from the excitation current by using a phase sensitive detector to measure this quadrature component of the fault current (the core fault heat producing component). The component in phase with the excitation current is called the PHASE (or P) and the component indicating the core imperfections is referred to as the QUAD (or Q) component.

To carry out the EL CID test, the Chattock is adjusted to the slot/tooth width and it is scanned along each and every tooth pair and the current responses (Y axis) and distance from the core end (X axis) are recorded. These traces are examined and faults are apparent when the quadrature component exceeds a certain threshold. In a perfect fault-free uniformly constructed generator, a slot QUAD trace would be a straight line along the zero axis and the PHASE trace would be another straight line with an offset depending on the excitation current. In practice, however, a number of effects may cause QUAD trace deviation from zero level (e.g. stator winding currents, varying core loss, etc.). At the standard excitation level of 4% of rated flux, a QUAD current level of 100mA was established in the early days of the technology as a threshold above which more detailed examination is required. Although correlation with thermal tests depends on a number of factors, the 100mA QUAD threshold corresponds approximately to a 5° - 10° C rise in core temperature. [8] Faults are identified and located by examining the traces measured along and around the core, correlating features on adjacent slots. Figure 6. shows laboratory measurements on a section of core with three artificial faults, each of equal severity and each 10mm long, applied at various positions on a tooth. The shape and polarity of recorded adjacent slots QUAD traces is used to identify the location of the fault. The amplitudes of the measured currents were fairly constant (Y axis) even for fault C near the base of a slot. This higher sensitivity to deep seated faults is one of EL CID's important advantages over the High Flux Ring Test. Many field test comparisons were done to verify the sensitivity of EL CID in comparison to High Flux Ring Test, and all confirmed that for every hundred mA of QUAD current, the temperature increase at the fault was in the range of 5-10° C, for all three types of high voltage rotating machines, hydro and turbo generators and motors. [9,10]

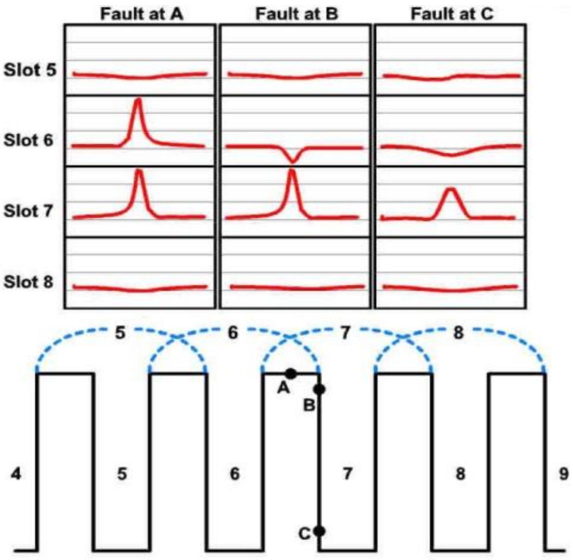

Fig. 6. EL CID Quad traces fault location analysis

The correct interpretation of an EL CID test result depends on the polarity of the measured QUAD response in relation to the polarity of the measured PHASE signal, both recorded by the instrument. If the QUAD signal has the opposite polarity to the PHASE signal, at the same distance, then a core fault lies within the span of the Chattock. This criterion is also important for the proper recognition of heat generating faults from various core imperfections that would not cause hot spots and as such will not be detected by the High Flux Ring Test. As a result, interpretation of EL CID results is relatively simple, increasing the diagnostic value of this test.

3 HV Machines On-line Testing

There are many advantages of on-line testing and most important are that machine does not need to be stopped for the test and normal operating conditions (temperature, current, etc.) are present. However, on-line testing requires installation of permanent or temporary sensors. The two most frequent tests performed with the machine in operation are the Partial Discharge test of stator winding and the detection of shorted rotor turns.

3.1 On-line Partial Discharge testing

Partial discharges (PD) are small electrical sparks resulting from the electrical breakdown of a gas (for example air) contained within a void or in a highly non-uniform electric field. If the void is within an organic solid or liquid, the PD will degrade the organic material and may eventually cause the failure of the electrical insulation. PD, in addition to causing electrical aging as discussed above, may also be a symptom of thermal, mechanical and environmental aging in high voltage apparatus. For example, voids within epoxy mica insulation may occur as a result of operation at high temperature, which delaminates taped insulation systems. Similarly mechanical stresses can lead to voids, and contamination by partly conductive coatings can lead to high, localized electrical stresses on insulation surfaces that result in discharges in the air. Thus the presence of PD not only indicates that electrical aging is occurring, but that mechanical, thermal or environmental aging processes may be present. When a partial discharge pulse occurs, there is a very fast flow of electrons from one side of the gas filled void to the other side. Since the electrons are moving close to the speed of light across a small distance, the pulse has a very short duration, typically a few nanoseconds. The PD current pulse creates a disturbance and results in pulse current and voltage that flows away from the PD site. For on-line detection of PD, various types of sensors are used, permanently or temporarily installed. Any sensor (also called a coupling device) sensitive to high frequencies can detect the PD pulse currents, however not every sensor will provide sufficient Noise to Signal Ratio. Generally two types of sensors are used, capacitive (High voltage coupling capacitors) and inductive (various antennas and high frequency current transformers). Typical capacitances are in the range of 80 pF to 1000 pF. The capacitor is a very high impedance to the high AC (50 or 60 Hz) voltage, while being a very low impedance to the high frequency PD pulse currents. The selection of the sensor and PD detector will determine the frequency range of the whole system and, for use on rotating machines, two commonly used methods are Low (0.8 – 10 or 20 MHz) and High (40-350 MHz) frequency. [11,12] The major problem in establishing a proper diagnosis based on on-line PD measurement is the possible presence of noise or electrical interference. Electrical interference can come from corona on air-insulated transmission and distribution lines, power tool operation, arc welding, poor electrical contacts, electrostatic precipitators, etc., all of which produce sparks/discharges that create current pulses similar to PD. Separating this noise from the test object PD is important since if the noise is mistaken as PD, then a false indication of the insulation deterioration is given, reducing the usefulness and the credibility of the PD test. The most effective methods of noise rejection are applied hardware methods, employed in on-line rotating machine PD detection. One method measures the risetime or width of the pulse: a fast risetime (<6 ns) pulse is likely to be PD in the stator winding; whereas a noise pulse tends to have a longer risetime, due to transmission line dispersion as the noise pulse propagates along a power cable to the motor or generator. Another method depends on the propagation time between a pair of sensors. That is, two capacitive sensors per phase are mounted on the machine terminals, separated by at least 2 m, or on two parallel paths within hydrogenerator. Since the current pulses have a finite transmission speed on a bus or power cable, PD pulses will arrive at the sensor closest to the stator winding first, whereas noise from the power system will arrive at the other sensor first. Digital logic can then determine on a pulse-by-pulse basis whether the pulse is stator PD or power system noise. Both of these hardware based noise separation methods require the bandwidth of the measurement system to be 100 MHz or more in order to distinguish small differences in arrival time, or accurately measure the risetime/pulse width. If only one sensor per phase is used, it is impossible to the detect direction of the pulse arrival, i.e. its place of origin, within the rotating machine or externally. This compromise (use of just one sensor per phase) can have a significant impact on the quality of data collected from all machines, except smaller machines connected to a power system with sufficient (i.e. more than 30 m) length of high voltage cables. Most of the instruments used for collection of PD data measure number of pulses per second, their polarity and amplitude and phase position of each pulse. Using that data, various graphs can be created indicating results from one or more measurement, for trending purpose. In addition to noise presence, as the major problem in data collection, next problem is understanding of measurement results and credibility of various methods used in PD data collection [13]. Possibility of false positives (wrong conclusion that problems are present in the winding as a result of noisy results or wrong interpretation) and occasional (wrong!) claim that on-line PD monitoring can detect all insulation problems creates difficulties in diagnostics based on PD results. Absence of any standards defining acceptable levels of

PD in rotating machines, with uncertainties related to measurement methods and fact that calibration is not possible [12], tends to minimize diagnostic value of this technique. However, standardization in selection of the sensor and instrumentation used for data collection on large number of machine (more than 10,000) provided conditions for statistical data evaluation [14]. More than 400,000 on-line PD results were collected and compiled to indicate distribution of Qm levels on machines of different voltage class and installation method. The range in Qm from all the tests for the particular operating voltage was established for each set of the above factors. A sample of the statistical distribution is shown in Table 1. For example, for 13-15 kV stators in hydrogenerators or pump-storage units, 25% of tests had a Qm below 35 mV, 50% (the median) had a Qm below 93 mV, 75% were below 193 mV and 90% of tests yielded a Qm below 376 mV. Thus if a Qm of 400mV is obtained on an 13.8 kV hydrogenerator, then it is likely that this stator will be deteriorated, since it has PD results higher than 90% of similar machines. In fact in over two hundred cases where a machine was visually examined after registering a PD level >90% of similar machines, significant stator winding insulation deterioration was observed.

Rated kV	6-9kV	10-12kV	13-15kV	16-18kV	> 19kV
25%	12	19	35	37	67
50%	33	50	93	118	142
75%	72	111	193	334	441
90%	201	231	376	687	838
95%	322	389	561	1016	956

Table 1. Distribution of Qm for Hydrogenerators, 80 pF coupling capacitors installed inside machine

Publishing of these levels, together with taking account of the trend in PD, seems to have reduced the risk of both false positives and false negatives and improved diagnostic value of this test. An attempt was made to provide a study of PD level correlation to visually observed and in 216 cases PD indicated different failure mechanism, such as contamination, design and manufacturing problems and vibration. [15] As a result of large number of installations using the same type of PD sensor , standardized approach in data collection and well established correlation between PD patterns and insulation condition, PD monitoring has identified many pending service problems, prevented a significant number of generator service failures, and has resulted in a major cost saving to the power generation industry.

3.2 Rotor Winding shorted turns detection

Generally, two types of rotors are used in synchronous electrical machines, round, for high speed machines, and salient pole for lower speed machines. A turbine generator rotor usually consists of a solid forging made from magnetic alloy steel and copper windings, assembled in slots machined in the forging. The winding is secured in slots by steel, bronze or aluminum wedges. At each end of the rotor, end sections of the rotor winding are supported by retaining rings. Modern rotor winding insulations are made mostly from epoxy/polyester glass/Nomex™ laminate strips and channels. The strips are used to provide inter-turn insulation and molded channels are used to provide ground insulation. The rotor insulation should be designed to withstand electrical, mechanical, thermal and environmental stresses.

For moderate and large size hydro-generators and pump-storage generators, the most common type of salient pole rotor has a 'strip-on-edge' type of winding on each pole. Such winding is composed of strips of copper that are fabricated around the pole piece much like a picture frame. Electrical insulation, most commonly fiberglass reinforced epoxy, is used to insulate each copper turn from adjacent turns, as well as provide ground insulation between the copper and the rotor pole. Failure of the rotor winding insulation can result in shorted turns. Shorted turns on rotor may lead to unbalanced magnetic pull, which in turn may cause an increase in bearing vibration. However, shorts can exist with no increase in vibration and thus bearing vibration is not an infallible way to detect rotor winding aging. The condition of the rotor winding insulation is difficult to assess during a shutdown due to limited access and the frequently intermittent nature of faults at operational speed and at standstill. Consequently, on-line testing is a more effective way to detect shorted turns. Flux monitoring using temporary or permanently installed flux probes on turbo-generators has been used since the early 1970's [16]. Flux measurements are used to determine existence of turn-to-turn shorts in the rotor winding. All of the methods available are based on measurement of relatively weak stray flux (rotor slot leakage flux) using flexible or non-flexible polymer encased stator wedge mounted probes. The stray flux is proportional to the total ampere-turns in each rotor slot. If shorts develop between turns in any slot, then the ampere turns in that slot drop, and stray flux across that slot is reduced. The magnitudes of these stray fluxes can be measured using portable or permanently installed instrument and shorted turns can be identified by comparing the difference in the induced voltages from pole to pole. The main challenge in existing technology is the need to manoeuvre turbo generator load to achieve the maximum sensitivity to shorted turns in every slot of a rotor. This, together with other problems like the type of the probe and instrumentation/algorithms used for detection of shorted turns limited use of this technology in power industry. To overcome this problem, new hardware and algorithms were developed in an attempt to make the flux test sensitive to shorted turns in all coils, even if the generator load could not be changed to move the FDZC to be aligned with all slots [17]. One aspect was to improve the temporal and magnitude resolution of the hardware compared to the conventional test. Another aspect of the approach is to concentrate on the main magnetic flux rather than the leakage flux. Thirdly, three different proprietary numerical methods were developed to improve the sensitivity to small differences between pole A and pole B main flux plots. Finally, the results from the three algorithms were compared to develop an index of the confidence in the conclusion of the presence (or not) of shorted turns in each coil. The new approach can be used with conventional wedge-mounted coils that protrude into the air gap. However, an alternative probe was also developed that can be glued to the stator core tooth, rather than the stator wedge. This probe, known as a TFProbe^{TM}, (Total Flux Probe) directly measures the main magnetic flux that passes through the core tooth. Typical measurement result from two pole turbo generator is shown in Figure 7, where gray line indicate measured and green line integrated signal.

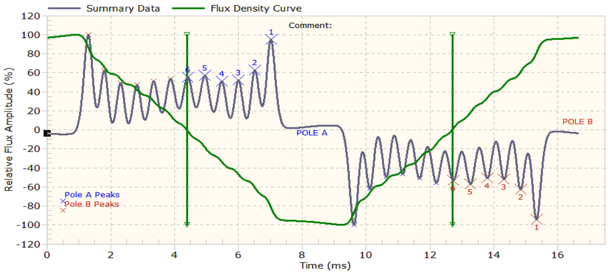

Fig. 7. Low load two pole turbo-generator test result

Vertical green line indicates position of Flux Density Zero Crossing (FDZC), a point with maximum measurement sensitivity, as indicated in Figure 7, at coil 6. With load increase FDZC will move towards lower number coils, but will never reach coil 1. Measurement result, as shown in Figure 7 is of very low diagnostic value, since pole to pole difference, per coil, is not visually detectable, so no judgment on presence of shorted turns can be made. Graph shown in Figure 8, is more useful, but still lacks clear, easy to detect indication of shorted turn existence.

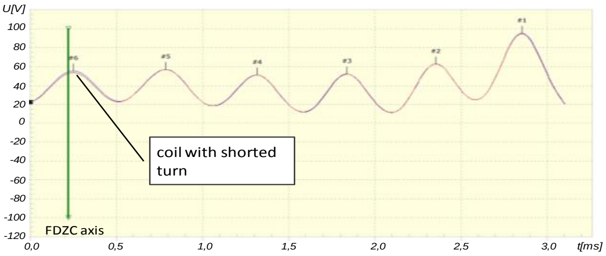

Fig. 8. Pole to pole comparison, indicating difference in flux peak per coil

Use of multiple algorithms enabled great improvement in analysis reliability and measurement results can become diagnostic result, as shown in Figure 9.

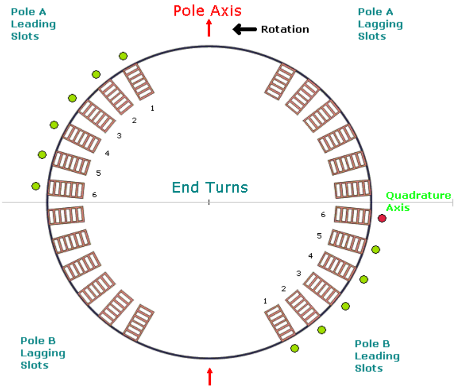

Fig. 9. Identification of pole and coil with shorted turn

4 Conclusions

Condition diagnostic of rotating machines has evolved from off-line testing to combination of off-line tests and on-line monitoring. No single test is perfect or sufficient to establish complete diagnostic of rotating machine condition and graphical presentation of multiple measurement results is frequently of better diagnostic value than simple numerical measurement result. Combination of visual inspection with multiple technologies can provide further improvements in diagnostic, using information from on-line monitors, such as Partial Discharge, Rotor Flux and End Winding Vibration**.**

5 References

[1] Greg C. Stone, Ian Culbert, Edward A. Boulter, Hussein Dhirani, Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair, 2nd Edition, July 2014, Wiley-IEEE Press

[2] B.K. Gupta, G.C. Stone, J. Stein, "Stator Winding Hipot (High Potential)Testing", *IEEE Electrical Insulation Conference*, Montreal, QC, Canada, 31 May - 3 June 2009.

[3] Relu Ilie, Greg Stone," Turbine Generator Rotor and Stator Winding Hipot Testing" IEEE Electrical Insulation Magazine, March 2012

[4] Lory Rux, Mladen Sasic, "Advantages of the Ramped Direct High-Voltage Method of Assessing Stator Winding Insulation Condition", HydroVision 2004, August 16-20, 2004, Montreal, Canada

[5] F.R. Schleif, "Corrections for Dielectric Absorption in High Voltage D-C Insulation Tests, "*AIEE Transactions (Power Apparatus and Systems)*, Vol. 75, Part III, pp. 513-517, 1956.

[6] Bert Milano, “Acceptance Testing Stator Windings Using Ramped High-Voltage DC Testing” 2006 Doble Conference

[7] John Sutton, Mladen Sasic, David Bertenshaw, “30 Years’ Experience with ELCID Stator Core Testing” 2008 IRMC Long Beach, USA

[8] D. R Bertenshaw, Prof. A. C. Smith, "Field Correlation Between Electromagnetic and High Flux Stator Core Tests”, PEMD 2012, Bristol, 27-29th March 2012

[9] D. B. Paley, et al., "Verification of the Effectiveness of EL CID on a Hydrogenerator Stator Core," Hydrovision ’98., pp. 1-14. (1998).

[10] K. Ridley, "Hydrogenerator EL CID results referred to High Flux Ring Test results," CIGRE Session, pp. 1-9. (2002).

[11] IEEE Std 1434, IEEE Trial-Use Guide to the Measurement of Partial Discharges in Rotating Machinery

[12] IEC Standard 60034-27-2, On-line partial discharge measurements on the stator winding insulation of rotating electrical machines

[13] Greg Stone, “A Perspective on Online Partial Discharge Monitoring for Assessment of the Condition of Rotating Machine Stator Winding Insulation”, IEEE Electrical Insulation Magazine, September/October 2012

[14] V. Warren, “PD Progress Report” IRMC 2015

[15] Partial Discharge-A Valuable Stator Winding Evaluation Tool, C. Maughan, 2006 IEEE International Symposium on Electrical Insulation

[16] D. R.Albright, “Inter turn short-circuit detector for turbine-generator rotor windings,” IEEE Trans. Power App. Syst., vol. PAS-90, no. 2, pp. 478–483, Mar./Apr. 1971.

[17] M.Sasic, B. Lloyd, A. Elez, “Finite Elements Analysis of Turbine Generator Rotor Winding Shorted Turns” IEEE Transactions on Energy Conversion, Vol. 27. NO. 4, December 2012, p 930-937

[18] IEEE Std 1129 IEEE Guide for Online Monitoring of Large Synchronous Generators (10 MVA and Above)

[19] IEEE Std 62.2 IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus-Electrical Machinery