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TESTING OF INTER-LAMINAR INSULATION OF STATOR CORES USING ELCID

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ABSTRACT

The reliability of large generators is of major importance to maintain the integrity of power plant. Continuous monitoring or frequent inspection is therefore desirable to be able to remedy growing defects before a catastrophic failure or more major work becomes necessary. Recent test information may also permit more effective use of routine or unscheduled outages by means of additional preparation and provisioning.

The stator core is a major electro-mechanical component of a generator to which this applies in particular, as failure and associated repair or replacement necessitates major disassembly of other parts of the machine. Information on condition of the core structure is therefore significant, but is increasingly difficult to obtain at frequent intervals. Low power core testing can be performed more quickly and easily than using traditional full flux methods and may need to be considered an indispensable tool to increase or maintain essential monitoring levels.

Low power core testing presents opportunities to maintain the level of stator core lamination monitoring in a more time and resource efficient manner using comparatively short windows in available outage time, often partly overlapping with other concurrent maintenance activities.

These opportunities are enhanced with wider use of low power EL CID testing without removal of the rotor, not feasible with thermal loop tests.

Keywords: rotating machine core, interlaminar insulation, low power testing.

INTRODUCTION

The stacked core of any generator or motor is made up of separate laminations typically less than a millimetre thick, insulated from each other over their surface but frequently shorted together at the back edges by support bars. This design method reduces core eddy currents, thus avoiding unnecessary power loss, but depends on the effectiveness of interlamination insulating materials. In order to keep core length as short as possible and magnetic density high these insulation layers or coatings must be very thin.

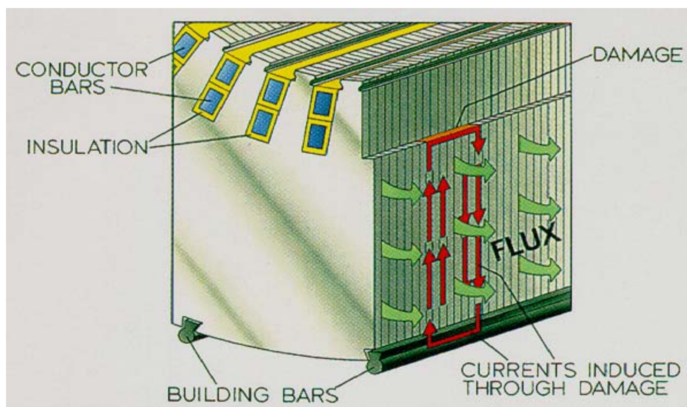

Fig. 1. Typical fault current paths resulting from damage

With a large number of laminations there is a high probability of insulation breakdown. Single shorts between two laminations may not be too serious but with several shorts along adjacent layers the fault currents induced can be large and cause excessive local heating. Sometimes this heat cannot be dissipated adequately by local cooling causing more inter-laminar failures. If not detected and repaired at an early stage, faults could in extreme cases burn insulation and melt laminations, requiring the replacement of sections of the core structure, or at earlier stages at least a partial stator rewind. Periodic core inspection is therefore a crucial part of any maintenance or fabrication programme to avoid excessive breakdown costs.

TEST METHODS

A traditional method of detecting faults is the High Flux Ring Test, often referred to as a Thermal Loop Test. The rotor is removed from the machine and the stator core magnetically energized by a high voltage high current excitation winding.

The magnetic flux produced follows a single path circumferentially around the core, rather than the rotating split path of the flux induced by the rotor field, but with substantially the same voltage generated along the core and associated heat from faults. Hot spots are detected by a variety of means including thermal cameras.

The Thermal Loop Test has long been used as an effective tool. However the required degree of dismantling of the machine, together with the requirement for the high voltage excitation winding and associated high power source and safety requirements, normally requires an extensive outage. Further disassembly may be required in order to detect temperatures behind stator bars.

The tendency towards extended periods between major planned outages provides less opportunity for frequent Thermal Loop Test core monitoring. Opportunities to inspect core condition must be considered during intermediate shorter outages including those where the rotor may not be removed.

The principal time related disadvantages with the Thermal Loop Test are those associated with the high power and voltage which are time consuming and not compatible with other work, besides cost considerations.

Any alternative method would therefore require to be quicker and easier at a safe, low power level and with the potential to be used without removal of the rotor. Although heat produced by faults at low level excitation is not readily discernible, the presence of low level currents gives rise to electromagnetic fields which are detectable and not affected by the presence of windings in the slots.

A system was devised to sense these fault currents by electronic means and to separate them from other magnetic fields present due to the excitation winding, giving rise to the now familiar EL CID acronym derived from Electromagnetic Core Imperfection Detector.

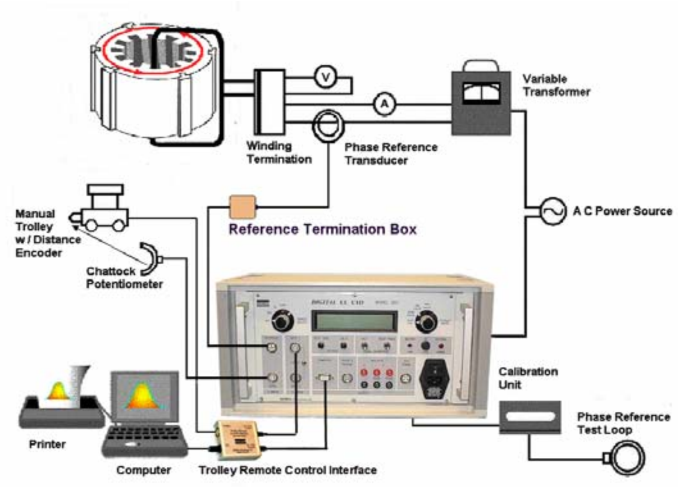

Fig.2. Typical ELCID test configuration

Originally it was assumed that as with the Thermal Loop Test, EL CID would always be carried out with the rotor removed. A more complete overview of this work and other fundamental considerations is provided by J. Sutton in [1].

Initial wider application of the EL CID test method by other utilities and generator manufacturers tended to concentrate on turbo generators. [2]

EL CID testing has subsequently also been adopted as routine by many utilities on hydro generators. [3] [5] Despite a number of spurious effects not present in turbo generators, due mainly to method of construction, the ability to carry out tests on hydro generators with the rotor in situ, particularly if a pole is removed to improve access, is a major attraction.
For low power testing the system will need to make provision to acquire and process the additional electrical signals.

The stator core is energized in a manner similar to that with a high power test but at an excitation level of 4% the required VA will be reduced to 1/25 of that for 100% excitation. At only a few volts per metre along the bore length, operators may work inside the bore whilst energized and even carry out non-EL CID test maintenance activities concurrently. Accurate adjustment of the excitation level may be carried out by means of a variable autotransformer
although it is often possible to arrange the number of excitation turns to match the available voltage supply. Care is required on positioning the excitation winding to prevent near field effects on the electrical sensors and excessive field distortions.

The ideal positioning of the excitation winding is along the central axis of the core and at least one metre beyond before commencing the outer return path. This may not always be feasible within the confines of the available space, particularly with tests with the rotor fully or partly in position, and distortions of the test result background levels will normally result.

Fig.2 shows a standard EL CID test configuration. Apart from any large excitation winding and any associated auto-transformer, the system parts will normally fit within a large portable case.

EL CID fault current signals are detected by a sensor in the form of a Chattock coil, a long flexible solenoid of fine wire [4] providing an output proportional to the magnetic potential between its two ends in contact with the core surface.

To scan a complete core for faults (a Global Test) the core is divided into a number of strips along its length. Each of the strips is scanned in turn to cover the whole core internal surface. A suitable strip for this purpose is conveniently defined by each slot. By scanning each slot including the width of both adjacent teeth a degree of overlap between scans is achieved which is useful in providing additional information on fault location. Fig. 3 shows the location of a Chattock sense coil across a slot and tooth pair.

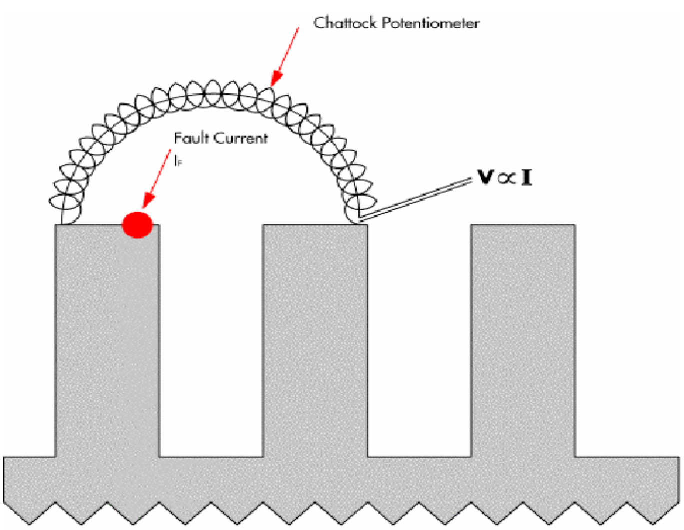

Fig. 3. Chattock coil positioning on stator core

The magnetic potential across each tooth pair will be comprised of in-phase excitation field (PHASE signal) together with any phase quadrature (QUAD signal) produced by a fault current. The QUAD signal is separated from the PHASE signal by a phase discriminator in the EL CID signal processor unit. The phase discriminator requires a phase angle reference for the in-phase component and this is provided by a phase pickup coil. This signal may be derived in a number of ways including from the excitation current, as shown in Fig.2, or background excitation field within the bore. The stator bore may be scanned by various manual or automatic means dependent upon the size and orientation of the core and whether the rotor is removed as is currently more normal.

Test results may advantageously be displayed in the form of a test trace of the amplitude of the QUAD signal against distance along the bore, now more normally displayed on a computer screen and stored on PC media. Similar traces for the PHASE signal vector may yield additional information for test result interpretation.

In a fault free uniformly constructed generator, a slot QUAD trace will theoretically be a straight line along the zero axis and the PHASE trace will be line corresponding to the level of excitation. However in practice a number of effects may give rise to offsets and perturbations in the QUAD trace and faults will normally be indicated by deviations from a mean level. At the standard excitation level of four percent, a threshold of 100mA fault signal is normally taken as a level above which more detailed examination is required. Although correlation with thermal tests will be dependent upon a number of factors, this threshold level corresponds approximately to a 5° - 10° C rise in temperature. The correlation for a number of different faults is given in [2] and [3].

Fault interpretation also makes use of adjacent slot trace information and a guide to recognition of common faults and locations is provided in [1] which also covers the possibility of improved detection of faults deeper in the core body by means of scanning across multiple slots. Polarity of the magnetic potential difference sensed by the Chattock Potentiometer may be used to determine whether the source of the signal is within the span of the coil.

The low voltages used in EL CID testing permit an operator to enter the excited core to perform local tests with small hand-held coils to obtain precise location of faults detected in the Global scan.

ELCID TEST DELIVERY METHODS

A Robotic Inspection Vehicle (RIV) and accessories shown in Fig.4. allows remote and robotic testing to be achieved. This operates by magnetic attachment to the stator teeth, self-guiding down each slot.

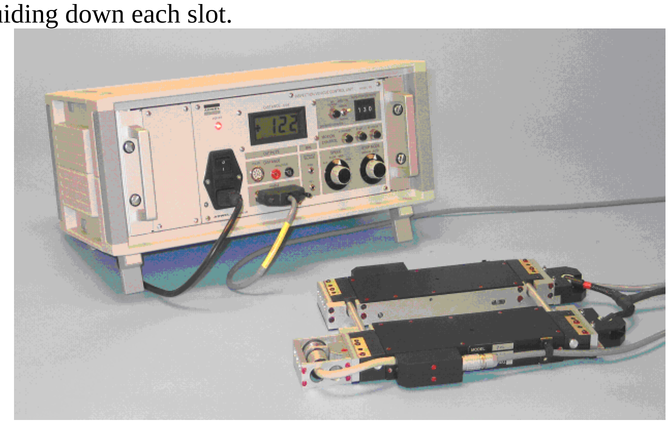

Fig. 4. Robotic Inspection Vehicle

This is of value where there is limited access due to small stator size, or a large amount of testing and automation requires a means to reduce the labour involved. The greatest gain however comes in allowing tests to be performed with the rotor still in place, where the RIV can be run inside the rotor-stator air-gap. Chattocks can be mounted on both ends of the RIV to allow complete coverage of the whole core without the RIV having to exit either end. Fig 5. shows the RIV being launched into the air-gap in a typical situation.

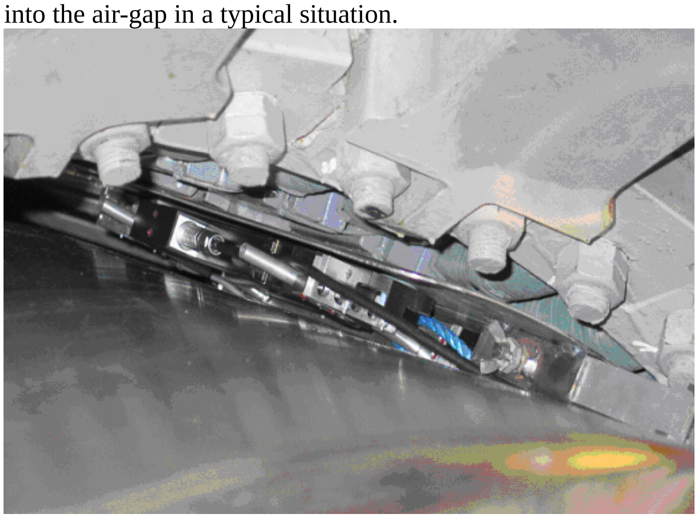

Fig. 5. Robotic Inspection Vehicle in turbo generator

This method of test is usually restricted to larger turbo-generators from about 200MW upwards, depending on access past the rotor end rings/bell. In hydro-generators the air-gap is usually too small, but the gap between the poles can be exploited, possibly with a pole removed, then the rotor turned to allow testing of the whole core.

The ability to introduce the RIV into the air-gap with the rotor still in place also allows measurement of wedge tightness and visual inspection. The RIV has been adapted to carry a low-profile WDT-501 Wedge Tightness Probe, allowing a survey of the wedging system without rotor removal. The video camera is the same height as the RIV with a built-in illumination system. It can be steered via a rotating mirror to allow inspection up/down or transverse, with remote focussing allowing inspection close-up or at a distance, eg down ventilation holes.

LOW POWER TESTS ON HYDROGENERATORS

Although the basic principles of EL CID testing are the same as for turbo-generators, there are significant differences in the way tests on hydro-generators should be carried out. These practical aspects are addressed in this section.

The major differences in construction that affect the preferred test procedures are:-

The core diameter is generally much greater in hydro-generators. Hence larger excitation currents (Ampere-turns) are required.

Hydro-generator cores are often built in two or more sectors (spanning 180°, 120° or 90°, etc) and then assembled on site. There are then inevitably circumferential gaps at the joints between the sectors of laminated core, which cause high PHASE and QUAD readings. These high background readings can mask signals from nearby faults. Procedures for managing these difficulties are given later.

Hydro-generators are, more often than turbo-generators, tested with the rotor partially or fully in situ as access is normally less difficult. Extra steel in the vicinity of the core in the form of the rotor bearings, the rotor itself, etc. can cause tilting of the base lines of measured QUAD traces.

An analysis of ELCID application on hydro-generator cores is given in [5].

The preferred excitation winding configuration for turbo-generators, Fig. 6., i.e. wound along the axis of the bore and returning to the back of the core at a single circumferential position, can cause difficulties with hydro-generators. The return loop to the back of the casing, which should be as far as possible from the ends of the core, is often restricted to less than one metre by the available space at the bottom of the core. The large leakage fields from the high excitation current flowing in this radial section of the winding close to the core may then cause unwanted tilting of the EL CID trace base lines on the nearby slots.

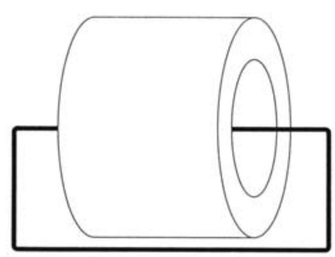

Fig. 6. Preferred Winding Position for Turbo-generators

The central winding configuration shown in Fig. 7. is recommended for testing hydro-generators when the rotor is removed, unless there are other practical reasons why it cannot be employed. The main winding is through the centre of the bore and, as with the close-wound configuration, the return windings are distributed into three, four, or more sections, equally spaced positions around the core. The number of excitation winding sections is determined by number of core splits, there should be one winding sections symmetrically located within each core section.

Although it may take longer to install the winding, it is much more straightforward to carry out the test since there is no need to keep moving sections of the winding to maintain minimum required distance to the winding from Chattock sensor.

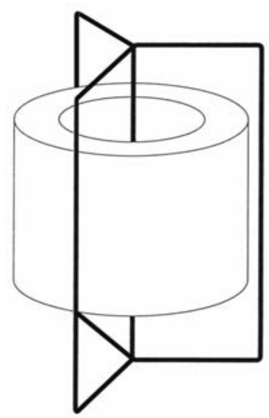

Fig. 7. Preferred Winding Position for Hydro-generators

CASE STUDY

The following case study [6] is based on 99 MW, 13.8 kV hydro-generator test experience. Some of the stator coils were damaged and before partial rewind, the utility wanted to test quality of inter-laminar insulation. An ELCID test was conducted and numerous surface and slot faults located, see Figure 8.

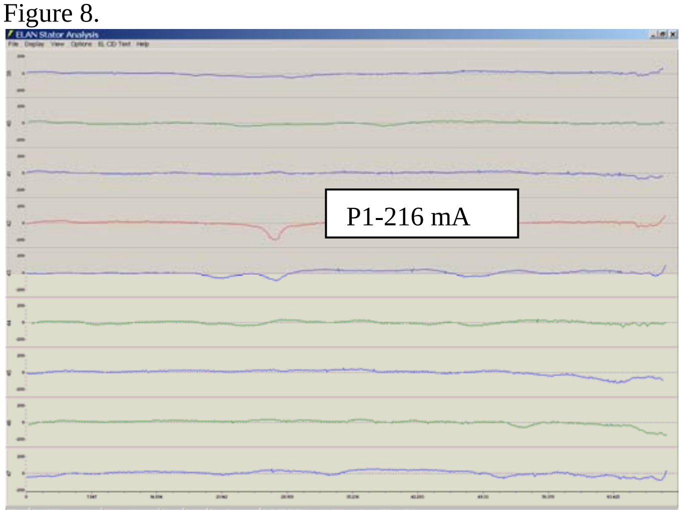

Fig. 8. ELCID test results, fault P1 in slot 42

A deviation from flat line, indicates peak value in measured current and its location from edge of the core. Red line, result of test on slot 42, had a peak value of 216 mA, marked as fault P1. A subsequent high flux test (loop test) confirmed local heating as a result of slot and surface damage.

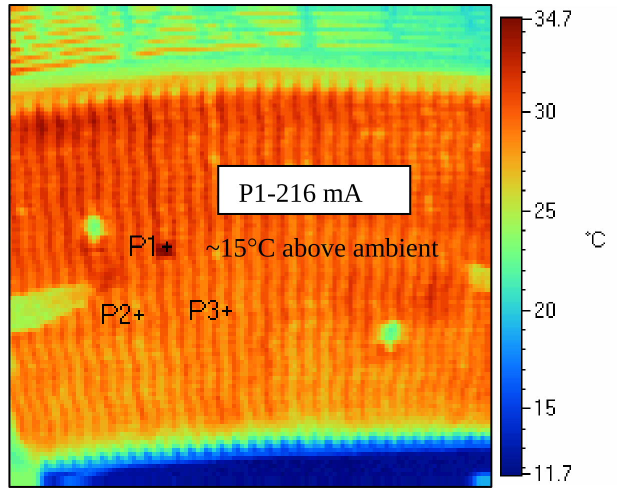

Fig. 9. Infrared image of damaged area

A sample of the damaged areas and the resultant increase in core temperature is shown in Figure 9.
After considerable repair efforts and one final ELCID inspection to confirm the effectiveness of repairs, the utility was able to salvage the existing stator core, install new coils, and return the unit to service.

CONCLUSION

Massive improvements in ac electrical machine efficiency have been made over the last century and are continuing, making it ever more necessary to maintain the condition of stator cores in peak condition to survive the stresses they are now under. Traditional test methods using core loss and high-flux ring test heating may not detect all defects, which could lead to in-service failure.

An electromagnetic test system known as EL CID is described which has the advantage that the flux levels used avoid any risk of damage, and allow ease of use in manufacture QA as well as repair and maintenance, allowing detail investigation of suspect problem areas. It may also be used to test rotor bar integrity. Practical trials have shown that EL CID has enhanced capabilities to detect faults buried under windings, and new theoretical and F.E.A modelling is in progress to enhance the capabilities and show ways that the test can offer still more insight into the nature of any faults.

Use in conjunction with advanced analysis software and robotic vehicle delivery systems, allows a flexible system that has now a long and recognised reputation of successful use in the field.

REFERENCES

[1] J. Sutton "History of EL CID and Fundamentals" *EPRI Motor & Generator Predictive Maintenance & Refurbishment Conferenc*e November 1995

[2] J.W.Shelton & B.M.Reichman "A comparative analysis of turbo-generator core inspection techniques". *47th Annual Meeting of the American Power Conference* April 1985

[3] D.Paley, B.McNamara & G.Mottershead "Verification of the effectiveness of EL CID on a hydro generator stator core" *Hydrovision Conference* July 1998

[4] A.P.Chattock "On a magnetic potentiometer" *Phil. Mag*., 24 1887

[5] G.K.Ridley "Hydro generator stator core condition monitoring by EL CID" *EPRI Motor & Generator Predictive Maintenance & Refurbishment Conference* November 1995.

[6] B. McNamara "Electromagnetic Core Imperfection Detection (ELCID)", *Latin America Power 2000, Caracas, Venezuela, May 2000*

[7] D. Bertenshaw " Low Power Core Testing using the ELCID Method" , *LH Marthinusen Rotating Machine Conference, Pilanesburg, South Africa, 25-27 July 2005*