Improvements in Testing Stator Core Condition of Medium to Large Motors

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Abstract

Stator cores in motors and generators are becoming ever more dependant on the maintenance of the inter-lamination insulation to prevent eddy currents as loadings increase. Traditional test methods such as ring flux and core loss require substantial power, and may not detect or locate local failures to allow diagnosis and repair. An electromagnetic system (the MCT2) allows detail inspection and quantification of the degree of eddy fault currents, and is able to detect hidden defects. The low flux levels used avoid any risk of damage and allow ease of use in manufacture QA as well as repair and maintenance.

1. Introduction

The stator cores of all ac electrical machines are laminated, compromising of very thin laminations of magnetic iron, each with a layer of insulating varnish or film on one surface to prevent the circulation of eddy currents through the layers. If the insulation is missing or damaged, then the effect of the alternating magnetic fields induced in the stator iron is to cause eddy currents to flow through the iron in the same direction as the conductors (fig 1), leading to undesirable energy losses and heating in the stator.

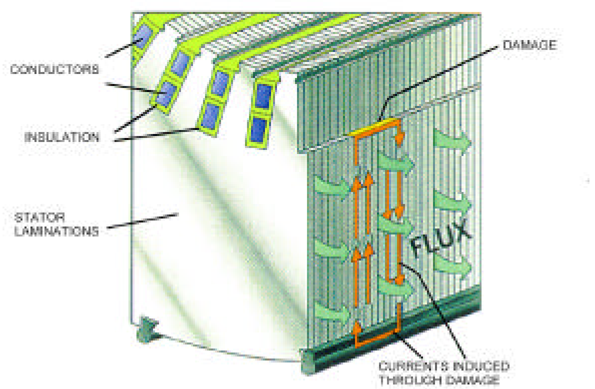

Fig 1 Eddy currents induced in a laminated core due to inter-lamination damage at the base of a slot

It is thus important that the inter-lamination insulation remains intact in manufacture and service, and this requirement is well known to those involved in motor design and maintenance.

The increasing importance of monitoring this aspect of machine construction is seen from Glew's study[1] of the progressive efficiency gains in motor design over the last century. The graph in fig 2 summarises the reported increase in W/kg, showing a 14-fold increase in the output per kg of electric motors achieved over that period. This trend is continuing with no sign of limiting yet!

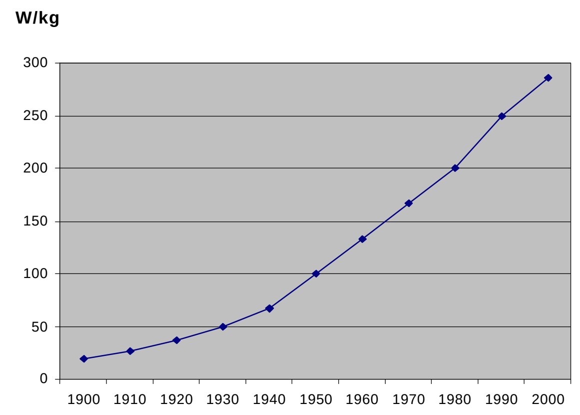

Fig 2 Output per unit mass as a function of year.

Since the largest mass is the stator, this demonstrates how the stator iron is becoming ever more loaded and more efficiently used. Whilst modern motors continue to be as reliable as their predecessors, this must be increasingly dependent on the condition of all components remaining at their design level to achieve this performance and reliability. From this the importance of being able to effectively measure and diagnose defects in stator iron inter-lamination insulation has never been more vital than today.

Common methods of testing the stator core include measuring overall core loss or by testing for local heating (Ring Flux test), both when energised to near full flux. In comparison the Electromagnetic technique utilised by the Motor Core Tester uses low power and flux levels, and is able to detect and localise very low levels of fault currents. In addition, as it is derived from test techniques used on large electrical machines[2], it is well proven.

2. Principle of Operation of Improved Test Method

Faults in the stator iron may come from a number of sources. In manufacture they can come from poor quality lamination insulation, accidents in assembly or wedging burring over teeth or slot edges, or core studs shorting on the laminations. In service they can come from foreign bodies entering the machine and damaging the teeth surface or excess heating or age causing deteriorating of the insulation.

For the test the rotor is removed and the core is excited to a low level by the temporary winding of an excitation loop around the core. A single (or multiple) turn is wound round the core as shown in fig 3, and the voltage set by means of a variable transformer to give a single turn voltage on the core of 4% of that normally applied in service. The 4% is normally used because of field experience of fault current correlation with resultant core heating.

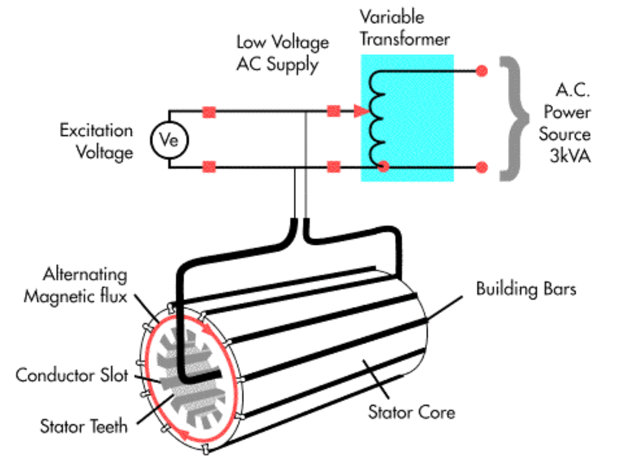

Fig 3 Excitation winding

The eddy currents induced in any damaged areas are detected by sensing the magnetic fields resulting from them. Particularly for defects on or near the surface, their magnetic field extends beyond the surface and is detected by a sense coil applied across the teeth of the core.

3. Detection Method and Measurement

The sense coil at the heart of the detection system is the Chattock magnetic potentiometer[3] (named after its inventor). It consists of a flexible uniform air-cored coil, which can be positioned to measure the magnetic potential difference between its ends. In this application, it is placed across the teeth straddling a slot, in order to measure the field caused by a typical fault current on a tooth tip as shown in fig 4.

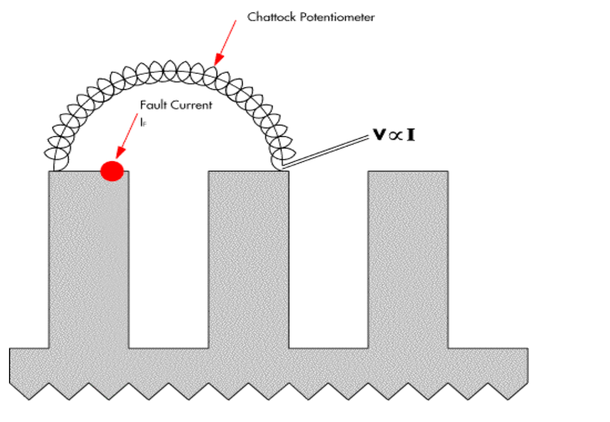

Fig 4 Chattock potentiometer positioned across fault

The ability of the Chattock to measure the actual fault current is due to Ampère's law that the integral of the magnetic field surrounding a current is equal to the current enclosed, shown in fig 5. In the situation of a chattock coil across an iron/air interface as in this case, this is the sum of the integrals in the iron and air sections (the upper and lower integrals). Since the permeability of iron is so much more than air (2000:1 typically), then essentially all the field occurs in the air part of the path and is sensed by the coil. This is described in greater detail in reference[2].

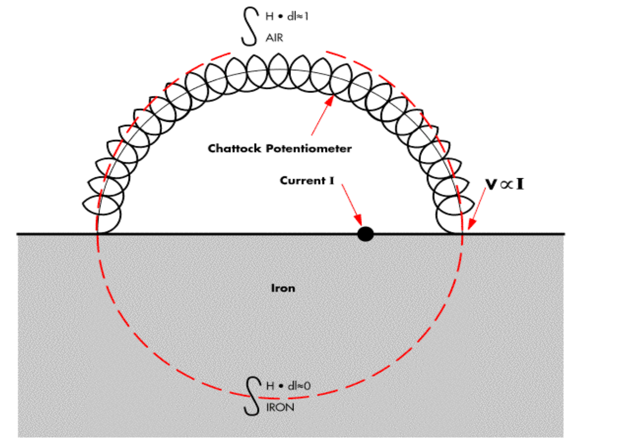

Fig 5 The two parts of the magnetic integral surrounding the fault current.

It might be expected that the iron surrounding a fault would substantially "short-circuit" the external field of a short fault. However laminations with low permeability insulation between them act to force the magnetic field to remain in the plane of the laminations. Sutton[2] has shown that even with a span of 160mm across a 10mm long surface fault, 45% of the current is still detected by the chattock, whist a more normal 40mm span detects 82%. The effect of conductor slots is to improve this further. Sutton also showed that faults deep within the body of the core can be readily detected, for example 60% of the fault current can be detected at 100mm depth if a broad (around 25°) Chattock span is used.

Thus the voltage on the Chattock coil is nearly equal to the magnetic field in that section of the core enclosed. However this is due to both the fault current to be detected and the excitation flux applied, with the problem of discriminating between them.

Fortunately the induced voltage driving the fault current is proportional to the rate of change of excitation flux, and is thus in quadrature to the excitation flux as shown in the vector diagram in fig 6. Since the fault current usually flows through some resistance (iron is a poor electrical conductor and the insulation breakdown areas are usually very localised), the current also remains substantially in-phase with the fault voltage. It thus enables the quadrature vector of the fault current (also the heat producing component) to be discriminated from the excitation by a phase sensitive detector using the excitation current as a reference.

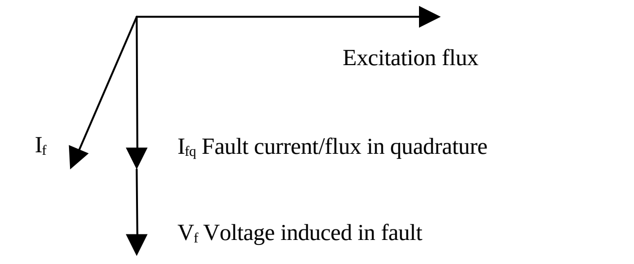

Fig 6 Vector diagram of excitation and fault voltages and currents.

This reference should in principle be derived from a measurement of the core flux. However an adequate signal can be derived from the excitation current (which is in phase with the flux), sensed by a current probe whose output is in phase with the excitation current.

In the instrument an electronic signal processor analyses the in-phase and quadrature components of the signal with respect to the reference input. The result is displayed on a meter as shown in fig 6, which can be switched to show either the in-phase signal (i.e. the excitation level) or the quadrature signal (the "quad" fault current).

Fig 6 MCT 2 Instrument

The centre-zero meter allows for positive and negative quad signals to be displayed, which is important in diagnosing the precise location of a fault. In addition the increase or decrease of signal is indicated in headphones by a variation in tone pitch. This use of "old fashioned" analogue indications and tone signals is due to the need to find maxima and minima, where digital indicators are less easy to read.

4. Operation of Test System

In use, the system is set up as laid out in fig 7, and the excitation system connected and energised. A trace winding round the core (to eliminate errors due to excitation winding resistance) is measured and the excitation current adjusted so that its induced voltage in the trace winding is 4% of normal motor operation.

The chattock coil is connected to the signal input, and the Current Reference probe is set to provide a reference signal from the excitation current. Since the chattock coil's output is in quadrature to the sensed flux, the reference signal is also delayed 90° within the Termination box to match the chattock signal.

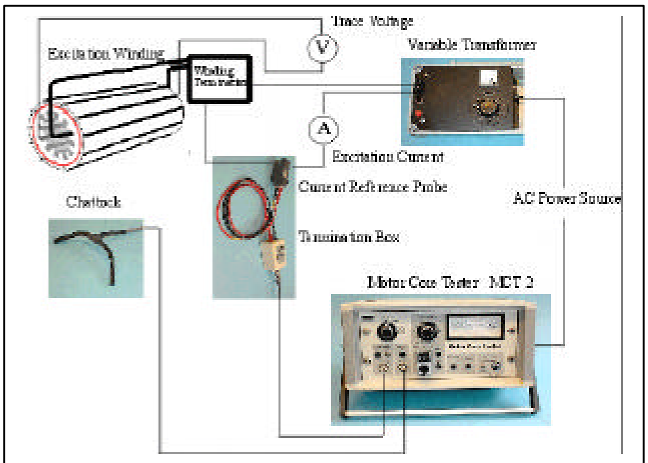

Fig 7 MCT 2 Test Setup

A section of the core that is assuredly not defective (determined by cross-checking at several different points) is tested by bridging a pair of teeth with the chattock, and adjusting the MCT 2 reference phase adjust to trim the quad signal to zero. This sets the phase sensitive discriminator ready for use.

Using a suitable range (usually 200mA), the chattock coil is then scanned across pairs of teeth down the core, such that the coil spans the opposite edges of the teeth as shown in fig 4. The meter/headphones are monitored for any rise (+ or –) in the quadrature signal, which would indicate a core fault. To assist operators, the chattock coil can be supported in a holder that aligns the coil with the teeth edge.

Any rise in quad signal above a pre-defined amount, typically 100mA, is registered and its variation with scan distance down the core is monitored and noted. By comparing this data with that from the same distance down adjacent pairs of teeth, a profile can be built up that allows interpretation of the results.

5. Interpretation of Results

In normal operation, the in-phase magnetic potential between a pair of teeth is constant, being the excitation ampere-turns divided by number of slots. The signal variation across the surface of a tooth will be minor. This fact is exploited by measuring across the opposite edges of the teeth so that any surface defects are included in both scans that include that tooth, and allows discrimination between defects that are on the tooth surface and those down the slot.

Fig 8 shows the possible alternative signals that may be seen, and their likely meanings. Three possible scenarios are shown. In case A, a simple fault on the tooth surface is indicated by a similar sharp rise in quad signal across both slots 13-14 and 14-15, indicating both measurements enclose the fault within the chattock.

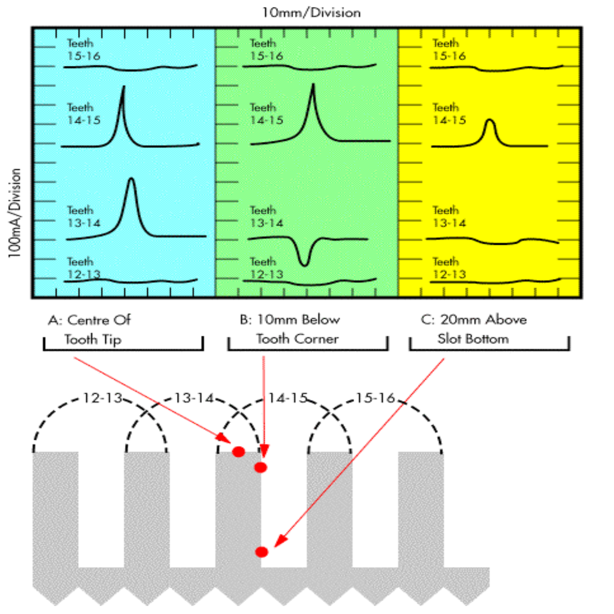

Fig 8 Plots of MCT 2 meter readings, possible faults and their signal responses

In case B with the fault down the slot side, only span 14-15 encloses the fault, whereas 13-14 has it alongside but outside. This gives rise to a similar but negative signal for 13-14, clearly showing that this fault is within the 14-15 span and near but outside 13-14.

In case C, only span 14-15 shows a quad signal, and the fact that neither of the adjacent spans show a significant signal indicates that the fault is deep seated in the slot

In the case of a defect within the body of the iron, a weaker signal will be registered when the chattock is “over” the fault, reducing but remaining in the same polarity as the spans move away from the locality either side. In addition by bridging more teeth with a longer chattock, the fault signal will increase, indicating a buried fault.

The level that is considered a problem requires consideration. Broad industry experience has concluded that quad signals under 100mA are normally not problematic at a 4% excitation level. Levels substantially above this will give rise to significant local heating in service, and potential consequent reduction in life and reliability. Field experience with large machines[4] has shown 5-10°C temperature rise correlation with 100mA fault currents.

6. Benefits of Electromagnetic testing

The alternatives to the Electromagnetic test are usually core loss testing, or high power Ring Flux testing using thermal checks or IR imaging to detect defects. The former will fail to pick up small local faults which do not contribute significantly to the loss, but which could still lead to serious local over-heating. In addition no information about fault location is provided.

The latter test has the disadvantage that high voltage and current levels can be needed, time is required to allow local hot-spots to become established, and there is a risk of causing further damage to a defective motor core since the normal motor cooling is not functioning. In addition faults buried in the core may not be evident, and if they are near a conductor slot will affect insulation life.

The Electromagnetic test avoids all these disadvantages and also has the ability to detect faults in slots with the windings still in place. Further, as the test does not cause any heating and can be repeated on a repair at any time, the effectiveness of repair work can be immediately assessed as it progresses. It may also be applied as a QA check on machines in production, remembering that a 10% over-temperature on winding insulation can reduce its life by 50%.

Another application is the rapid testing of rotor bar continuity in squirrel-cage rotors. If the excitation current is passed through the rotor cage (end-to-end across diagonal corners to equalise current distribution) then the magnetic field from each rotor bar may be tested. In this case the MCT 2 is set to read phase and a small chattock is positioned across each bar in turn. Any broken bars, or bars with poor connection, will be readily evident as having little or no current flow. Analysis of the current profile along defective bars provides further information on the nature and scale of partial faults.

7. Excitation Techniques

As the quad fault current is in proportion to the excitation flux, it is important that this flux is uniform around and along the core. Thus the ideal excitation winding is one where the wire(s) are run axially down the centre of the stator as shown in fig 9a.

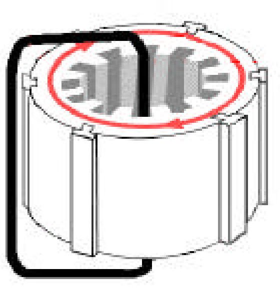

Fig 9a Axial excitation winding (preferred)

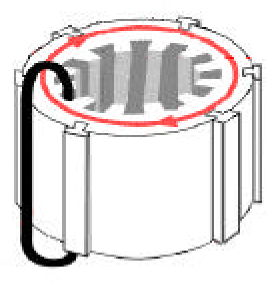

Fig 9b Side excitation winding

In addition, to prevent the ends of the core being unduly over-induced by the excitation winding, the winding should extend at least the radius of the bore past the end of the stator before coming back around the core.

It is also important that the chattock coil does not come too close to the excitation winding, else it may pick up the field from the winding, as well as the stator core. On smaller machines this may mean that the winding has to be bunched around one part of the core, opposite the area under test, as shown in fig 9b. In this case the excitation winding should be moved around the core as the test progresses, so that it is always approximately opposite the test slots.

As the excitation voltage is only about 4% of normal operation, the power needed is very low. This allows testing of almost all machines using normal 10-16A mains supplies. Whilst in an ideal situation the voltage is adjusted to the preferred level with a variable transformer, by judicious choice of number turns it is often possible to match the total turns voltage to the mains supply a or step-down isolating transformer, eliminating the need for the variable transformer.

8. MCT 2 Instrument and System

The MCT 2 Instrument (fig 6) is the heart of the measurement system. It has inputs for the chattock and reference signals, the latter also able to be switched to use the mains supply as reference (since the excitation supply is inevitably mains powered). The meter is switch-able to show the phase and quadrature parts of the signal, with an extensive set of ranges provided from 20mA to 50A fsd. Indicators show if the reference or signal is outside satisfactory bounds.

Fig 11 MCT 2 System

The phase adjust is used to set the phase of the quadrature discriminator so that only the quad signal indicative of faults is shown. This is necessarily adjustable, as different cores may have marginally different phase differences between the excitation current and the resultant core flux in certain areas (such as the ends).

To allow easy use around the workshop or field, the unit can be battery powered for up to 20hrs, or operated off mains whilst the battery is recharging.

Whilst compliance with the CE marking requirements is now normal for EU sale, an important operational facet is compliance with the immunity requirements of the EMC Directive. As the chattock signal input has a sensitivity of 100uV/A, this means that the signal level for the 100mA problem threshold is only 10uV, less than the input expected on radio receiver aerial inputs! Consequently the achievement on the instrument of 30A/m 50Hz (A) magnetic field and 3V/m (B) RF immunity, as required by the EMC standard EN61326, is commendable and indicates that spurious pickup is unlikely.

The complete MCT 2 test system shown in fig 11 includes all components needed for a full motor test.

9. Typical Test Results

Sample test results using this technique are shown below to demonstrate the ability to rapidly and visually see defects. The first is from a test done on a 10MW motor with 120 slots. The quad signal in the majority of the core was well below the 100mA threshold, however significant amplitudes were detected in the vicinity of slots 23-25. In order to demonstrate the effect, the quad signal was recorded at 10mm intervals along the 350mm core for slots 22 to 26, and is shown plotted in fig 12.

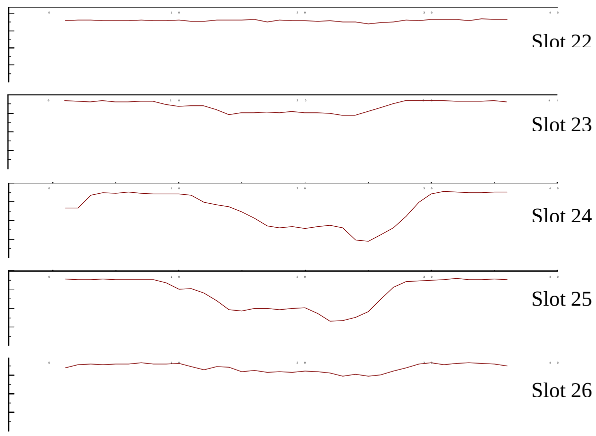

Fig 12 Quad results for 10MW motor stator (vertical scale 0 to -400mA)

This showed that a substantial defect existed on the teeth between slot 24 and 25.

In a second test on a rotor from a 80HP motor, the integrity of the 46 rotor bars was checked by the method described in section 6. A current of 2A was passed through the rotor cage from end ring to end ring, and the phase signal monitored across each bar. The results are plotted as a histogram in fig 13.

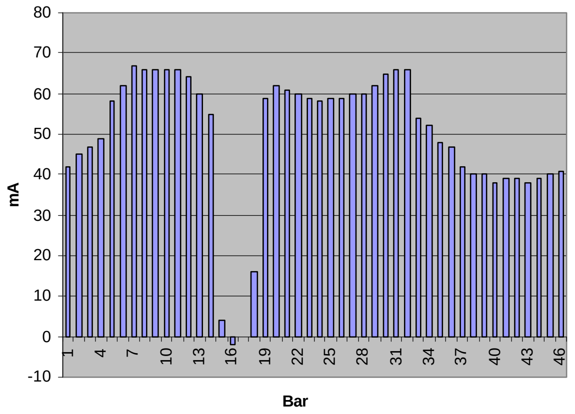

Fig 13 Rotor bar test currents

This clearly shows that bars 15 to 18 are defective (they were open circuit).

10. Conclusions

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 ring-flux heating may not detect all defects, which could lead to in-service failure. In addition they may cause further damage to the machine.

An electromagnetic test system is described which has the advantage that it operates at very low energy levels, allows detail inspection of suspect problem areas and can be used to immediately monitor the effectiveness of repairs in progress. It may also be used to test rotor bar integrity. Using techniques proven in large machines, quantitative test results are provided which can be compared between machines and used as a metric in both production quality control and repair and refurbishment activities.

11. References

1. Glew N., “Design and manufacture of energy efficient and environmentally friendly large machines”, IEE Power Division Colloquium 99/178, Sept 1999.
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3. Chattock A.P. “On a magnetic potentiometer” Phil. Mag. 24, 1887
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